"Errors using inadequate data are much less than those using no data at all.”
— Charles Babbage, circa 1850

Chapter III
Intercomparison of Ground-based Meteorological Instruments
Characteristics of Boundary Layer and Precipitating clouds are not easy to measure and a single meteorological sensor never enough to depict the whole picture. There are no ground-based instruments which can do it all. Different sensors have to be combined in a clever, synergistic way. The combination of instruments should give better accuracy of the individual sensors.

3.1 Introduction

Ground-based remote sensing observations of atmospheric variables are collected in many sites worldwide for several applications, ranging from weather monitoring, meteorology, climatology, aviation support, etc. (Gage and Balsely, 1978; Ecklund et al., 1979; Balsley and Gage, 1980; Carter et al., 1989; Doviak et al., 1995; Carter et al., 1995; Angevine, et al., 1998; Reddy et al., 2002; 2010; Pan et al., 2010; Maruri et al., 2013). Ground-based remote sensing instruments based on different physical principles and working at different wavelengths of the electromagnetic (EM) spectrum are diversely sensitive to the different atmospheric properties. Thus, instrumentations are able to observe diverse aspects of the atmosphere, such as composition, motion, and thermodynamically properties (temperature, humidity, etc.). Microwave and infrared radiometers are sensitive to atmospheric temperature, humidity, cloud content, and microphysics; Raman and Doppler lidars are sensitive to atmospheric aerosols, temperature, and wind; weather and cloud radars are sensitive to precipitating and non-precipitating hydrometeors; wind profiler radars and sodars are sensitive to wind direction and speed (Larsen 1982; Strauch et al., 1984; Weber et al., 1993; Angevine et al., 1998; Luce et al., 2001; Cohn and Goodrich 2002; Adachi et al., 2005). Each of these atmospheric parameters can be retrieved from ground-based observations with some degree of accuracy and certain advantages and limitations. However, instead of a single instrument, quite commonly a variety of ground-based instrumentation is deployed at the same site in order to cover more than one aspect of the atmosphere at the same time. While these instruments are typically used in standalone mode, their combination offers new possibilities to overcome intrinsic limitations. For example, a single instrument/technique may present limitations related to short range of application, poor spatial resolution, poor accuracy, ambiguous
solution, simultaneous sensitivity to more than one parameter, or a combination of the above. In other words, each single instrument provides information about one or more parameters with the accuracy and the limitations associated with the used technology and technique, but sometimes part of these limitations may be overrun by the synergetic use of the other independent instrumentation operating at the same site (Webster and Houze, 1991; Russell et al., 1993; Stephens 2005; May et al., 2008; Rao et al., 2008; Romo et al., 2012; Penide et al., 2013; Sengupta et al., 2013).

Several examples of integrated approaches are using different ground-based instruments and observations from the last decade. Out of which one of the most important European atmospheric anchor observatories, the Cabauw Experimental Site for Atmospheric Research (CESAR) in the Netherlands (Figueras, et al., 2009). In those and other research activities [North American Monsoon Experiment (NAME), Tropical Warm Pool International Cloud Experiment (TWPICE) (May et al., 2008), Hydrometeorological Arrayfor ISV-Monsoon AUtomonitoring (HARIMAU) (Sakurai et al., 2005), both physical and statistical methods are used to retrieve atmospheric parameters from ground-based observations.

The concept of an integrated approach relies on finding observations that can be used in synergy for either estimating a parameter with better accuracy or getting information about new parameters that can be derived from the ones obtained by the single instruments. Therefore, the characteristics of the instrumentation taking part in an integrated approach should be,

- providing independent observations (different instruments)
- providing complementary observations (different spectral regions, viewing angles, active/passive methods)
- measuring different aspects of the atmosphere
- sensing a somewhat common observation volume

In case the physical process of the radiation–atmosphere interaction is properly understood, retrieval algorithms can be made physically consistent. This approach is used when the theory is well understood and the relationships between the variables and the observations are analytically solvable and easy to invert and implement. Conversely, if the relationships between the variables and the observations are not analytically
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solvable and/or difficult to invert and implement, statistical methods are typically used. Thus, this approach is often used when the retrieved parameter is linked to the observations by complex relationships with a large number of degrees of freedom.

3.2 Data-Base

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is carrying out research at Palau Islands focusing on the Pacific Area Long-term Atmospheric observation for Understanding of climate change (PALAU) project to understand the mechanism of cloud-precipitation processes and air-sea interactions over the warm water pool, focusing on seasonal and intra-seasonal variations. JAMSTEC installed ground based multi sensors viz., a Vaisala (formerly Radian) Wind Profiler Radar (WPR), Vaisala CT25K Laser Ceilometer, Joss-Waldvogel disdrometer (JWD), METEK Micro Rain Radar (MRR) and Automatic Weather Station (AWS) at Aimeliik observatory (7.3°N, 134.3°E). Field experiments in Palau provided long-term high-temporal resolution observational data over the off-equatorial region of the warm-water pool. This impressive variety of measurements makes Aimeliik observatory as an ideal location for many studies, especially on evolution marine boundary layer and type of precipitation studies. Radiosonde observations are made at the National Weather Service (NWS) office in Palau provided by the National Oceanic and Atmospheric Administration (NOAA) in the capital city of Koror (7.33°N, 134.48°E) with a spatial separation of 7 km.

Figure 3.1 shows the data availability of wind profiler radar, Joss-Waldvogel Disdrometer, micro rain radar, automatic weather station and Ceilometer, at Aimeliik Observatory, Palau Islands. From the figure one can notice that fairly good amounts and large volume of data from all ground-based sensors are available during Easterly and Westerly monsoon.
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Fig. 3.1 Ground-based remote sensing observations of atmospheric variables data between April 2003 and March 2007 are collected at Aimeliik Observatory using (a) Wind Profiler Radar (WPR), (b) Joss-Waldvogel Disdrometer (JWD), (c) Micro Rain Radar (MRR), (d) Automatic Weather Station (AWS) and (e) Ceilometer.
Non-availability of the data, mainly, is due to the power failure at the observational site and also due to the malfunctioning of the instrument. Power failures are very often in the westerly monsoon period due to heavy winds that causes big trees to fall down on to the electrical cables and power loss will continue even from days to a week even though a 10 KVA dedicated UPS attached for data collecting/acquisition systems.

The large amount of meteorological data collected at Aimeliik Observatory is surely unique. The data measured with the instruments is stored in a database. In the data base the data is sorted by the different instruments. Periodically, every fortnight, the time is synchronized for all the data acquisition systems and computers by using Global Positioning System (GPS) standard time.

At Aimeliik Observatory, instead of a single instrument, several ground-based instruments are deployed to cover more than one aspect of the atmosphere at the same time. Table 3.1 shows the atmospheric variables and the associated instrumentation which is able to provide useful information over Palau from Aimeliik observatory.

The Wind Profiler radar data output contains three [Zonal(U), Meridional (V) and Vertical beam (W)]; spectrum data and also three moments data viz., signal-to-noise ratio (SNR) dB, Doppler Velocity (m/s) and Spectral Width (m/s). Furthermore, carrier 30-minutemean wind components U, V, W, in m/s and the standard deviations of these. The total horizontal wind (m/s) and direction (0-360°) is available as well. Wind profiler data is available from April 2003 to March 2007. Although Figure 3.1(a) shows the observation period as of the end of March 2007, wind profiler operation is continued. During this period, a total of 1140 days of wind profiler data are available for analysis.
Table 3.1: List of instrumentation and its associated atmospheric variables.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Name of the Instrument</th>
<th>Physical quantities measured</th>
<th>Temporal, Vertical Height resolutions and Maximum Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Wind Profiler Radar</td>
<td>radar reflectivity (Clear and Precipitation), radial velocity, Spectral width $V_h(z)$, $W(z)$, $C_n^2(z)$</td>
<td>Low Mode: ~30 sec, 60 m 0.1 to 4 km High Mode: ~30 sec 200 m 0.3 to 12 km</td>
</tr>
<tr>
<td>2.</td>
<td>Lidar Ceilometer CT25K</td>
<td>backscatter profile $\beta(z)$, cloud base height</td>
<td>1 min, 15 m 0.015 to 7.6 km</td>
</tr>
<tr>
<td>3.</td>
<td>Radiosonde</td>
<td>Vertical profiles of temperature $T(z)$, $p$, $e$, $V_h$</td>
<td>00 &amp; 12 GMT every day Surface to 30 km</td>
</tr>
<tr>
<td>4.</td>
<td>Micro Rain Radar</td>
<td>profile of drop size distribution $N(D,z)$, $DSD(z)$, $W(z)$</td>
<td>1 min 100 m /200 m 0.1 to 3 km/ 6 km</td>
</tr>
<tr>
<td>5.</td>
<td>Joss-waldvogel Disdrometer</td>
<td>drop size distribution $N(D)$, $DSD$</td>
<td>1 min Surface measurements</td>
</tr>
<tr>
<td>6.</td>
<td>Automatic Weather Station</td>
<td>$T$, $p$, $e$, $V_h$, Rain intensity</td>
<td>10 sec Surface measurements</td>
</tr>
</tbody>
</table>

Rainfall plays a key role within the hydrological cycle. Its accurate and spatially revolved quantitative measurement is one of the main current challenges within the hydro-meteorological community (Marzano et al., 2002). Several techniques may be enumerated for this purpose: local direct instrumentation (such as rain gauges and disdrometers) and ground-based remote instrumentation (Micro Rain Radars). The synergy between all these instruments, with their advantages and drawbacks, is fundamental for a better comprehensive analysis of the rainfall features. For example, the measurement of hydrometeor size distributions from disdrometers can provide a powerful opportunity to directly investigate the microphysical properties of convective precipitating clouds and allow a comparison from retrievals performed, for example, by Wind Profiler Radars.
Raindrop size distributions (DSD) are crucial for understanding microphysical characteristics and rain formation processes. At observational site, Joss–Waldvogel impact-type disdrometer (RD-80) (JWD) is operated from June 2003 [as shown in Figure 3.1 b] whereas micro rain radar data collected from March 2004 to March 2007 [Figure 3.1(c)]. The basic parameter of a vertically pointing Doppler radar with FM-CW technology is a vertical profile of the velocity spectrum of falling hydrometeors (Loffler-Mang et al., 1999), which is derived from Doppler shift and radar reflectivity. Derived parameters are the average drop spectrum N(d) \( \text{m}^{-3}\cdot\text{mm}^{-1} \), the mean fall velocity \( \text{m}\cdot\text{s}^{-1} \), rain rate \( \text{mm}\cdot\text{h}^{-1} \), liquid water content \( \text{g}\cdot\text{m}^{-3} \) and radar reflectivity (dBZ) (Peters et al., 2002).

An Automatic weather station (AWS) is an automated type of weather station to measurements of meteorological parameters from remote areas to save human labour. An instrument which is able to collect and measure the rainfall intensity can be regarded as a Rain Gauge (or pluviometer). Ordinary Rain Gauge (ORG) is a part of AWS system that is in operation since June 3003. For the present study, ORG data collected from June 2003 to September 2007 is utilized. ORG can provide reliable rainfall measurements and often used to calibrate and validate rainfall estimates derived from Disdrometer, Micro Rain Radar and Wind Profiler radar observations.

The backscatter intensity depends mainly on the particulate concentrations in the air. As the size of particles varies with their moisture content, the reflectivity is influenced by atmospheric humidity, too. Clouds, fog and precipitation inhibit measurements. The performance of the CT25K ceilometer is sufficient for analyzing cloud-base height and boundary-layer structures. Compared to more sophisticated LIDAR systems commonly used for these investigations it has several advantages, including the low first range gate, its ability to operate eye safe and maintenance-free for several years in any climatic environment with just some regular window cleaning, and its comparably low price. Main disadvantage due to the low emitted power is its relatively low maximum range, but for mixing layer studies (mostly below 3 km) this does not present a problem. Raw ceilometer profiles were obtained every 15 s (integrated over 65 536 individual pulses). For this study, the original ceilometer data were averaged over period of 30-min. As shown in Figure 3.1(e), the data collected...
between July 2003 to September 2007 is utilized to understand / characterize marine atmosphere.

Regular radiosonde launches (every 12 hours) were performed throughout the deployment to characterize the thermodynamic state of the atmosphere, as well as the wind speed and direction. The radiosondes collect measurements every 2s during its ascent, providing a typical vertical resolution of 10 m in the troposphere (depending on the conditions at the launch time). These measurements can only be interpolated to the WACR time steps with limited confidence, due to the coarse temporal resolution of the radiosondes. However, some statistics can still be determined around the balloon launch times, since there are 60 months of data, comprising more than 3500 atmospheric profiles.

3.3. Performance (availability, accuracy) of ground-based Instruments

Important questions related to weather, climate, etc., cannot be answered without a broad view of the atmospheric processes and their mutual links. Some of the ground-based remote sensing sophisticated instruments viz., Wind Profiler Radar, Ceilometer/Lidar, Micro Rain Radar, Disdrometer, and Automatic Weather station are utilized to understanding these processes over Palau in Pacific Ocean. Of course, all these observing systems have strengths and weakness, but none meet the breakthrough levels of user requirements for all aspects. The solution to these requirements could be best met by a composite of different observing systems.

In meteorological sciences the role of wind profiles is becoming increasingly important. A good temporal and spatial resolution is required for this. To achieve this objective, remote sensing technology offers new systems a higher temporal resolution than radiosonde. The improvement of short-term synoptic weather forecasts as well as numerical weather prediction requires a new type of data concerning information on the mesoscale kinematic structure in good time and in the vertical. The standard method for sounding of the free atmosphere using radiosonde/rawinsonde is not able to provide data with the necessary temporal and spatial resolutions for mesoscale analyses in view of acceptable economic efforts. Due to the high temporal resolution and good vertical spatial resolution of wind profiler data, fine structures and mesoscale system features of the continuous evolution of wind fields in the atmosphere during the rainfall process can
be investigated in detail through analysis of wind directions and speeds in the vertical
direction. This high-resolution lower atmosphere meteorological data are essential for
monsoon precipitation cloud studies, mesoscale weather forecasting and climate
variation models.

3.3.1 WPR Measurements

Palau is a suitable location for studying precipitating clouds because it is
influenced by the western North Pacific monsoon (WNPM) given by Murakami and
Matsumoto (1994) and by the ENSO cycle. In addition, information about marine
boundary layer, Precipitating clouds, melting layer height and thickness in tropical
ocean regions has been particularly sparse due to the lack of experimental data.

The WPR was installed on 08 March 2003 and continuously in operation. Figure
3.2 shows a typical example of horizontal wind (vectors) at 30-minute intervals for 09
March 2003 obtained using ~200 meter height resolution. Vectors are directed upward
for a northward (southerly) component, and towards the right for a eastward (westerly)
component. Vectors are plotted at times and heights for which a consensus was obtained
among the observations in the 30-min averaging period. This is the most familiar way of
presenting WPR data. On this day, the trade wind is from the north-northeast at about
10 m/s in the lower height ranges and is overlain by wind from the south at a height
about 3 km. The WPR data for this day provides a detailed picture of how the wind
turns with height as a function of time.
3.3.1.1. Height coverage

The vertical range and temporal availability of wind and temperature measurements are an important criterion for an operational use of wind profiler radar. Especially, the maximum range depends not only from technical specification of the system but also from the meteorological conditions (especially on humidity and hydrometeor). Therefore, the maximum range shows significant temporal variations. The maximum range is determined by the strength of the backscattered power and its ratio to the noise. The dependence of the backscattered power on the atmospheric properties is described by the radar equation.

For given system parameters variations in the availability, especially in the maximum range, are caused by variations of volume reflectivity and/or the attenuation of the electromagnetic and acoustic waves in the atmosphere. The relative availability was calculated in order to evaluate the performance of the different wind profiler radar systems.

Relative availability in% = \( \frac{\text{Number of possible values}}{\text{Number of valid values}} \times 100 \)
Fig. 3.3 Wind profiler radar data availability during (a) low and (b) high mode operation.

Figure 3.3 (a and b) shows the relative availability of wind intensive observational periods. The WPR is very sensitive to precipitation particles, so that the height coverage is greatly increased up to 6 km in the high mode (with 80% probability).
3.4 Intercomparison of Wind profiler Radar and Radiosonde wind measurements

A large number of publications have discussed the accuracy and precision of WPR data based on comparisons with independent measurements (meteorological towers, tethered balloon sounding systems, Radiosondes, aircraft measurements and Doppler wind lidar) (e.g. Larsen 1983; Strauch et. al., 1987; Wuertz et. al., 1988; Weber et. al., 1990; Martner et. al., 1993; Angevine et. al., 1998; Daniel et. al., 1999; Luce et. al., 2001; Cohn and Goodrich 2002; Adachi et. al., 2005). Meanwhile, numerical weather prediction models (NWPM) data are increasingly used in lieu of independent upper-air wind measurements to estimate the quality of a wind profiler (Steinhagen et. al., 1994; Panagi et. al., 2001; Hooper et. al., 2008).

![Figure 3.4](image_url)

*Fig. 3.4: Typical example of wind speed measured simultaneously with WPR and Radiosonde on two different days.*

In order to test the reliability and consistence of the wind profiler data, simultaneous measurements with Radiosonde are necessary. We adopted a simple statistical procedure similar to that of Weber et. al., (1993) for the comparison of WPR and Radiosonde wind data. The rainy periods are excluded for the inter comparison of wind data. The simultaneous observations of wind speed and wind direction measured by WPR and Radiosonde on different day in different seasons are shown in Figure 3.4.
Typical vertical profiles of strong and moderate wind speed observed on different days in different seasons show a good agreement between WPR and Radiosonde data. In a number of situations a nearly constant bias between the WPR and Radiosonde winds has been found over the range of overlap, although the structure of the wind profiles was nearly the same. Taking into account all the differences in the two systems, fairly good agreement between the two sets of observations can be noticed/reported.

To evaluate the performance of the WPR, to perform a statistical intercomparison with the simultaneous observation of the Radiosonde. The two measurement locations are about 6 km apart. Comparison is made only when valid data are available from both wind profilers. Weber and Wuertz (1990) made an extensive comparison of wind measured with a UHF wind profiler and rawinsondes at Stapleton Airport in Denver, Colorado. Differences with standard deviations of 2.5 m/s were attributed mainly to natural variability in the wind fields. Strauch et. al., (1984) used a five-beam UHF wind profiler to derive independent near-simultaneous three-beam measurements of the horizontal wind. They found a standard deviation of 1.3 m/s for clear-air observations. Wuertz et. al., (1988) repeated the experiment between May and August during the rainy period. When raindrop fall speeds were properly included in the horizontal wind calculations, errors of 2–4 m/s were found. Schlatter and Zbar (1994) documented a detailed assessment/performance report for the Wind Profiler Demonstration Network in the United States. McAfee et. al., (1994 and 1995) have examined in detail the quality of agreement in simultaneous measurements of vertical velocities measured by two collocated profilers in Platteville, Colorado. They found that the long-term mean vertical velocities agree within about 1 cm/s after the data have been edited to remove spurious values. Our results show that the root-mean-square differences for the WPR-Radiosonde inter-comparison have been found to range within about 1.62 m/s for the wind speed. The two systems are shown to complement each other quite well considering both the availability and the reliability of the wind measurements.

In order to test the reliability and consistency of the wind profiler data, simultaneous measurements with other wind-profiling systems are necessary. Numerous studies compared the wind profiler radar measured winds with the winds
measured by other types of instruments (spatial separation between the two measurements is 6 km or greater). Inter comparison of WPR and Radiosonde observations at 1.5 km, 2.5 km and 3.5 km Scatter plot for wind speed are shown in Figure 3.5. The correlation coefficient of 0.86, 0.88 and 0.90 is observed at 0.92 at 1.5 km, 2.5 and 3.5 km, respectively. The observational results are in fairly good agreement and acceptable in view of the differences in the measurement technique. Comparisons have shown that the accuracy of the wind measurement a well-operated and maintained WPR is comparable to the accuracy of Radiosonde wind data.

Table 3.2: Statistical results from the inter comparison of WPR and Radiosonde.

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>Height, km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>N (samples)</td>
<td>1477</td>
</tr>
<tr>
<td>Mean</td>
<td>7.25</td>
</tr>
<tr>
<td>R²</td>
<td>0.87</td>
</tr>
<tr>
<td>SD(standard deviation)</td>
<td>4.52</td>
</tr>
<tr>
<td>SEM(standard error)</td>
<td>0.12</td>
</tr>
<tr>
<td>RMS</td>
<td>8.54</td>
</tr>
</tbody>
</table>
Fig. 3.5: Wind profiler radar (WPR) and Koror Radiosonde wind speed data collected during 0000 GMT and 12 GMT using for assessing the WPR performance. (a), (b) and (c) shows scatter gram of Wind speed data obtained from WPR and Radiosonde at 1.5 km, 2.5 km and 3.5 km heights. (d), (e) and (f) shows deviation of wind speed for same heights.
3.5. Comparison of Marine Boundary Layer Height estimated from Wind Profiler Radar and Ceilometer

Air–sea interactions are considered as interactive processes between nearly geostrophic, essentially non-turbulent oceanic and atmospheric flows. The physics of the atmospheric and oceanic boundary layers plays a major role in the interaction process. The different types of vertical profilers (Sodars, Wind Profiler radars, ceilometers, etc.) have the potential to provide better and more continuous information on the vertical structure of the Marine Boundary Layer (MBL) and to estimate the mixing marine boundary layer height or mixing height (MH) than radiosondes. MBL are related to the surface heat exchange between the ocean and the atmosphere and are considered to be an important physical driver in the MBL generation over the Pacific Ocean. The MBL is found to approach a quasi-stationary equilibrium over time and instance, characterized by a near constant potential temperature profile in the lower part of the boundary layer. The temperature will gradually approach the sea surface temperature (SST), and the MBL will be capped by a temperature inversion of increasing strength over time. Important physical properties about the vertical structure of the MBL can be investigated keeping both sea roughness and temperature constant and letting the MBL evolve over time towards a horizontal homogeneous state with a quasi-stationary vertical structure.

The median of the maximal SNR over all beams defines the marine boundary layer height. Therefore, the maxima air density variations are analyzed. As one range gate is 60 m depth, the highest possible inaccuracies of the MBL height are ±30 m. The marine boundary layer (MBL) height is analyzed on following fair-weather days without precipitation. Wind profiler cannot measure during precipitation and thus MBL heights cannot be detected during periods with precipitation above the Aimeliik.
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Fig. 3.6: Diurnal variation of Marine Boundary Layer evolution on 16th May 2004. Time height cross section of (a) Range corrected Signal to Noise Ratio (dB) (b) Backscatter Coefficient [1/m/str].

Fig. 3.7: Intercomparison of Marin Boundary-layer height obtained from Ceilometer and Wind Profiler radar.
Eresmaa et al., (2006) method applied for estimating the mixing height from (an idealised backscatter profile is fitted to the observed backscatter profile) ceilometer measurements. To evaluate the performance of the WPR [for estimation of Marine boundary layer Height (MH)], the statistical inter comparison with the simultaneous observation of the Ceilometer has been made. The WPR and Ceilometer are about 1.5 m apart. Figure 3.7 shows a scatter plot of MH measured simultaneously with WPR and Ceilometer. The correlation coefficient is around 0.88, which is probably acceptable in view of the differences in the measurement technique. The two systems are shown to complement each other quite well, considering both availability and reliability of the MH measurements.

3.6 **Inter comparison of Rain rate obtained from JWD and Ordinary Rain gauge (ORG)**

The disdrometer gives the number of drops that impact its sensor each minute in twenty different size classes, from which the rainfall intensity can be computed. The data from the disdrometer are compared with observations using an ordinary rain gauge. The JWD was originally designed for the purpose of calculating radar reflectivity factor and rainfall rate. The JWD is a reliable instrument that can be operated continuously and unattended. At Aimeliik site the disdrometer and Ordinary Rain Gauge (ORG) are collocated with a spatial distance of about 2 meters. It is checked the performance and reliability of disdrometer, and ORG in a variety of rainfall regimes during easterly and westerly monsoon.

For comparison study data collected from JWD and ORG from April 2003 to March 2005 are taken. These data were compared with the rainfall rate obtained using the disdrometer, as a means of validating the disdrometer data. The disdrometer data corresponding to this period was taken for comparison. Generally, a visual comparison tells us that both the instruments agree in rain rate measurements.

In general, the rainfall rate obtained from the ordinary rain gauge was less than that computed from the disdrometer data [Figure 3.8]. When comparing the data from the ordinary raingauge and the disdrometer, it is useful to note the following points.
Fig. 3.8: Comparison of rain rate obtained from disdrometer and ORG on different rainfall events.

The disdrometer is a very sensitive instrument that detects even a single drop that falls on its sensor. Consequently, rainfall intensities are recorded with as low as 0.001 mm/hr. But there are certain factors that affect its measurement. The most important factor is that the disdrometer requires electric power, and hence, loss of power could lead to loss of data. Further, since the disdrometer is sensitive only to raindrops of diameter greater than 0.3 mm, the contribution from smaller drops to total rainfall, though small, is not accounted for. Similarly, since all drops larger than 5.3 mm fall into the same size class, there is a possibility that the mean drop size...
may be underestimated if very large drops are present, as could happen during heavy rain. All these would tend to reduce the total rainfall obtained from the disdrometer. Another possibility is that of raindrops splashing on the surface, and some of the droplets thus produced falling on the sensor. The company recommends keeping the sensor at the surface level to reduce the impact of winds that could produce spurious data. The sensor was, accordingly, kept on a low stool, so that the possibility of rainwater splashing on the ground and falling on the sensor was virtually zero.

Figure 3.9 shows a comparison of different rain events during July 2004. High correlation of 0.9 is found in Westerly monsoon when compared with about 0.8 in Easterly monsoon rainfall. Figure 3.9 (a) shows time series of rainfall rate estimates from the disdrometer and ORG during July 2004 for 8 different precipitation events and total duration of 918 minutes. Different rainfall conditions encountered during July 2004 including stratiform rainfall, summertime convective precipitation (>100 mm/hr) and mesoscale convective systems in the easterly to westerly monsoon.

Rain rates obtained from the JWD were compared with ORG estimated rain rates during different seasons. The results of a linear least-squares fit for each season are given in Table 3.2. The standard error of estimate (SEE) is expressed as a percentage of the average rain rate from the ORG for all seasons. The summer transition (May) showed the smallest value of the linear fit about 17% and winter transition (October) the largest of 29%. Overall, the disdrometer and ORG performed well, with inter correlations of order 0.85 and bias less than 15%, however both instruments showed some limitations under different rainfall situations. In particular, under extremely heavy rainfall rates (> 100 mm/hr), the bias between the disdrometer and the optical rain gauge was low. Under light rainfall rates the optical gauge was more sensitive than the disdrometer and the bias is high. This may be due to the background noise levels. It has been suggested that variations in the drop size distribution are responsible for the disagreement between the ORG and JWD. Though there exists small variations in the estimation of rainfall from both systems, they are fairly good in agreement. Comparison results are very much encouraging
that the disdrometer data can be used for the investigation of seasonal variation of DSD.

**Comparison of Rain rate**

![Comparison of Rain rate](image)

**Scatter plot of Rain Rate**

![ Scatter plot of Rain Rate](image)

**Fig.3.9** (a) Comparison of rain rate obtained from JW disdrometer and ORG for 8 precipitation events during July 2004.

(b) Scatter plot of rain rate obtained from JW disdrometer and ORG for 8 precipitation events during July 2004.
Table 3.3: Two-year (from April 2003 to March 2005) statistical comparison of rain rate obtained from JWD and Ordinary Rain Gauge.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Year</th>
<th>Season</th>
<th>Number of Observations (min.)</th>
<th>Intercept</th>
<th>Slope</th>
<th>Standard error of estimate (Percentage of Mean) (SEE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2003</td>
<td>Easterly</td>
<td>1843</td>
<td>0.18</td>
<td>1.05</td>
<td>17%</td>
</tr>
<tr>
<td>2</td>
<td>2003</td>
<td>Westerly</td>
<td>2855</td>
<td>-0.49</td>
<td>1.33</td>
<td>20%</td>
</tr>
<tr>
<td>3</td>
<td>2004</td>
<td>Easterly</td>
<td>2343</td>
<td>0.90</td>
<td>1.00</td>
<td>24%</td>
</tr>
<tr>
<td>4</td>
<td>2004</td>
<td>Westerly</td>
<td>2754</td>
<td>0.11</td>
<td>0.88</td>
<td>29%</td>
</tr>
</tbody>
</table>

3.7 Comparison of Joss-Waldvogel Disdrometer with Micro Rain Radar

Information on raindrop size distribution (DSD) at near surface and aloft is of interest in different areas like radar meteorology and cloud physics. There is much interest in these areas for several reasons, including climatic change due to human activities. With the development of JWD and MRR instruments that can give drop size data continuously and at relatively low costs, DSD measurements are becoming more common.

The reliability of the MRR data has been assessed by comparing the data obtained from the MRR with that from a co-located Joss–Waldvogel impact-type disdrometer. Monsoon precipitation (3369 minutes) data from 01 to 31 July 2004 were used to evaluate the precision of the Micro Rain Radar. The compared quantities were: 1-minute averages of the first six moments of the Rain drop size distribution viz., rain rate, Radar Reflectivity and the accumulated precipitation. Figure 3.10 shows comparison of Rain integral parameters obtained from MRR and JWD during the passage of different precipitating cloud systems. From the observational results it is found that rain rates are fairly in agreement with the rain gauge, but the MRR measured higher accumulation during lower rain rates - due to lower JWD sensitivity-and heavy rain, partly caused by splashing losses. Small drops are subject to turbulence, which masks the true terminal velocity leading to measurement error, whilst large drops are often under sampled by the MRR. Further
errors are attributed to wetting losses, wind effects, drop splashing and dirt, condensation on instrument, evaporation and on-site turbulence. MRR also suffer detectable wind induced error when measuring run rate, since Doppler spectra is shifted if the vertical alignment of the radar beam is worse than $\pm 3^\circ$. Vertical wind can lead to over estimation of drop size and therefore an under estimation of drop numbers. However, the MRR's DSD (at its lowest level) shows good agreement with that of Disdrometer.

Fig. 3.10 (a) Comparison of Radar Reflectivity obtained from disdrometer and Micro Rain Radar on 25 July 2005.
(b) Comparison of rain rate obtained from disdrometer and Micro Rain Radar on 25 July 2005.

Figure 3.11 (a) and (b) shows the correlation plot of MRR and Disdrometer Reflectivity and rain rate measurements. Correlation coefficient between two measurements is found to be about 0.9- 0.8. Scattering of rain rate is higher above 10 mm/h. This may be due to the different measuring principle of the instruments and because of the fact that backscattered signal is noisy at high rain rates.
Fig. 3.11 (a) Scatter plot of Radar Reflectivity obtained from disdrometer and Micro Rain Radar during July 2005.

(b) Scatter plot of rain rate obtained from disdrometer and Micro Rain Radar during July 2005.

Rain accumulations and rain rate measurements from different instruments has been compared to understand the reliability of the data. Since this thesis mainly depends on the rain DSD data and its integral parameters, it is essential to have a comparison between the DSD obtained from Disdrometer and MRR. Such a comparison carried for a rain event on 12th October 2005, that lasts for hardly five minutes (02:00 to 02:05 hrs) is shown in Figure. 3.12. The average rain rate of this event was 3.34 mm/h. The decreasing trend as diameter decreases below a diameter of 0.6 mm is shown by both the instruments. The minimum available altitude at which DSD is given by the MRR is 200 m. The DSD data obtained from the Disdrometer and also that given by MRR for a height of 200 m follows a gamma distribution function. The decreasing trend as diameter decreases below a diameter of 0.6 mm is shown by both the instruments. The tailing end of the DSD spectrum also showed good agreement.
III. Intercomparison of Ground-based Meteorological Instruments

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Fig.3.12 Comparison between JWD and MRR DSD from 02:00 to 02:05 IST, hrs, on October 12, 2005.

Comparison of the DSD data obtained from Disdrometer and UHF wind profiler done by Williams et. al., (2000), shows that good agreement was there for the drop size measurements whose diameters > 1.5 mm, but poor agreement was there for small drops (Williams et. al., 2000). The magnitude of the difference in small drop estimation was proportional to the reflectivity (and rain rate). MRR has good agreement with optical Disdrometer throughout the drop diameter, as far as the DSD measurements are concerned. But the small drops are being underestimated by JW Disdrometer. The comparison with an ordinary rain gauge (1 min integration time) for a 5 months summer period show a correlation coefficient of $r = 0.87$ for the rain rate and agreement within 5% for the total rainfall integrated over the whole period (Peters et. al., 2002).

3.8 Comparison of JWD, MRR and TRMM 3B42-V6 data

The 3-hourly rain rate derived from Disdrometer and MRR is compared with the TRMM satellite 3B42-V6 data (Figure 3.13). It is apparent from the figure that the data from Disdrometer and MRR agree well. Since the TRMM data is an area averaged data, the difference from former 2 instrument’s data could be clearly made
out. In order to compare with the Ordinary rain gauge data, the daily accumulations are derived from all other three sensors. Agreement between all the four sensors is very clear from such a comparison.

![Comparison of July 3-hourly (top panel) and daily (bottom panel) rainfall obtained from TRMM, Disdrometer, MRR and Ordinary Rain Gauge.](image)

The data collected from ground-based instruments at Palau have been compared and their acceptability for the studies has been brought out. The rain rate, rainfall and DSD data obtained from JWD, MRR and Ordinary Rain Gauge instruments are found to be agreeing very well within the limits of experimental error. Now, with this confidence, analysis of this data for the study being presented in the further chapters can be explained.
3.9 Monsoon Activity over Palau

Seasonal variation over Western Pacific region is closely related to the Asian monsoon. Western North Pacific region is one of the distinct monsoon regions (Murakami and Matsumoto, 1994). The term “monsoon” has been generally defined by a seasonal variation of surface wind. Western Pacific region has been recognized that low-level wind changes its direction apparently from easterly to westerly during northern hemisphere summer monsoon. Previous reports suggested that not only convective activity but also low-level wind direction is useful tool for monsoon definition over this region.

Easterly and westerly monsoons (wind regime) are over Palau definition by utilizing long-term radiosonde data and wind Profiler radar data. Figure 3.14 illustrates the easterly and westerly wind regime at Palau from 1973 to 2007 by using radiosonde data. From this figure it can be noticed that onset of the westerly wind regime occurred between May and July, and the withdrawal dates appear between September and December. The westerly winds did not exceed the threshold of 5 m s\(^{-1}\) until August in 1973, 1988, 1995, and 1998. Onset of the westerly wind regime was vague and undefined during these years. Westerly winds exceeded the threshold before May.

However, considering previous studies of the seasonal march, we did not take these dates into account for the onset of the westerly wind regime. Tanaka (1992) suggested that the onset date of the western North Pacific monsoon delayed in the El Niño years and appeared early in the La Niña years. There were three El Niño years in which the westerly winds did not exceed the threshold. There were four La Niña years in which the westerly winds exceeded the threshold before May. The monsoon onset defined by low-level westerly wind at Palau was also affected by ENSO events as suggested by previous studies (Tanaka 1997; Wu and Wang 2000). We used the term of El Niño and La Niña years defined by the Japan Meteorological Agency (more information available online at http://okdk.kishou.go.jp/products/elnino). Two major concentrations of the onset of the westerly wind regime occurred in the middle of May and the middle of June. The dates of the onset of the westerly wind regime may be affected by the intra-seasonal oscillation.
Fig. 3.14 Koror-Radiosonde Observations from 1952 to 2007. Onset of Westerly and Easterly monsoon.
Fig. 3.15 Wind Profiler Radar estimated 10-day averaged horizontal winds observed during 2003, 2004, 2005 and 2006.

We also defined the monsoon by using Wind Profiler radar observations over Palau. The arrows indicate the direction of wind: arrows pointing upward indicate wind blowing toward the north (i.e., southerly winds); arrows pointing right indicate wind heading the east (i.e., westerly winds). The lengths of arrows are proportional to wind velocities (see legends at the bottom-right corner). The coordinates indicate the height from the ground. Wind data are drawn up to 5 km at intervals of 150 m. To make it easier to note the variation in seasonal winds, the westerly winds are indicated in red and easterly winds in blue. In case of failure of the wind profiler radar, or a few effective observations caused by weak atmospheric echoes, no arrows are drawn in Figure 3.15 westerly monsoon onset appears around May to July.
Withdrawal dates appear around September to December. The dates are affected by the phase of intrapersonal oscillation. We can see that westerly wind does not always blow even during westerly monsoon season.

**Table. 3.4: Classification of the study period into Easterly and Westerly monsoon period in 2003, 2004, 2005 and 2006.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Easterly Regime</th>
<th>Westerly Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Mar, Apr, Dec</td>
<td>May, Jun, Jul, Aug, Sep, Oct</td>
</tr>
<tr>
<td>2004</td>
<td>Jan, Feb, Mar, Apr, May, Dec</td>
<td>Jun, Jul, Aug, Sep, Oct, Nov</td>
</tr>
<tr>
<td>2005</td>
<td>Jan, Feb, Mar, Apr, Oct, Nov</td>
<td>May, Jun, Jul, Aug, Sep</td>
</tr>
<tr>
<td>2006</td>
<td>Jan, Feb, Mar, Apr, May, Oct, Nov</td>
<td>Jun, Jul, Aug, Sep, Oct</td>
</tr>
</tbody>
</table>

The study period is classified into westerly and easterly monsoon regimes (Kubota et al., 2005) as shown in Table 3.3. The onset of westerly monsoon occurred between June and July and the withdrawal occurred between September and December (Easterly monsoon). The present observations are categorized as non-precipitating, easterly and westerly monsoon convective days. Here convective day implies that the precipitation has taken place during that day, which is subjective.