Chapter 2

Experimental Site and Instrumentation
CHAPTER 2

2.1. INTRODUCTION

This chapter describes the experimental site and the instruments that are used to measure black carbon concentrations, ozone, NO\textsubscript{X}, and SO\textsubscript{2} mixing ratios, solar radiation and meteorological parameters.

2.2. Experimental Site

The observations are made from the climate observatory (known as ICON short for Indian Climate Observatory Network) of National Atmospheric Research Laboratory (NARL) located at Gadanki (13.48° N, 79.18° E), a rural site in the Southern part of India (Figure 2.1 a).

![Figure 2.1](image)

Figure 2.1: (a) Location of Gadanki in India. (b) ICON observatory located at NARL

The observatory is located on a hillock, a place whose altitude is the highest in the NARL campus. The instruments are kept on the top floor of the ICON building (Figure 2.1 b). There is no major industrial activity near the observational site except for the road connecting Tirupati and Bangalore, where the traffic is low. The areal distance from the road to the observation site is 1.5 km and height difference between
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the road, and the place of observation is about 50 m. The location is approximately 390 m above mean sea level. The laboratory is surrounded by hills having average heights of ~750 m.

2.3. Black Carbon Measurements

Black carbon is a graphitic carbon particle produced in incomplete combustion. The concentrations of black carbon are being measured from ICON observatory since April 2008 using Aethalometer, which uses optical attenuation method. In this method, the attenuation of the light beam through filter paper containing aerosols is measured at seven wavelengths and is used to calculate the absorption coefficient and black carbon concentration.

Figure 2.2: Model AE31 Aethalometer being operated from ICON observatory

Magee-Scientific (Model AE31; USA) aethalometer is used for the measurements of black carbon. It has seven lamps of wavelengths 370 nm, 470 nm, 520 nm, 590 nm, 660 nm, 880 nm and 950 nm. A schematic diagram of the aethalometer is shown in Figure 2.3. It is an automatic device in which ambient air is
drawn into the instrument and is made to pass through quartz fiber filter since it is chemically inactive and usable for offline chemical analysis of particulate matter collected on the filter. The air is drawn by a vacuum pump connected to the inlet tube of length of 2 m and diameter 6 mm.

Figure 2.3: Schematic diagram of Aethalometer

The rate of accumulation of black carbon particles on filter paper depends on the flow rate and sampling spot area. The high sensitive measurements can be achieved by having more flow rate and smaller spot area. The flow rate for NARL aethalometer is set to be 2.9 litres per minute (LPM). The concentration of black carbon is derived from the formula

\[ BC = \frac{d(\text{ATN})}{\sigma} \cdot \frac{A}{V} \quad (2.1) \]

where BC – black carbon concentration
ATN = 100*\log(I_0/I) – attenuation of light through filter tape
I₀ and I – initial and final intensities of light

σ – specific attenuation cross section for a particular wavelength (cm²/g)

A – spot area on the tape

V – volume of air sampled

The concentration measured at 880 nm wavelength channel is considered as equivalent black carbon (black carbon) concentration, since it has minimum interference from other species and is considered to be the standard channel for BC measurements with this technology (Hansen, 2005). The signal is corrected for dark current (the current measured by the detectors when the lamps are off). The changes in absorption coefficient of filter paper are converted to equivalent BC mass by dividing it with mass absorption cross-section 0.166 cm²/µg (at 880 nm). The error estimated by the supplier is 5% in BC concentrations. In addition to this, there can be errors due to variations in temperature, loss of particles in the inlet and shadowing effect. Due to multiple scattering in the filter matrix, non-linearity creeps in for a high amount of BC particles on filter paper. This effect is known as shadowing effect. The estimates of error due to shadowing effect are arrived at using procedure as follows following (Weingartner et al., 2003). Absorption coefficient of the particle accumulated on the filter is calculated from the attenuation formula 2.2.

\[
\beta_A = \frac{\beta_{ATN}}{C \cdot R_{ATN}} \quad \text{(2.2)}
\]

Where

\( \beta_{ATN} \) = absorption coefficient of the soot particles on filter paper (Eqn. 2.3)

\( \beta_a \) = absorption coefficient of soot particle suspended in the air

C = empirical constant

R(ATN) = empirical function of Attenuation (2.4)

\[
\beta_{ATN} = d \cdot \left| ATN \right| \cdot \left( \frac{A}{V} \right) \quad \text{(2.3)}
\]
\[ R_{ATN} = \left( \frac{1}{f} - 1 \right) \frac{\ln(\text{ATN}) - \ln(10\%)}{\ln(50\%) - \ln(10\%)} + 1 \text{ (2.4)} \]

In the equation 2.4, “f” is known as a correction factor for shadowing effect. It is a function of the amount of accumulated soot particles on the paper and single scattering albedo of the particles. Hence, scattering type of particles can reduce the shadowing effect. Gadhavi and Jayaraman (2010) estimated value of “f” 1.17 using a statistical approach. This represents a 8% error in the absorption coefficient of BC mass concentration due to shadowing effect, but it could be less than that since Gadanki is a rural site. The total error in estimating BC concentration is less than 10% (Gadhavi and Jayaraman, 2010)

### 2.3.1. Flow Meter Calibration

The flow meter calibration is done by using an external flowmeter with a flow rate range in 2 to 10 Standard Liter Per Minute (SLPM). In this process, the instrument is kept for 30 minutes for stabilizing the flow. After the flow stabilization, a flow meter that can be adjustable for a known flow rate is connected to the inlet. The readings on the instrument display panel are adjusted based on the flow rate given by the external flow meter. After saving the new flow rate values, the new calibration factors will be set to the instrument.

<table>
<thead>
<tr>
<th>( \lambda ) (nm)</th>
<th>( \text{Sigma (BC) cm}^2/\text{g}^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>370</td>
<td>39.5</td>
</tr>
<tr>
<td>470</td>
<td>31.1</td>
</tr>
<tr>
<td>520</td>
<td>28.1</td>
</tr>
<tr>
<td>590</td>
<td>24.8</td>
</tr>
<tr>
<td>660</td>
<td>22.2</td>
</tr>
<tr>
<td>880</td>
<td>16.6</td>
</tr>
<tr>
<td>950</td>
<td>15.4</td>
</tr>
</tbody>
</table>

*Ref: Hansen (2005)
2.4. Trace-Gases Measurements

Trace-gases mixing ratios are being measured from ICON observatory using online trace-gas analysers (Figure 2.4). Presently ozone, SO$_2$, NO$_X$, CO gases are being measured using Thermo Scientific gas analysers. The set up of analysers in ICON observatory is as shown in Figure 2.4. The specifications of the analysers are given below in the Table 2.2.

Table 2.2: Specifications of the trace-gas analysers

<table>
<thead>
<tr>
<th></th>
<th>Ozone</th>
<th>NO$_X$</th>
<th>SO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Date</td>
<td>08-01-2010</td>
<td>08-01-2010</td>
<td>08-01-2010</td>
</tr>
<tr>
<td>Lower Detection Limit</td>
<td>1 ppbv for 30 sec. res.</td>
<td>0.4 ppbv for 1 min. res.</td>
<td>0.5 ppbv for 1 min. res.</td>
</tr>
<tr>
<td>Response time</td>
<td>20 sec</td>
<td>40 sec</td>
<td>80 sec</td>
</tr>
<tr>
<td>Flow rate</td>
<td>1 – 3 LPM</td>
<td>0.6 – 0.8 LPM</td>
<td>0.5 – 1 LPM</td>
</tr>
<tr>
<td>Zero Calibrations</td>
<td>Weekly basis</td>
<td>Weekly basis</td>
<td>Weekly basis</td>
</tr>
<tr>
<td>Span calibrations</td>
<td>Monthly basis</td>
<td>Monthly basis</td>
<td>Monthly basis</td>
</tr>
</tbody>
</table>

Figure 2.4: Trace-gas analysers located at ICON observatory.
2.4.1. Ozone Analyser

Surface ozone mixing ratios are measured using Thermo Scientific – USA (model 49i) online ozone analyser over Gadanki since 2010. The lower detectable limit of the ozone analyser is 1 ppbv with a response time of 60 seconds. The schematic diagram of ozone analyser is shown in Figure 2.5. It works based on Beer-Bouguer-Lambert law in which absorption of UV light in the air sample is related to ozone mixing ratio.

2.4.1.a. Working Principle:

Ozone analyser consists two absorption cells cell-A, cell-B, an ultraviolet lamp which emits 254 nm wavelength radiation, flow sensors, pump, ozone scrubber, photo diodes that detect the attenuated light. Ambient air is drawn through the sample bulk head and splits into two gas streams. One gas stream flows through the reference cell (cell-A) through ozone scrubber to become reference gas (ozone free air), and another gas stream flows to the sample cell (cell-B). Two UV light beams are made to pass through the two cells A and B, which contain reference and sample air. The UV light intensities from the two cells $I_0$ and I are measured by the detectors.

Figure 2.5: schematic diagram of ozone analyzer
Ozone mixing ratio is calculated using Beer-Bouguer-Lambert's law as follows. The Beer-Bouguer-Lambert's law relates absorption of light to the ozone mixing ratio as

\[
\frac{I}{I_0} = e^{-KLC} \quad (2.5)
\]

Where \( K \) is molecular absorption coefficient = 308 /cm
\( L \) = length of cell = 38cm
\( C \) = ozone mixing ratio in ppm
\( I \) = intensity of UV light with sample gas
\( I_0 \) = intensity of UV light without ozone

The solenoid valves alternate the reference and sample gases between cells A and B in order to minimize the errors because of changes in optical properties of cells.

Trace-gases analysers are calibrated in 2 modes of calibration viz. zero calibration and span calibration.

**2.4.1.b. Zero Calibration:**

Zero calibration is to determine ozone background correction. It is the difference in light intensities between two cells when the analyser is sampling ozone free air. Zero calibrations are done on a weekly basis. To do zero calibrations, the zero air must be supplied to the instrument. The zero air generator can be a compressed cylinder that is nonsynthetic or can be the ambient air that is scrubbed by the scrubber equipment. The scrubber should remove the pollutants like NO, NO\(_2\), SO\(_2\), hydrocarbons from the ambient air. The USA's Environmental Protection Agency regulations for generating zero air for calibrating ozone analyser consists four steps.

In the first step the ambient air is irradiated with UV lamp that generates ozone, this ozone converts NO in the air to NO\(_2\) or the ambient air is passed through a Purafil (Air Filtration medium) to convert NO to NO\(_2\) and to remove NO\(_2\) from the air sample. In the second step, the air is passed through large column of activated charcoal to remove residuals of NO\(_2\), O\(_3\), SO\(_2\), hydrocarbons, etc. In this process, there can be the generation of particles also. In the next step, the air is filtered through a molecular sieve and a fine particulate filter to remove the molecules and aerosols.
generated during the scrubbing process. Ozone analyser has internal zero check facilities standardized according to USA's EPA standards, which is controlled by the pump. This facility is used for zero checks of the instrument.

2.4.1.c. Span Calibration:

In span calibration, the instrument is checked for its response to increasing in the known amount of gas. The span calibrations are done on a monthly basis.

Table 2.3: Span calibration values fixed and tested for ozone analyser by the manufacturer

<table>
<thead>
<tr>
<th>Level</th>
<th>Lower Limit</th>
<th>Measured</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>797</td>
<td>798.7</td>
<td>803</td>
</tr>
<tr>
<td>Level 2</td>
<td>597</td>
<td>599.7</td>
<td>603</td>
</tr>
<tr>
<td>Level 3</td>
<td>397</td>
<td>400.4</td>
<td>403</td>
</tr>
<tr>
<td>Level 4</td>
<td>197</td>
<td>201.2</td>
<td>203</td>
</tr>
<tr>
<td>Level 5</td>
<td>97</td>
<td>100.5</td>
<td>103</td>
</tr>
</tbody>
</table>

Span calibrations are done using calibrated Ozonator (EPA standards) for five different ozone mixing ratios. It is based upon the current EPA approved procedure using a UV photometer as a calibration standard. Level 1 to level 5 calibration is being done as prescribed by the manufacturer for the instrument as given in Table 2.3. The optional internal ozonator operates on the photolytic principle. The ozone level produced is a function of light intensity at 185 nm and gas flow. The light intensity is varied by changing the current into the lamp. The gas flow is held constant by a pressure regulator followed by a capillary. The changes in the consecutive calibrations have been very small. The zero offset reduced by 0.1 ppbv and span constant reduced by 2% during the study period.

2.4.2. NOX Analyser

NOX (NO + NO2) mixing ratios are measured using Thermo Scientific – USA (model 42i) NOX analyzer at Gadanki since 2010. The lower detection limit of the NOX analyzer is 0.4 ppbv with a response time of 60 seconds.
The lower detection limit is better than 0.4 ppbv for higher averaging time. The schematic diagram of NOX analyzer is shown in Figure 2.6. NOX analyzer employs chemiluminescence technique. NO present in the air sample reacts with ozone to produce NO$_2$ in its high energy state (Eqn. 2.6). While coming down to the ground state NO$_2$ emits infrared radiation. The intensity of emission is linearly proportional to the amount of NO present in the sample.

\[
NO + O_3 \rightarrow NO_2 + O_2 + h\nu \quad \text{(2.6)}
\]

The ambient air is drawn into the instrument; ozone generator produces ozone and sends to the reaction chamber. There are two modes of operation of the instrument i.e. NO mode and NOX mode. In NO mode ambient air directly goes into the reaction chamber and reacts with ozone. The amount of NO present in the sample is calculated based on the intensity of light emitted in the chemiluminescence reaction detected by Photo Multiplier Tube (PMT). In NOX mode, ambient air flows through molybdenum converter that is heated to 625° C temperature. This converts the total
NO₂ present in the sample to NO, which goes to the reaction chamber. Hence, amount of NO₂ + NO (=NOₓ) is measured during this mode. The difference between NO mode and NOₓ mode gives the amount of NO₂ present in the sample. Molybdenum converter can also convert other nitrogen containing substances to NO and hence NO₂ measured by this analyser should be regarded as the upper limit. The analyser is equipped with facilities of zero and span calibrations. The zero calibration checks are done on a weekly basis. Span calibration checks are done on a monthly basis.

2.4.2.a. Zero Calibration:

Figure 2.7: Calibration certificate for zero air cylinder.
NO\textsubscript{x} zero calibrations are done using internal zero air generator. The zero air source should be at high pressure in order to obtain accurate calibrations. NO present in the air sample is oxidised to NO\textsubscript{2} by ozonation process or chemical oxidation method. In chemical oxidation method, air sample passes through a filter bed containing reacting beds like CrO\textsubscript{3} coated on aluminium foil. The air sample passes through fixed bed reactors (charcoal – for ozone, SO\textsubscript{2} and hydrocarbons and soda lime – for NO\textsubscript{2}) for removing the contaminants either by reaction or absorption. From April 2012 onward NIST standard zero air cylinder is used for calibrations. The calibration certificate for the zero air cylinder is shown in Figure 2.7.

2.4.2.b. Span Calibration:

![Calibration Certificate of NO\textsubscript{2} Permeation Tube](image)

Figure 2.8: Calibration certificate of NO\textsubscript{2} permeation tube

Span checks are done using NIST standard permeation tubes that generate NO\textsubscript{2} gas of known mixing ratios based on the burnt rate using the formula

\[
Output \ (ppm) = \frac{R \cdot K}{Q_0} \quad (2.7)
\]
Where:

\[ R = \text{permeation rate in ng/min} \]
\[ Q_0 = \text{flow rate of gas (Sec/min) during span mode} \]
\[ K = \text{constant for the specific permeant} = 24.45/\text{MW} \]
\[ \text{MW = molecular weight} \]
\[ K(\text{NO}_2) = 0.532 \text{ Calibration constant of NO}_2 \text{ permeation tube} \]

Calibration certificate of NO\textsubscript{2} permeation tube and NO\textsubscript{2} cylinder (NO\textsubscript{2} = 23 ppbv) are shown in Figure 2.8 and Figure 2.9 respectively.

![Figure 2.9: NIST standard calibration certificate of NO\textsubscript{2} cylinder](image-url)
2.4.3. SO$_2$ Analyser

SO$_2$ mixing ratios are measured using Thermo Scientific – USA (model 43i) SO$_2$ analyzer at Gadanki since 2010. The lower detection limit of the SO$_2$ analyzer is 0.5 ppbv with a response time of 60 seconds and better for longer averaging time. The SO$_2$ analyser works on the principle of fluorescence. When SO$_2$ molecules are irradiated with UV light, they go to excited state. They emitted the light at different wavelength when they were irradiated while coming down to the ground state as shown in Equation 2.7

$$SO_2 + h\nu_1 \rightarrow SO_2 \rightarrow SO_2 + h\nu_2$$

--- (2.7)

Figure 2.10: Schematic representation of SO$_2$ analyser

The schematic representation of SO$_2$ analyser is shown in Figure 2.10. Ambient air is drawn into the instrument and flows through the hydrocarbon kicker that removes the hydrocarbons from the sample. The sample enters the optical chamber and is irradiated with UV light, which will make SO$_2$ molecule go to it is higher energy state. The SO$_2$ molecule in higher energy state emits another UV light
while coming down to the ground state. Intensity of the emitted photons is observed using a PMT, which is used to calculate SO$_2$ mixing ratio. The analyser has in-built zero calibration facilities and span calibration using permeation tube. The span calibration checks are done once every two months using permeation tube and zero calibration checks are done once in a week.

2.4.3.a. Zero Calibration:

SO$_2$ zero calibrations are done using internal zero air generator. Activated charcoal acts as an absorbing column of SO$_2$ and removes the SO$_2$ present in the ambient air. The charcoal should be changed more frequently depending on ambient conditions.

2.4.3.b. Span Calibration:

Span checks are done using NIST standard permeation tubes that generate SO$_2$ gas of known mixing ratios based on the burnt rate using the formula

\[
Output \ (ppm) = \frac{R \times K}{Q_0} \quad (2.7)
\]

Figure 2.11: Calibration certificate of SO$_2$ Permeation tube
Where: \( R \) = permeation rate in ng/min
\( Q_0 \) = flow rate of gas (Sec/min) during span mode
\( K \) = constant for the specific permeant = \( 24.45 / MW \)
\( MW \) = molecular weight
\( K(SO_2) = 0.382 \)

Calibration certificate of SO\(_2\) permeation tube and SO\(_2\) cylinder (SO\(_2\) = 22 ppbv) are shown in Figure 2.11 and Figure 2.12 respectively.

Figure 2.12: NIST standard calibration certificate of SO\(_2\) cylinder.
2.5. Pyranometer

Pyranometer (Kipp and Zonen, model CMP21) is used for measuring total solar irradiance. The unit has three pyranometers as shown in Figure 2.13 to measure the diffuse and total radiations in the broadband region of 2.8 to 2800 nm. The sensors have black surface that gets heated when solar radiation fall on it. The change in temperature produces an electric potential in thermocouple below the surface with respect to thermocouple kept away from the black surface at ambient temperature. The difference in voltage between two thermocouples is related to solar radiation.

Figure 2.13: Pyranometers and pyrheliometer installed on top of the ICON observatory.
The two pyranometers fixed at the ends are always under shadow of black color bobs that move as solar position. Hence the radiation measured by these two pyranometers is diffuse radiation. Where as the central pyranometer measures total (direct + diffuse) radiations. There is a pyrheliometer (CH-01) for measuring direct solar radiation. Pyrheliometer has field of view 1° and it always points toward sun. Each radiation sensor has a temperature sensor attached. The measured changes in resistances are converted into irradiance by dividing with the calibration coefficients of the sensors given by the company. The calibration constants are $9.11 \times 10^{-3}$ mvol/W/m$^2$, $8.92 \times 10^{-3}$ mvol/W/m$^2$, $9.29 \times 10^{-3}$ mvol/W/m$^2$ and $10.63 \times 10^{-3}$ mvol/W/m$^2$ for CMP21a, CMP21b, CMP22 and CH1 respectively. The instrument is calibrated on 24-05-2012. In the period of 3 years, the changes in calibration constants are found to be very small (0.75 %) and are as shown in Figure 2.14

![Figure 2.14: Old and new calibration constants of the pyranometers and pyrheliometer.](image)

2.6. Automatic Weather Station

The meteorological parameters are being measured by an automatic weather station that has six sensors for temperature, humidity, pressure, wind speed, wind direction and rainfall. The AWS located in NARL is shown in Figure 2.15. Piezo-
resistive pressure sensor with temperature compensation measures the atmospheric pressure. The piezo-resistive material is a diaphragm formed on a silicon substrate. The diaphragm bends based on the applied pressure on it. Due to this bending the crystal lattice of the diaphragm changes that leads to change in resistance of the material. The change in resistance is proportional to the pressure on the sensor based on the equation 2.8. The accuracy of this sensor is 0.1 mb.

\[ \Delta R = \Pi (P - P_0) \tag{2.8} \]

where \( R \) = Resistance
\( P \) and \( P_0 \) = initial and final pressures

Relative Humidity is measured by capacitive relative humidity (RH\%) sensor in which two conductive electrodes are separated by a dielectric medium. The dielectric absorbs the moisture so that the dielectric constant changes that lead to a change in the capacitance of the sensor. The change in capacitance is proportional to relative humidity present in the atmosphere, RH is calculated based on the equation 2.9. The accuracy of this sensor is ± 3 %.

\[ RH\left(C_c\right) = \left(\frac{C_{\text{MRH}} - C_{\text{s@55\%RH}}}{S}\right) + \%RH\left(C_s\right) \tag{2.9} \]

Where, \( S \) = Sensitivity of the capacitor
\( C_{\text{MRH}} \) = Measured capacitance value
\( C_{\text{s@55\%RH}} \) = Standard capacitance value at 55\%RH
\( \%RH\left(C_c\right) \) = Calculated relative humidity at measured capacitance
\( \%RH(C_s) \) = Standard relative humidity value (55\%RH)

Temperature is measured using Resistance Temperature Detector (RTDs). The resistance of the resistor (thin metal) foil changes with temperature. The changes in the resistances are related to the temperature. The sensor has an accuracy of 0.1 °C.

Wind vane with potentiometer arrangement is used for measurement of wind directions. Accuracy of the sensor is better than 1 °.
3-cup anemometer is used for measurement of wind speed. The revolution speed of the cup is proportional to the wind speed. The accuracy of the instrument is ±1%. Tipping bucket rain gauge is used for measurement of rainfall at Gadanki. The accuracy of the instrument is 0.5 mm.

Figure 2.15: Automatic Weather Station (AWS) located at NARL
2.6.1. Meteorology of the Site

Gadanki experiences tropical wet climate. Monthly mean relative humidity (RH), temperature, wind speed, wind direction and monthly total rainfall over Gadanki for 2010-11 are shown in Figure 2.16. RH over Gadanki varies from 45% in spring (pre-monsoon) to 90% in winter (north-east monsoon period). Monthly mean temperature varies from 31 °C (from the end of spring to beginning of summer) to 22 °C (in winter).

Figure 2.16: Monthly mean temperature, relative humidity, wind speed, wind direction and monthly total rainfall over Gadanki for 2010-2011.
Gadanki experiences two rainy seasons; one during the south-west monsoon (June to September) and another during north-east monsoon (October to December). The period from January to May has a minimum amount of rainfall. Total rainfall during the years 2008 to 2013 are shown in Table 2.4. The highest amount of rainfall (1150 mm) occurred during 2010 and lowest amount of rainfall (479.5 mm) was in 2009 which was a drought year in Andhra Pradesh state.

Table 2.4: Monthly accumulated rainfall (mm) for the observational period 2008 to 2013

<table>
<thead>
<tr>
<th>Month</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>February</td>
<td>6</td>
<td>0</td>
<td>0.5</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>March</td>
<td>113</td>
<td>1.5</td>
<td>6.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>April</td>
<td>0</td>
<td>2</td>
<td>27.5</td>
<td>86</td>
<td>140</td>
<td>43</td>
</tr>
<tr>
<td>May</td>
<td>60.5</td>
<td>7.5</td>
<td>68.5</td>
<td>0</td>
<td>80</td>
<td>76</td>
</tr>
<tr>
<td>June</td>
<td>54</td>
<td>0.5</td>
<td>72</td>
<td>28</td>
<td>128</td>
<td>181</td>
</tr>
<tr>
<td>July</td>
<td>125.5</td>
<td>0</td>
<td>307.5</td>
<td>115</td>
<td>91</td>
<td>77</td>
</tr>
<tr>
<td>August</td>
<td>41.5</td>
<td>4.5</td>
<td>207</td>
<td>193</td>
<td>179</td>
<td>144</td>
</tr>
<tr>
<td>September</td>
<td>118.5</td>
<td>98.5</td>
<td>163</td>
<td>47</td>
<td>57</td>
<td>161</td>
</tr>
<tr>
<td>October</td>
<td>98.5</td>
<td>123.5</td>
<td>24</td>
<td>83</td>
<td>215</td>
<td>136</td>
</tr>
<tr>
<td>November</td>
<td>308</td>
<td>142.5</td>
<td>200.5</td>
<td>187</td>
<td>131</td>
<td>61</td>
</tr>
<tr>
<td>December</td>
<td>3</td>
<td>99</td>
<td>73.5</td>
<td>60</td>
<td>57</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>941.5</strong></td>
<td><strong>479.5</strong></td>
<td><strong>1150.5</strong></td>
<td><strong>809</strong></td>
<td><strong>1080</strong></td>
<td><strong>880</strong></td>
</tr>
</tbody>
</table>

Wind rose diagram for the period 2010-11 is shown in Figure 2.17. The dominant wind directions close to the surface are south-westerly during June to September, north-easterly during October to December and south-easterly during February to April. The wind speeds are generally higher during the south-west monsoon with monthly mean values reaching as high as 2.3 m/s.
Figure 2.17: Windrose diagram of the observed winds during 2010-11.