Government of India & Government of The Netherlands

Technical Assistance
HYDROLOGY PROJECT

DHV CONSULTANTS & DELFT HYDRAULICS with HALCROW, TAHAL, CES, ORG & JPS

VOLUME 3
HYDRO-METEOROLOGY

REFERENCE MANUAL

Table of Contents

1 PILOT STUDY: DESIGN OF RAIN GAUGE NETWORK

1.1 INTRODUCTION

A Pilot Study for designing a rain gauge network was made for two sub-basins in the Mahanadi river basin in Orissa. The objective of the Pilot study was to provide an example of the theory and related practical aspects on network design as presented in Chapter 3 of Volume 3, Design Manual, Hydro-meteorology, including the integration of the hydro-meteorological network with the hydrometric network. The procedure presented in the Design Manual is general and can be applied to any basin irrespective of the climatic conditions. Furthermore, the procedure is also applicable for the design of evaporation networks.

For the Pilot Study, the rainfall networks of two tributaries of river Mahanadi namely: the Ib and Tel rivers have been considered. The catchment areas of these two rivers are 7,627 km^2 and 30,426 km^2 respectively. Data of 12 rain gauge stations in the Ib basin and 54 rain gauge stations in the Tel basin, for which monthly rainfall data for the period 1970-1995 have been made available by Orissa state. These 66 stations have been listed in Table 1.1 and their locations are shown in Figure 1.1.

The selection of the Ib and Tel basins for the Pilot Study was first of all based on their general representativeness with respect to climatic and drainage conditions. Furthermore, the readily availability of computerised series of historical data was considered a prerequisite for taking up any such study in the beginning of the Hydrology Project. The study was carried out in the period April to December 1997.

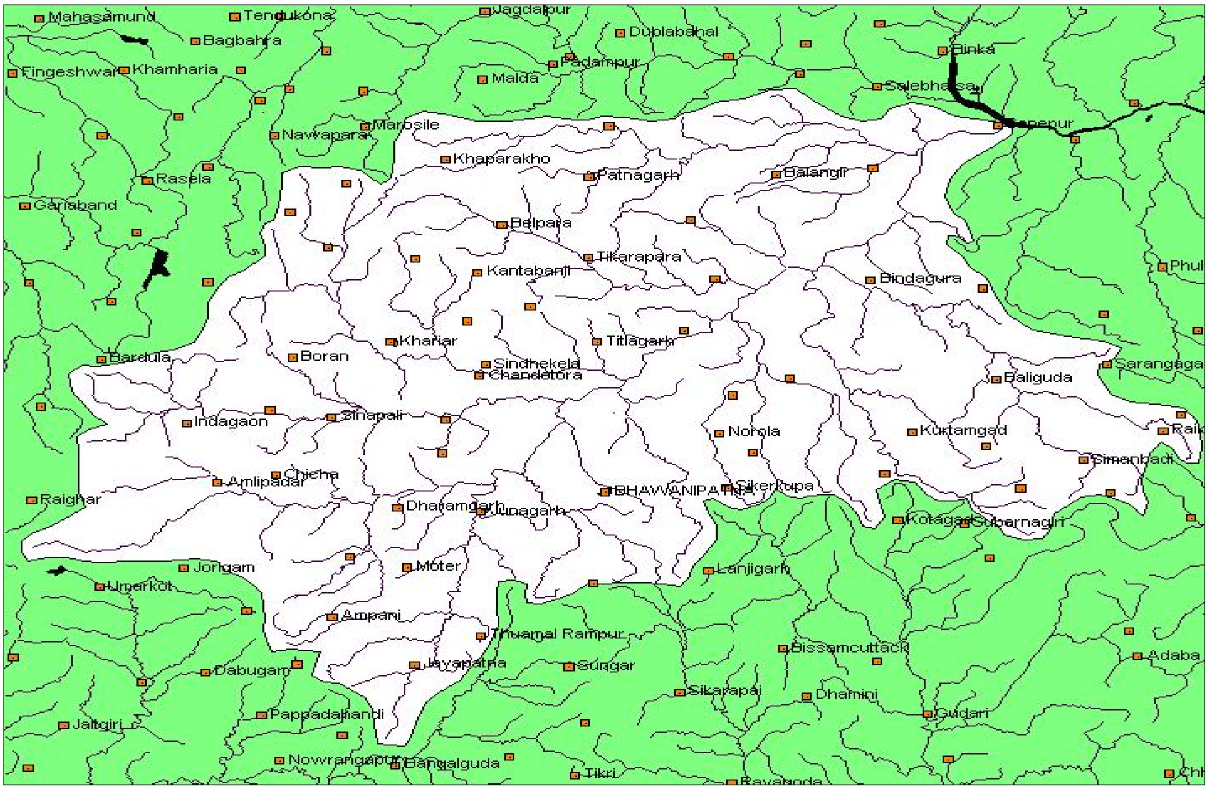

Figure 1.1: Rainfall network in Tel river basin, Orissa

Basin	No	Station	No	Station	No	Station
Ib	1	**Balisankara**	5	Kochinda	9	Sundergarh
	2	**Bamra**	6	Laikera	10	**Gurundia**
	3	Baragoan	7	**Rengali**	11	Hemgiri
	4	Jharsuguda	8	Subdega	12	**Jamunkira**
Tel	1	**Agalpur**	19	**Kalampur**	37	**Bolangir**
	2	**Attabira**	20	**Koksara**	38	**Deogoan**
	3	**Bijipur**	21	Bhawanipatna	39	**Kantamal**
	4	Binka	22	Kesinga	40	Luisinga
	5	**Dunguripally**	23	Lanjigarh	41	Saintala
	6	**Ghaisilat**	24	Narla	42	Tarabha
	7	Jharabandh	25	Nawpara	43	**Titlagarh**
	8	Padampur	26	Sinapally	44	Baragoan
	9	Paikmal	27	Bangamunda	45	**Karlamunda**
	10	Rairakhol	28	**Golamunda**	46	**Kotagarh**
	11	**Sambalpur**	29	Khariar	47	**Madanpurampur**
	12	Sohela	30	Buden	48	**Tumlibandha**
	13	Sonepur	31	Belpara	49	**Baliguda**
	14	Urlanda	32	Khaprakhol	50	Daringpadi
	15	**Dahugoan**	33	**Komna**	51	G. Udayagiri
	16	**Dharmgarh**	34	Muribahal	52	**Phulbani**
	17	Jayapatna	35	Patnagarh	53	Raikeda
	18	Junagarh	36	Tureikel	54	Tikabali

Note: in bold stations selected for regression analysis

Table 1.1: Summary of rainfall stations in Ib and Tel basin

1.2 DATA COLLECTION AND VALIDATION

Data collection

Time series of monthly rainfall data of the 12 rain gauge stations in the Ib basin and the 54 rain gauge stations in the Tel basin, as listed in Table 1.1 were made available by the State Surface Water Department of Orissa on diskette. The monthly series have been created by aggregation from daily observations in the period 1970-1995. For further analysis, the time series of monthly data with the station latitude, longitude and altitude were transferred to the database of the HYMOS software package for processing and storage of hydrological data.

Data validation

No information was available on any kind of validation or completion carried out on the data. Therefore, all data were subjected to an extensive data validation process, including:

- screening of data by tabulation and flagging of outliers,
- comparison of time series plots of neighbouring stations,
- application of the nearest neighbour technique to each of the series; this techniques compares the observed monthly value at a station with an estimate based on surrounding stations and flags the value if the difference with the estimate exceeds a pre-set absolute value or a relative one derived from the standard error of estimate, and
- double mass analysis on annual values for the 26 year period of data for each of the series.

The validation showed that a large amount of the data was of doubtful quality unfit for further analysis. The stations that passed the tests are summarised in Table 1.2 (see also Table 1.1 stations printed in bold letter type) presented per homogeneous area.

Ib	Tel, Northwest	Tel, Southeast	Tel, Southwest
Bamra	Agalpur	Baliguda	Golamunda
Balisankara	Attabira	Bijipur	Dharmgarh
Gurundia	Bolangir	Kalampur	Kaksara
Jamunkira	Gaisilet	Kantamal	Dahugaon
Rengali	Deogan	Karlamunda	
	Dungipally	Kotagarh	
	Komna	Pulbani	
	Sambalpur	Tumlibund	
	Tilagarh	Madanpurampur	

Table 1.2: Selected rainfall stations per region used in statistical analysis

The unreliable data in the selected series have been eliminated. The series with missing data have not been completed; this is essential in view of the determination of basic statistics and spatial correlation analysis to be carried as a next step. By filling in missing data using regression without applying a random component for the unexplained part in regression, the variance of the series will be reduced and the spatial correlation coefficient will be increased.

In all, only 40% of the series were found reliable. This shows that proper validation of the data prior to any further statistical analysis is a necessity. Once it is known that the data have been subjected to the validation process as presented in the Data Processing Manual, which are conformable to the methods applied in this study, the network design process can continue with further statistical analysis.

1.3 STATISTICAL ANALYSIS

Basic statistics and grouping of stations

The basic statistics of the monthly and annual series of all finally selected point rainfall stations have been computed. The statistics of the point rainfall series are displayed in the Figures 1.2 to 1.5 and Tables 1.3 and 1.4. The latter table includes the statistics of the annual series; here also the monsoon rainfall as a percentage of the annual rainfall is presented as well.

Based on these data the stations were grouped according to climatically homogeneous areas. The following areas were discerned:

- Ib basin,
- Tel basin, Northwest of the Tel river,
- Tel basin, Southeast of the Tel river, and
- Tel basin, in the south-western part of the basin, covering the upper reaches.

The tables and figures show that the areas nearest to the coast receive most rainfall, particularly in mid-monsoon. It is observed that, generally, August is the wettest month with slightly more rainfall than July. As indicated in the last column of Table 1.4 the rainfall is almost entirely concentrated in the monsoon period; 86-89 percent of the annual total is received in that period on average. Consequently, the coefficient of variation Cv is lowest in these months and is maximum in December when hardly any rain is experienced. In the Tables and Figures also the 90% reliable Cv-value is presented to analyse the variability of this coefficient among the various station records. Generally, these values are about 30% larger than the average values, with slightly larger ones in the post-monsoon period.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ib												
Mean (mm)	12.1	17.1	13.1	15.6	35	209.6	387.8	407.3	204.8	50.1	9.4	3.4
Cv-average	1.70	1.62	1.74	1.29	1.07	0.69	0.39	0.41	0.52	1.05	1.90	3.24
Cv-90%	1.98	2.05	2.13	1.46	1.46	0.78	0.49	0.46	0.65	1.17	2.26	4.50
Tel NW												
Mean (mm)	10.0	13.0	11.2	15.5	29.5	196.3	358.0	364.4	184.7	44.8	13.1	1.8
Cv-average	2.17	1.41	1.72	1.37	1.14	0.66	0.36	0.47	0.63	1.27	2.08	3.30
Cv-90%	2.98	1.94	2.32	1.94	1.53	0.87	0.48	0.63	0.84	1.70	2.74	4.65
Tel SE												
Mean (mm)	10.7	15.6	16.4	26.3	46.4	220.3	382.3	418.2	215.1	65.7	16.7	1.3
Cv-average	2.11	1.39	1.64	1.03	1.30	0.60	0.44	0.48	0.56	1.14	2.00	3.41
Cv-90%	2.81	1.81	2.17	1.41	1.72	0.80	0.58	0.64	0.74	1.60	2.69	5.28
Tel SW												
Mean (mm)	6.7	9.8	12.2	31.1	49.2	219.1	365.9	363.5	211.9	67.6	13.3	0.6
Cv-average	2.13	1.79	1.67	1.35	1.29	0.51	0.39	0.47	0.52	1.33	2.00	4.44
Cv-90%	2.97	2.46	2.29	1.88	1.89	0.70	0.54	0.65	0.74	1.89	2.73	6.25

*Table 1.3: Basic statistics of **monthly** point rainfall series, period 1970-1995*

Basin	Mean (mm)	Cv-average	Cv-90%	∑ (June-Sept)/Year (%)
Ib	1365.3	0.27	0.28	89
Tel NW	1242.3	0.25	0.33	89
Tel SE	1435.0	0.29	0.38	86
Tel SW	1350.9	0.27	0.39	86

*Table 1.4: Basic statistics of **annual** point rainfall series, period 1970-1995*

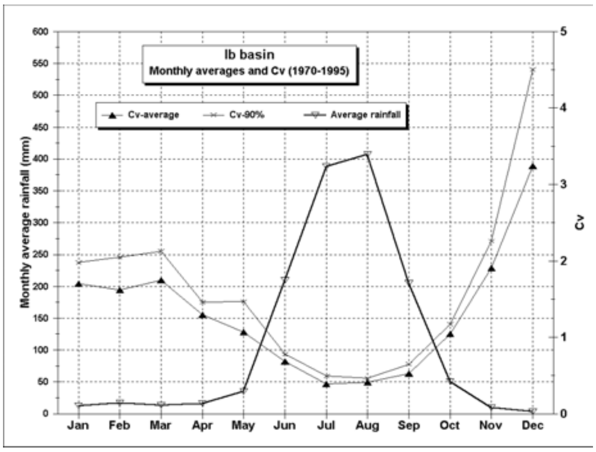

Figure 1.2: Basic statistics Ib basin

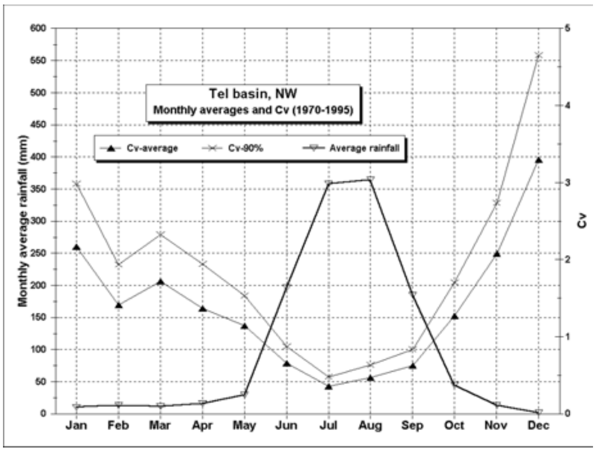

Figure 1.3: Basic statistics Tel NW basin

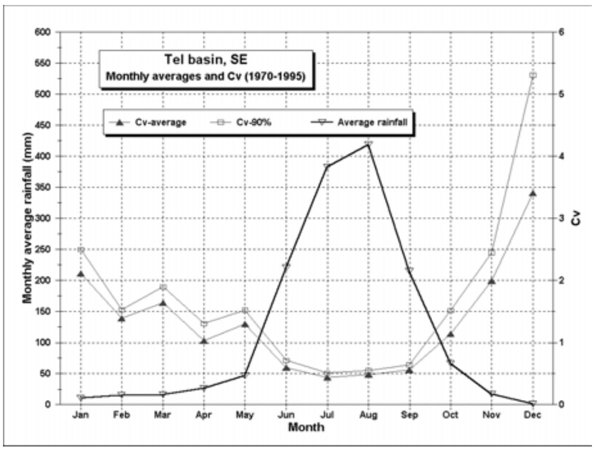

Figure 1.4: Basic statistics Tel SE basin

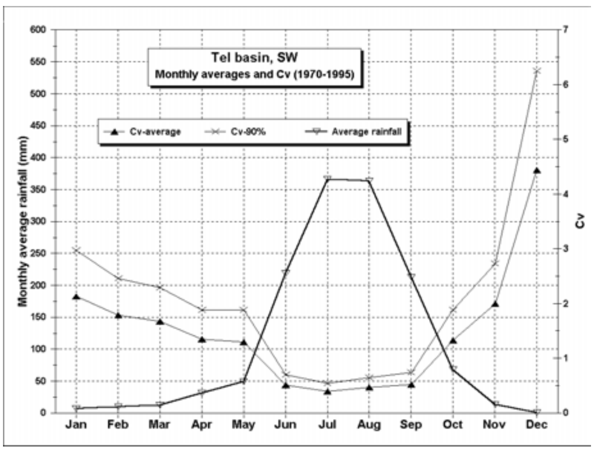

Figure 1.5: Basic statistics Tel SW basin

A comparison of the monthly average values and coefficients of variation for the various areas is presented in Figure 1.6 and 1.7.

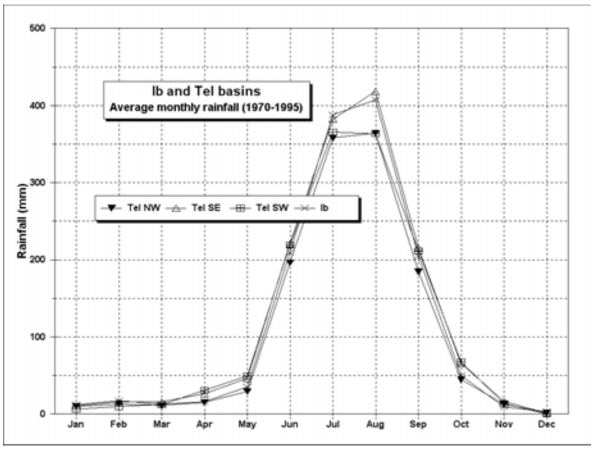

Figure 1.6: Monthly average rainfall in Tel and Ib basins

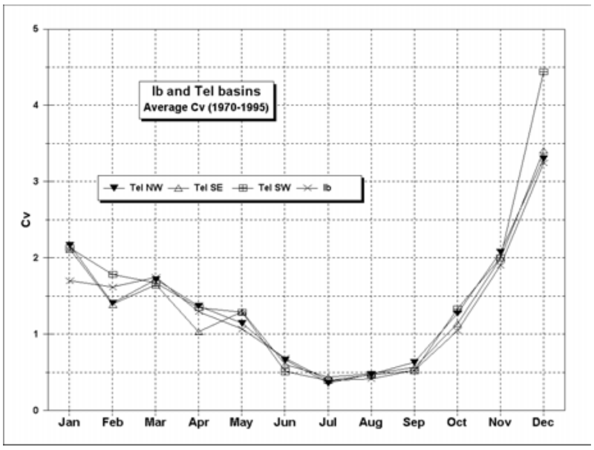

Figure 1.7: Average Cv-values in Ib and Tel basins

Orographic effects

To investigate if orographic effects could play a role in the rainfall observed in the Ib and Tel basins, the altitudes of all stations have been collected, either taken from files or estimated from topographical maps. Most stations are at an elevation less than 500 m, whereas a few are located between 500 and 600 m height. In the tropics like India, orographic influence is prominent above an elevation of 800 m. Hence, it is safe to state that transformations for orographic effects are not required in this case to arrive at homogeneous series.

1.4 ASSESSMENT OF SPATIAL CORRELATION STRUCTURE

Measure of effectiveness

From the analysis of basic statistics it is revealed that the rainfall in the Ib and Tel basins is almost entirely concentrated in the months June to September. Hence, for water resources assessment it is sufficient to concentrate on these months and on the annual total. Since no Hydrological Data User need inventory was made at the time of the analysis, it was assumed that the network should be able to provide monthly and as an alternative seasonal or annual areal rainfall. Consequently, we will use as a measure of effectiveness the estimation error in the areal average monthly and annual rainfall in the distinguished areas, which value should not be more than 10% on average.

Spatial correlation coefficients have therefore been computed for all the monsoonal months individually and for the annual series.

Spatial correlation coefficient

The spatial correlation coefficient between two stations is computed as follows:

$$r_{ij} = \frac{\frac{1}{n}\sum_{k=1}^{n}(h_{i,m,k} - \overline{h}_{i,m})(h_{j,m,k} - \overline{h}_{j,m})}{\sigma_{i,m}\sigma_{j,m}} \qquad (1.1)$$

where: r_{ij} = correlation coefficient between series at station i and station j
n = number of data in series i and j $\neq 0$
$h_{j,m,k}$ = rainfall at station i in month m and year k
$\overline{h}_{,m}$ = (time) average rainfall at station i in month m
$\sigma_{i,m}$ = standard deviation of rainfall series of station i in month m

In this way for each region the spatial correlation coefficient has been determined for each pair of stations. Subsequently the distance d in km between the stations was derived from the co-ordinates of the sites. For N stations this leads to N(N-1)/2 pairs and values for $r_{ij}(d)$.

When all r_{ij} -values are plotted against d a large scatter is generally observed. To reduce the scatter per distance interval of 10 km the average correlation coefficient and average distance was computed. The results are shown in Table 1.5. The technique presented in the Design Manual requires the correlation-distance relationship to be modelled by the following relation:

$$r(d) = r_0 \exp(-d/d_0) \tag{1.2}$$

where: r(d) = correlation as a function of distance
r_0 = correlation at d=0
d_0 = characteristic correlation distance: at distance d_0, the correlation is r_0e^{-1}

Basically, r(0) should be 1, but measuring errors and microclimatic variability at small values of d create r_0 values less than 1, see Design Manual. The average correlation coefficients and distance per distance interval have been plotted using a semi-logarithmic scale to fit a straight line through the observations, after elimination of outliers. From this the values of r_0 and d_0 have been obtained.

The estimates for r_0 and d_0 are listed in Table 1.6. The fit of function (1.2) to the observations is shown for each month and for the annual series in:

- for Ib: Figures 1.8 to 1.13
- for Tel NW: Figures 1.14 to 1.19
- for Tel SE: Figures 1.20 to 1.25

No estimates for r_0 and d_0 could be made for the south-western region in the Tel basin as the scatter in the r(d) data was too large and the data amount too small.

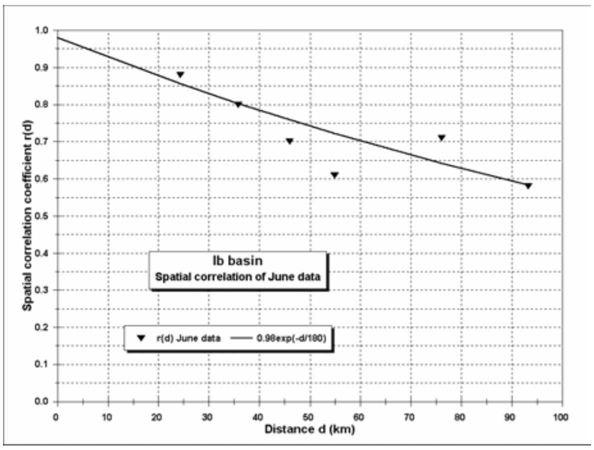

Figure 1.8: r(d) for June, Ib basin

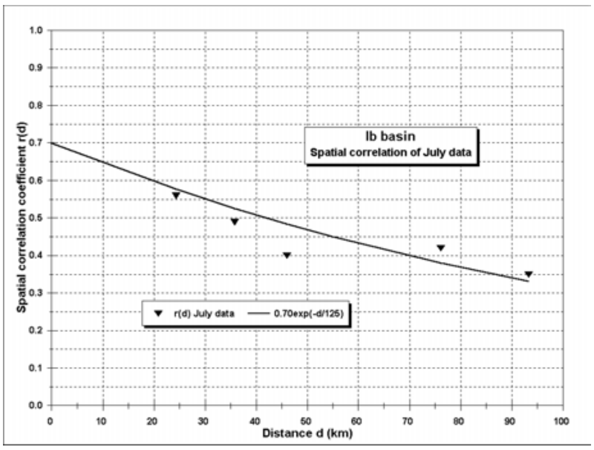

Figure 1.9: r(d) for July, Ib basin

Basin	Distance interval (km)	Average distance in interval (km)	r(d) June	r(d) July	r(d) August	r(d) Sept	r(d) Annual
Ib	20 - 30	24.30	0.88	0.56	0.71	0.84	0.67
	30 - 40	35.80	0.80	0.49	0.66	0.57	0.63
	40 - 50	46.00	0.70	0.40	0.63	0.83	0.60
	50 - 60	54.93	0.61	0.27	0.56	0.45	0.50
	70 - 80	76.07	0.71	0.42	0.55	0.33	0.50
	90 - 100	93.25	0.57	0.35	0.48	0.33	0.54
Tel North-West	0 - 10	8.00	0.70	0.67	0.84	0.85	0.79
	10 - 20	17.00	0.85	0.66	0.85	0.79	0.80
	20 - 30	24.70	0.80	0.55	0.85	0.83	0.63
	30 - 40	36.64	0.75	0.54	0.86	0.60	0.70
	40 - 50	45.40	0.66	0.79	0.65	0.72	0.56
	50 - 60	53.30	0.71	0.47	0.71	0.75	0.63
	60 - 70	62.95	0.90	0.12	0.82	0.45	0.68
	70 - 80	75.80	0.77	0.33	0.62	0.61	0.65
	80 - 90	83.80	0.82	0.34	0.69	0.71	0.72
	90 - 100	93.70	0.76	0.21	0.70	0.47	0.46
	100 - 110	106.00	0.93	0.45	0.74	0.51	0.57
	110 - 120	116.20	0.84	- 0.06	0.55	0.15	0.39
	130 - 140	131.00	0.71	0.37	0.55	0.51	0.52
	140 - 150	143.80	0.90	0.57	0.64	0.49	0.74
	150 - 160	154.20	0.43	0.01	0.39	0.36	- 0.05
	160 - 170	169.00	0.77	0.22	0.43	0.36	0.36
Tel South-East	0 - 10	5.00	0.60	0.80	0.91	0.92	0.83
	10 - 20	18.13	0.82	0.65	0.78	0.80	0.77
	30 - 40	37.85	0.75	0.67	0.91	0.77	0.85
	40 - 50	41.93	0.67	0.37	0.52	0.65	0.61
	50 - 60	57.00	0.76	0.48	0.57	0.67	0.71
	60 - 70	65.57	0.71	0.41	0.39	0.70	0.63
	70 - 80	77.47	0.60	0.49	0.45	0.57	0.65
	80 – 90	83.93	0.72	0.51	0.58	0.64	0.65
	90 – 100	96.50	0.49	0.62	0.56	0.46	0.57
	100 – 110	103.40	0.52	0.47	0.34	0.23	0.50
	110 – 120	114.70	0.40	0.52	0.49	0.41	0.52
	120 – 130	121.60	0.81	0.49	0.49	0.59	0.72
	130 – 140	140.00	0.72	0.27	0.35	0.69	0.77
	140 – 150	145.60	0.36	0.36	0.22	0.33	0.31
	170 –180	173.80	0.25	0.28	0.34	0.49	0.40
Tel South-West	0 – 10	7.60	0.59	0.43	0.45	0.03	0.43
	10 – 20	13.10	0.13	0.67	0.77	- 0.13	0.79
	20 – 30	22.25	0.33	0.61	0.57	0.57	0.31
	30 – 40	35.80	0.34	0.56	0.51	0.03	0.28
	40 – 50	43.40	0.56	0.57	0.83	0.53	0.69

Table 1.5: Average spatial correlation as function of distance per interval of 10 km

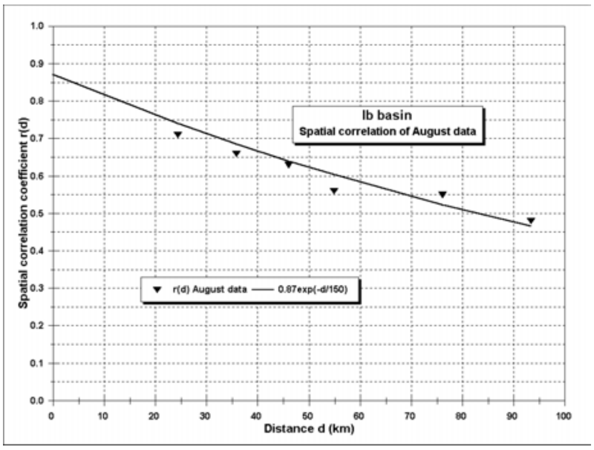

Figure 1.10: r(d) for August, Ib basin

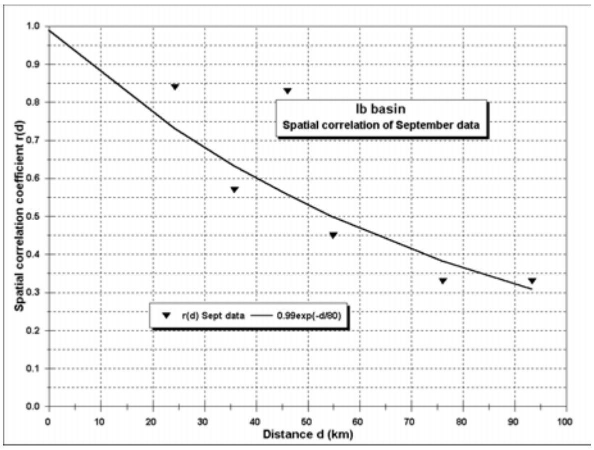

Figure 1.11: r(d) for September, Ib basin

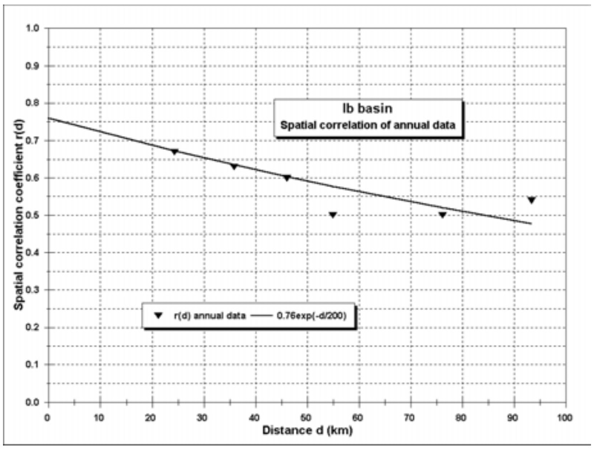

Figure 1.12: r(d) for Year, Ib basin

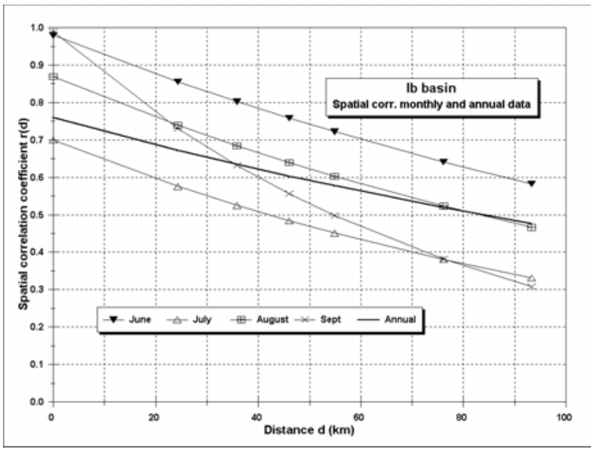

Figure 1.13: r(d) for monthly and annual data, Ib basin

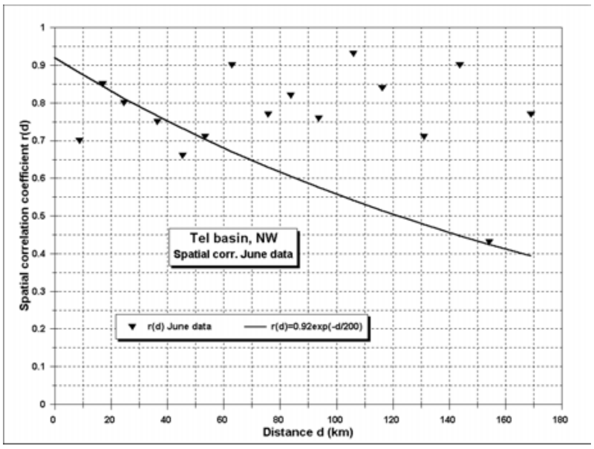

Figure 1.14: r(d) for June, Tel NW basin

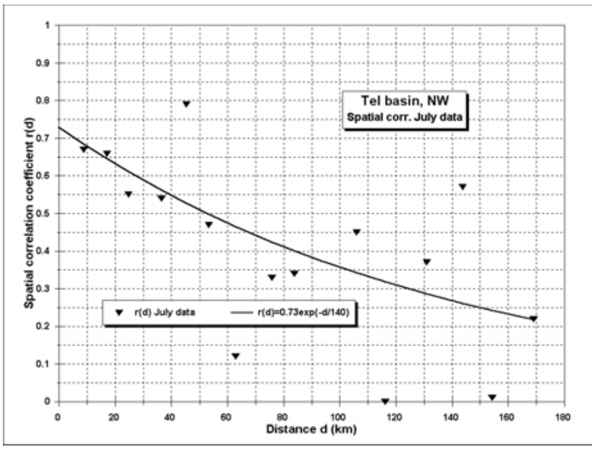

Figure 1.15: r(d) for July, Tel NW basin

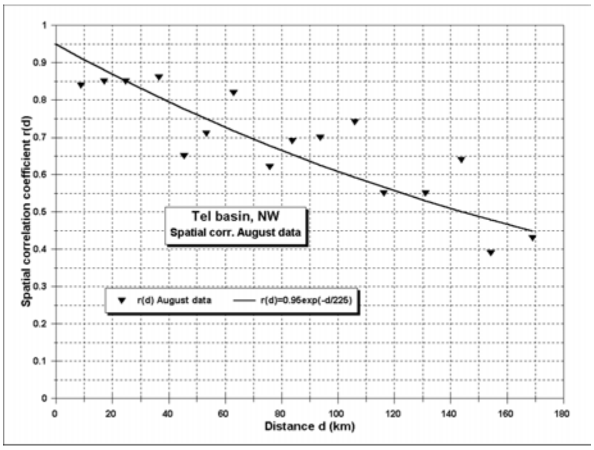

Figure 1.16: r(d) for August, Tel NW basin

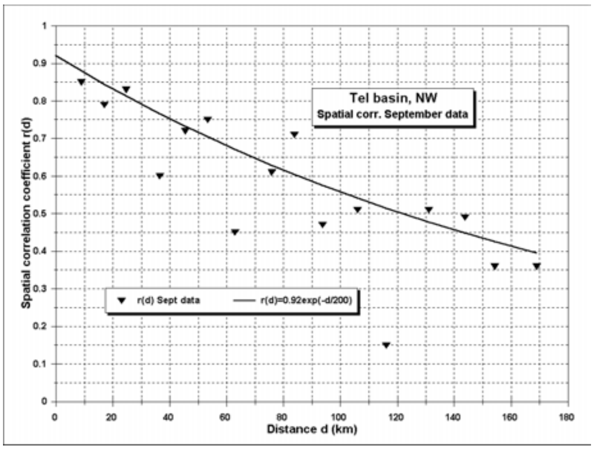

Figure 1.17: r(d) for September, Tel NW basin

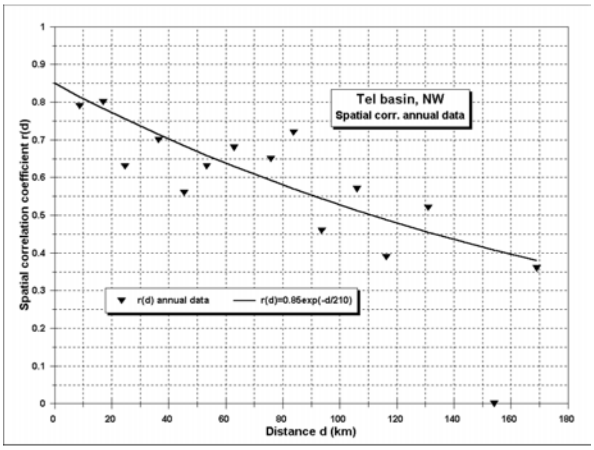

Figure 1.18: r(d) for Year, Tel NW basin

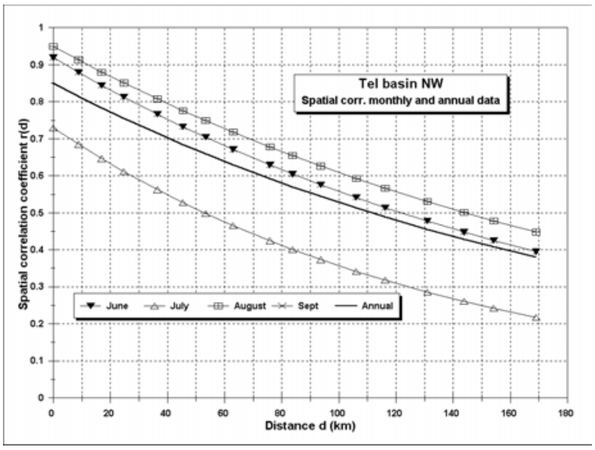

Figure 1.19: r(d) for monthly and annual data, Tel NW basin

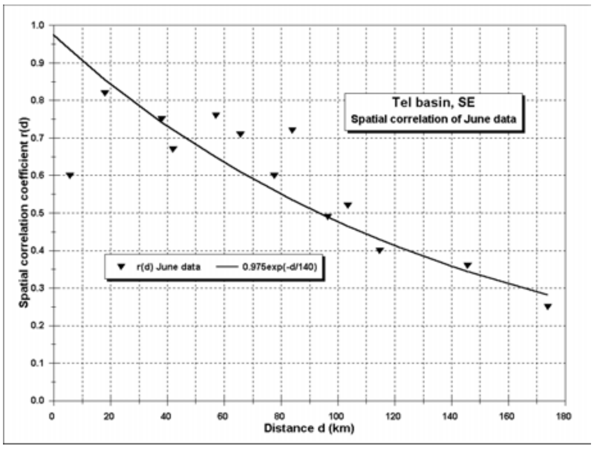

Figure 1.20: r(d) for June, Tel SE basin

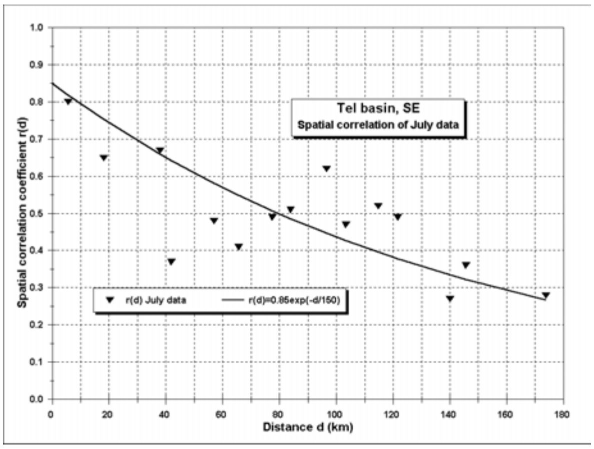

Figure 1.21: r(d) for July, Tel SE basin

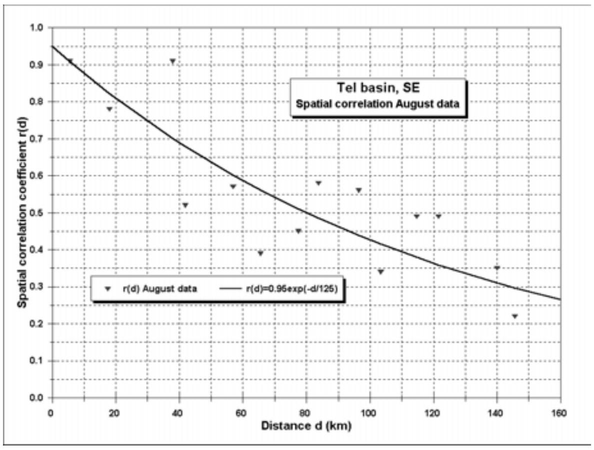

Figure 1.22: r(d) for August, Tel SE basin

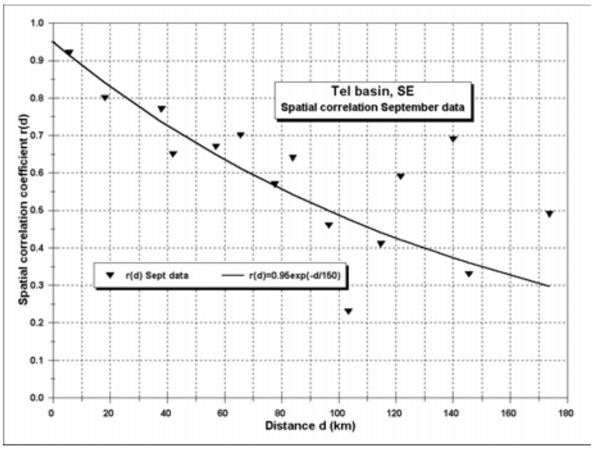

Figure 1.23: r(d) for September, Tel SE basin

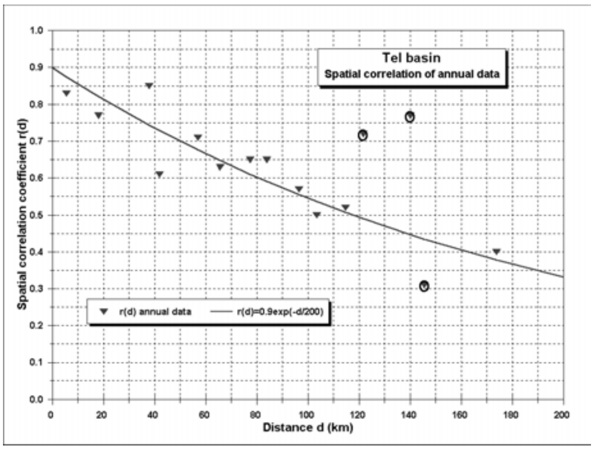

Figure 1.24: r(d) for Year, Tel SE basin

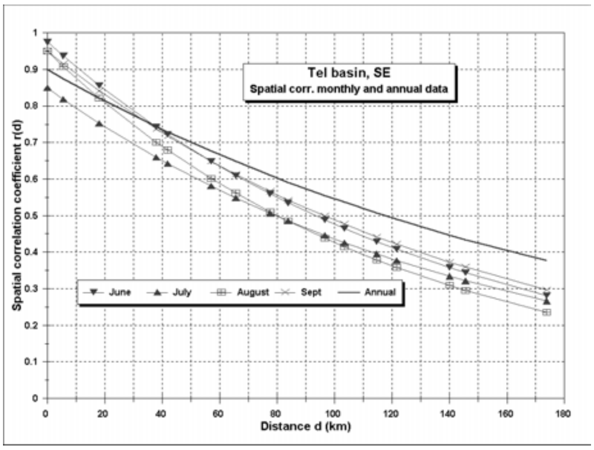

Figure 1.25: r(d) for monthly and annual data, Tel SE basin

Basin	**June**	**July**	**August**	**Sept**	**Year**
IB					
r_0	0.98	0.70	0.87	0.99	0.76
d_0 (km)	180	125	150	80	200
TEL NW					
r_0	0.92	0.73	0.95	0.92	0.85
d_0 (km)	200	140	225	200	210
TEL SE					
r_0	0.98	0.85	0.95	0.95	0.90
d_0 (km)	140	150	125	150	200

Table 1.6: Parameters in spatial correlation function

From Table 1.6 and Figures 1.13, 1.19 and 1.25 the following is observed:

- r_0 is smallest for July; a small value for July also brings down the r_0 for annual data
- d_0 is generally largest for the annual values.

The observation that the characteristic correlation distance increases with the aggregation level was to be expected. However, the low value for r_0 in July is not understood. It may either be due to measuring errors and/or microclimatic disturbances. Storm data (days with 500 mm of rainfall in one day) of this century do not show any anomaly for the month July compared to other monsoon months. There is also no evidence to ascribe it to measuring errors as there is no reason why the measurements in July would be less accurate than in the rest of the monsoon period. One is tempted to attribute it to the school holiday season, which starts in July, since many of the observers are schoolteachers. However, the holiday season also includes August, but an equally low r_0-value for that month is not observed. It might well be, that part of the data is not original, as can be observed from e.g. Figure 1.14; the high correlation coefficients at large distance in June do suggest that at least part of the series is artificial (obtained by regression analysis). Without having access to the original data the low r_0-value for July remains a mystery.

1.5 ESTIMATION ERROR ASSESSMENT

The error made in estimation of the areal rainfall of individual months in the monsoon period and of the annual total was taken as the measure of effectiveness of the rainfall observation network. This criterion was taken in view of absence of information on Hydrological Data User requirements at the time of the execution of the study. Since monthly and annual rainfall data are usually considered in water balance studies together with flow data, the estimation error in both types of data should be of the same order of magnitude. Since the error in individual discharge data derived from water levels will be in the order of 10% a similar estimation value is applied for rainfall data.

The root mean square error in the areal rainfall estimate relative to the point (time) average value Z_{areal} is computed from (see Chapter 6 of Volume 2, Design Manual, Sampling Principles):

$$Z_{areal} = Cv\sqrt{\frac{1}{N}\left(1-r_0+\frac{0.23}{d_0}\sqrt{\frac{S}{N}}\right)} \qquad (1.3)$$

The estimation error is seen to depend strongly on the point rainfall characteristic Cv, whereas furthermore the measuring error ($1-r_0$) and the characteristic correlation distance d_0 play a role. In equation (1.3) N is the number of gauges per area S. Essential in the application of equation (1.3) is the choice of area S. Since, the hydro-meteorological network should be integrated with the hydrometric network and/or the groundwater network the value of S should coincide with a characteristic unit of drainage area or aquifer. Considering surface runoff, a logical choice for S is the minimum area upstream of a stream gauging station. For the hydrometric network in the Hydrological Information System typically for the plain areas one stream gauging station per 2,000 km^2 drainage area is applied. Hence the design surface area S for the hydro-meteorological network in the plains is taken as S=2,000 km^2. The estimation error Z for each month and for annual data for each area is presented in Table 1.7 and Figures 1.26 to 1.28.

In Table 1.7 the area S/N to be covered by one rain gauge, to reach on average an areal rainfall estimate with an estimation error of not larger than 10% in a single month in a design area of 2,000 km^2, is presented. The S/N values are rounded to the nearest 50 km^2. In the Figures 1.26 to 1.27 the relationship between the estimation error and the network density is displayed. Interesting features are observed from e.g. Figure 1.26. The required network density for July would be four times as large if the acceptable estimation error would be halved from 10% to 5%. Apparently, highly accurate areal rainfall estimates can only be obtained with a disproportionate increase in network density. This observation stresses the need for a careful assessment of the acceptable estimation error.

Basin	June	July	August	Sept	Year
IB					
Cv	0.69	0.39	0.41	0.52	0.24
r_0	0.98	0.70	0.87	0.99	0.76
d_0 (km)	180	125	150	80	200
S/N (km^2)	750	400	700	800	1250
F_{WMO} (%)	8	11	8	7	6
TEL NW					
Cv	0.66	0.36	0.47	0.63	0.25
r_0	0.92	0.73	0.95	0.92	0.85
d_0 (km)	200	140	225	200	210
S/N (km^2)	450	500	1100	500	1650
F_{WMO} (%)	11	10	6	10	5
TEL SE					
Cv	0.60	0.44	0.48	0.56	0.29
r_0	0.98	0.85	0.95	0.95	0.90
d_0 (km)	140	150	125	150	200
S/N (km^2)	800	550	850	700	1650
F_{WMO} (%)	7	9	7	8	5

Table 1.7: Network density for 10% estimation error in average rainfall for a design area of 2,000 km^2.

1.6 NETWORK DESIGN

The objective was to arrive at a network capable in estimating the areal rainfall for catchment areas of 2,000 km^2 and beyond with an error less than 10% of the long term average rainfall for the month or year. From Table 1.7 it is observed that for the various distinguished areas the area per gauge ranges from 400 to 1100 km^2.

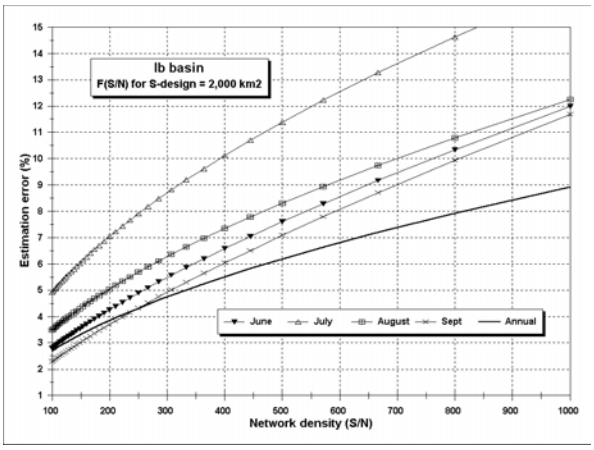

Figure 1.26: Est. error as function of S/N, Ib basin

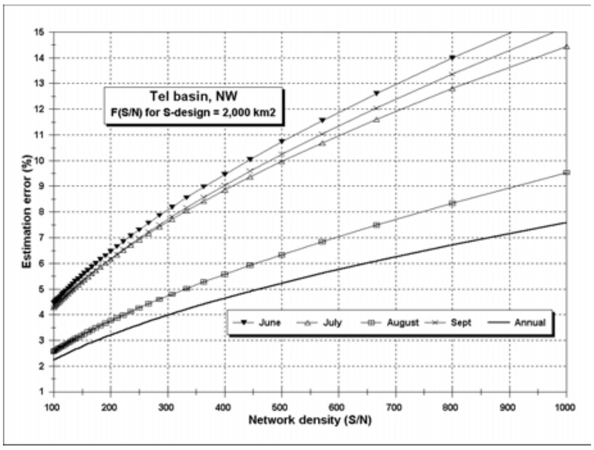

Figure 1.27: Est. error as function of S/N, Tel NW basin

A high density is generally required for estimating the July areal rainfall with the desired accuracy, mainly because of the low r_0 value for that month. To reach for all months the required accuracy, the network density should be one gauge per 400 and 500 km^2 for Ib and Tel, respectively. If the objectives are not applied to the last percent admissible error then for both basins a density of one gauge per 500 km^2 will do. To get a proper estimate of the annual value the demands on the network density are strongly reduced; the density can then be reduced with a factor 2 to 3.

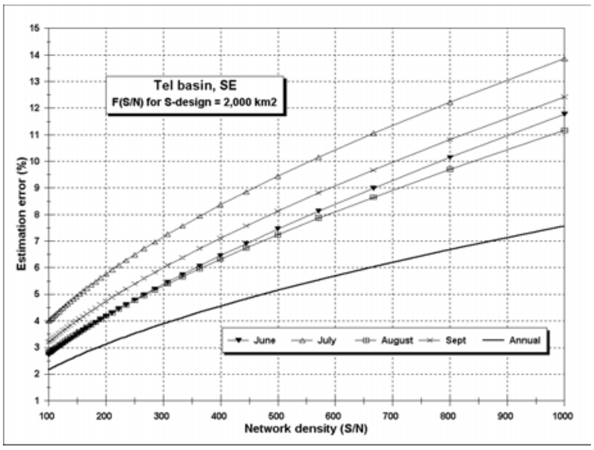

Figure 1.28:
Estimation error as function of S/N, Tel SE basin

It is noted that in the preceding analysis the computed values should not be considered to be very accurate, given the scatter in the spatial correlation plots used to estimate the values for r_0 and d_0. Rather, the analysis gives a first estimate of the estimation errors involved. A somewhat better estimate of the errors in the areal rainfall is obtained from kriging, as here the assumption of an equally spaced network is not a prerequisite as was the case in the above analysis. Nevertheless, the uncertainties in the estimation of the spatial correlation structure applies here as well.

WMO minimum network density requirement

WMO uses as standard for plain areas a minimum network density of one gauge per 500 km^2. In Table 1.7 it is indicated what the consequences would be with respect to the estimation error if this norm is applied. It is seen that the estimation error would vary for the monthly values between 6 and 11% and between 5 and 6% for the annual values. Given the various uncertainties it is observed that the WMO norm perfectly fits to the accuracy requirements for monthly values in the Ib and Tel basins.

Hence, assuming that the spatial correlation structure and the temporal variation of the point rainfall processes in areas outside Mahanadi do not differ too much from the variability in the Ib and Tel basins, as a first guess the WMO norm can be applied for preliminary network design.

Summing up

The total catchment areas of Ib and Tel are respectively 7,627 and 30,426 km^2. Applying a network density of one gauge per 500 km^2 the requirement becomes respectively 15 rainfall stations for the Ib basin and 61 stations for Tel. At present the network contains 12 and 54 stations respectively, hence some 10% increase in the number of stations in both catchments would be required.

It is stressed though, that much effort has to be put in proper upgrading of the stations. The analysis of the historical data has shown that some **60%** of the stations have series of **doubtful quality**. Hence, station conditions, equipment and operational practice has to be given serious attention.

2 ESTIMATION ERROR IN LONG TERM MEAN AREAL RAINFALL

The estimation or the standard error of long term mean areal rainfall can be split into 3 multiplicative components (Rodriguez-Iturbe, 1974), namely:

1. the standard deviation of the point rainfall process σ_h,
2. the temporal reduction factor $F_1(T)$, dependent on the period used for estimating the average areal rainfall $\bar{h}_A$, and the serial correlation coefficient, and
3. the spatial reduction factor $F_2(N, \bar{r})$, which depends on the number of stations used in the determination of $\bar{h}_A$ and the spatial correlation structure.

The error variance of the mean $\sigma^2(\bar{h}_A)$ is defined by:

$$\sigma^2(\bar{h}_A) = E[(\bar{h}_A - E[\bar{h}_A])^2] \tag{2.1}$$

Its root is the estimation error $\sigma(\bar{h}_A)$. To be consistent with Chapter 1, the error will be expressed relative to the long term mean rainfall. Hence, the relative error in the long term mean areal rainfall $Z(\bar{h}_A)$. becomes:

$$Z(\bar{h}_A) = \frac{\sigma(\bar{h}_A)}{\bar{h}_A} = \frac{\sigma_h}{\bar{h}}.F_1(T).F_2(N,\bar{r}_s)$$

or since $\sigma_h/\bar{h}$ = Cv

$$Z(\bar{h}_A) = Cv.F_1(T).F_2(N,\bar{r}_s) \tag{2.2}$$

with:

$$F_1(T) = \sqrt{\frac{1}{n}.\frac{1+r_{T,1}}{1-r_{T,1}}} \approx \sqrt{\frac{1}{n}} \tag{2.3}$$

and:

$$F_2(N,\bar{r}) = \sqrt{\frac{1-\bar{r}_s}{N} + \bar{r}_s} \tag{2.4}$$

where: $Z(\bar{h}_A)$= relative estimation error in the long term mean areal rainfall
h = average of point rainfall series
σ_h = standard deviation of the point rainfall series
Cv = coefficient of variation of point rainfall series
$r_{T,1}$ = auto-correlation coefficient at lag 1
n = length of rainfall series; here the number of years in the series
N = number of gauging stations
$\bar{r}_s$ = mean spatial correlation coefficient over the area considered

Two remarks are made here:

- the autocorrelation coefficient of monthly or annual rainfall series is generally about zero, hence the approximation made in equation (2.3) will often be applicable.

- the mean spatial correlation coefficient can be approximated by the spatial correlation coefficient at the average distance.
- If the distance between two randomly chosen points in the area of concern is considered as a stochastic variable (see Buishand, 1977):

$$E[r_s(\underline{d})] = \bar{r}_s \approx r_s[E(\underline{d})] \tag{2.5}$$

The distance E(d) or d_r is called the characteristic correlation distance of the homogeneous and isotropic area S. Values for d_r for some typical shapes of basins with unit surface are given in Table 2.1.

Type of basin	Circumference	d_r
Circle	3.545	0.5108
Regular hexagon	3.722	0.5126
Square	4.000	0.5214
Equilateral triangle	4.559	0.5544
Rectangle L/W=2	4.243	0.5691
Rectangle L/W=4	5.000	0.7137
Rectangle L/W=16	8.500	1.3426

Source: Matern, 1960
L/W = length-width ratio

Table 2.1: Characteristic correlation distance d_r for basins with area 1

To apply Table 2.1, the value for d_r in the table is multiplied with the root of the basin area. So if the area is a square with area S=5,000 km^2, then for d_r it follows: 0.5214*√(5000) ≈ 37 km.

Application

The above procedure is applied to the areal annual rainfall series of the south-eastern part of Tel basin. From Chapter 1, Table 1.7 it follows that the coefficient of variation of the annual point rainfall series is 0.29 and that the spatial correlation structure for annual data is well described by the following relation:

$$r_s(d) = 0.90\exp(-d/200) \tag{2.6}$$

From Figure 1.1 in Chapter 1 it is observed that the catchment area of the south-easter part can be approximated by a rectangle with a length-width ratio of about 2 and its size is roughly 12,000 km^2. So the characteristic correlation distance d_r becomes:

$$d_r = 0.5691\sqrt{12000} \approx 62\,\text{km} \tag{2.7}$$

With equation (2.6) then the mean correlation for the area will be:

$$r_s(62) = 0.90\exp(-62/200) = 0.66 \approx \bar{r}_s \tag{2.8}$$

It is further assumed that the auto-correlation at lag1 of the annual series is not significant, hence $r_{T,1}$ = 0. Filling in these values in equation 2.2, Z($\bar{h}_A$) as a function of the number of years n and the number of gauges N can be computed. The effects of F_1(T) and F_2(N, $\bar{r}_s$) on Z($\bar{h}_A$) separately is shown in Figure 2.1.

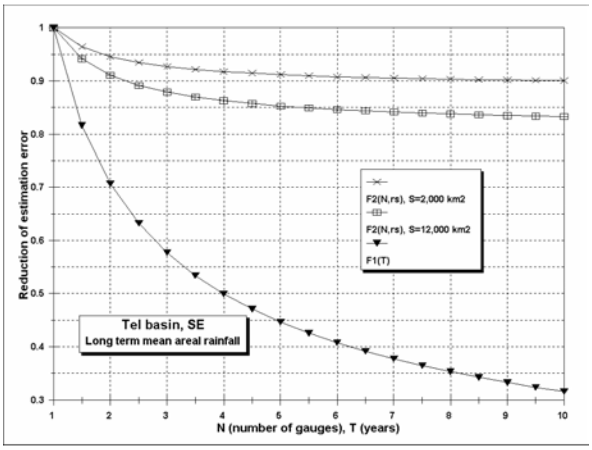

Figure 2.1:
Reduction of estimation error by $F_1(T)$ and $F_2(N, \bar{r}_s)$ for areas in Tel basin of size 2,000 and 12,000 km^2

It is observed from Figure 2.1 that to reduce the error in the long term areal mean rainfall, addition of a few more years of observation is much more effective than extending the network. This effect is stronger the smaller the catchment area, as is shown in the same figure by comparing $F_2(N, r_s)$ with the same function for an area of 2,000 km^2.

3 SUMMARY OF MONTHLY AND ANNUAL STATISTICS OF CLIMATIC VARIABLES

3.1 INTRODUCTION

In Chapter 2 of Volume 3, Design Manual on Hydro-meteorology the rainfall and evaporation processes have been described. To give insight in the variation of the relevant climatic variables, in this chapter a summary is given of the monthly and annual statistics of these variables for selected locations in peninsular India. The data are taken from published summaries by IMD (IMD, 1990: Climatological Tables of Observatories in India) and refer to the period 1931-1960. The following variables are presented:

- Temperature
  - Daily maximum
  - Daily minimum
  - Highest
  - Lowest
- Humidity
- Rainfall
  - Monthly/annual totals
  - Highest 24 hour rainfall
- Windspeed

The variables are given for the following locations:

1.	Andhra Pradesh:	Hyderabad and Kakinada
2.	Chhattisgarh	Raipur and Jagdalpur
3.	Gujarat:	Ahmedabad and Surat
4.	Karnataka:	Bangalore and Honavar
5.	Kerala:	Trivandrum and Calicut
6.	Madhya Pradesh:	Bhopal and Pachmarhi
7.	Maharashtra:	Mumbai and Mahabaleshwar
8.	Orissa:	Cuttack and Sambalpur
9.	Tamil Nadu	Chennai and Madurai

Above stations are the state capitals and a representative coastal/hill station. Their locations are shown in Figure 3.1

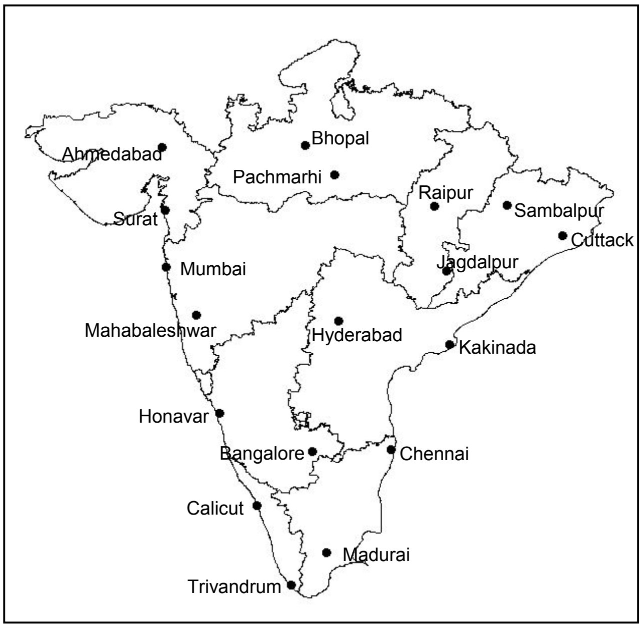

Figure 3.1:
Location of selected climatic stations.

3.2 ANDHRA PRADESH

The monthly and annual statistics of selected climatic variables for Hyderabad and Kakinada are presented in the Tables 3.1 and 3.2 and Figures 3.2 to 3.5.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Andhra Pradesh	Hyderabad	January	28.6	14.6	35.1	6.1	36	1.7	93.2	8.1
		February	31.2	17.6	37.2	8.9	35	11.4	42.9	8.9
		March	34.8	20.1	42.2	13.2	30	13.4	103.1	9.6
		April	36.9	23.7	43.3	16.1	31	24.1	60.7	10.9
		May	38.7	26.2	44.4	19.4	33	30.1	65.1	12.4
		June	34.1	24.1	43.9	17.8	54	107.4	122.7	23.8
		July	29.8	22.3	37.2	19.4	69	165.1	109.2	22.1
		August	29.5	22.1	36.1	19.4	70	146.9	190.5	18.3
		September	29.7	21.6	36.1	17.8	71	163.3	153.2	12.6
		October	30.3	19.8	36.7	12.2	58	70.8	117.1	8.9
		November	28.7	16.1	33.9	7.8	48	24.9	95.5	8.1
		December	27.8	13.4	33.3	7.2	42	5.5	44.5	7.4
		ANNUAL	31.7	20.1	44.4	6.1	48	764.4	190.5	12.6

Table 3.1: Summary statistics of climatic variables for Hyderabad

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Andhra Pradesh	Kakinada	January	27.3	19.1	32.8	14.4	70	3.6	78.2	10.3
		February	29.6	20.7	37.8	15.6	67	11.9	45.1	8.8
		March	33.1	23.1	38.9	17.2	62	11.8	71.6	8.3
		April	35.3	25.8	42.8	18.9	65	22.1	61.1	9.1
		May	36.9	27.7	46.7	21.1	64	45.7	109.7	11.1
		June	35.9	27.1	47.2	21.7	61	126.1	501.4	12.1
		July	31.8	25.4	41.7	21.1	73	218.2	127.1	12.3
		August	31.8	25.6	37.8	21.7	74	151.6	146.1	11.1
		September	32.1	25.5	37.2	21.7	76	158.2	285.7	8.6
		October	30.8	24.5	37.2	17.2	74	306.6	281.9	9.5
		November	28.7	21.6	33.9	15.6	69	107.1	276.3	12.1
		December	27.1	19.2	32.2	13.9	69	9.1	130.3	11.3
		ANNUAL	31.7	23.8	47.2	13.9	69	1171.9	501.4	10.4

Table 3.2: Summary statistics of climatic variables for Kakinada

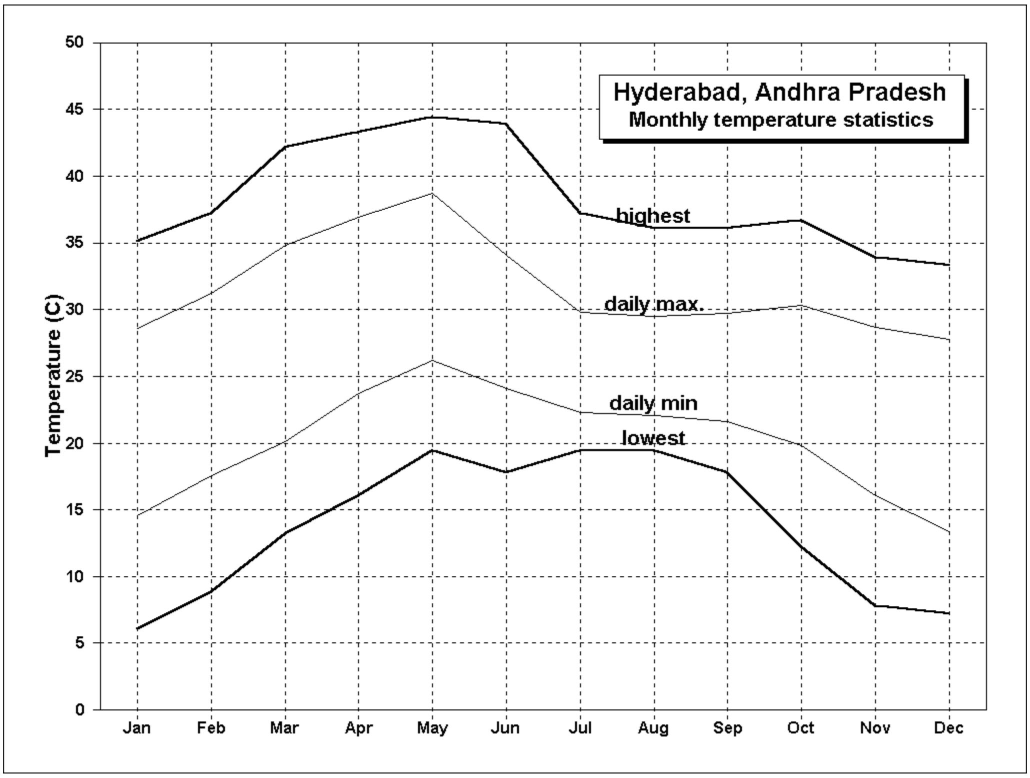

Figure 3.2: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Hyderabad

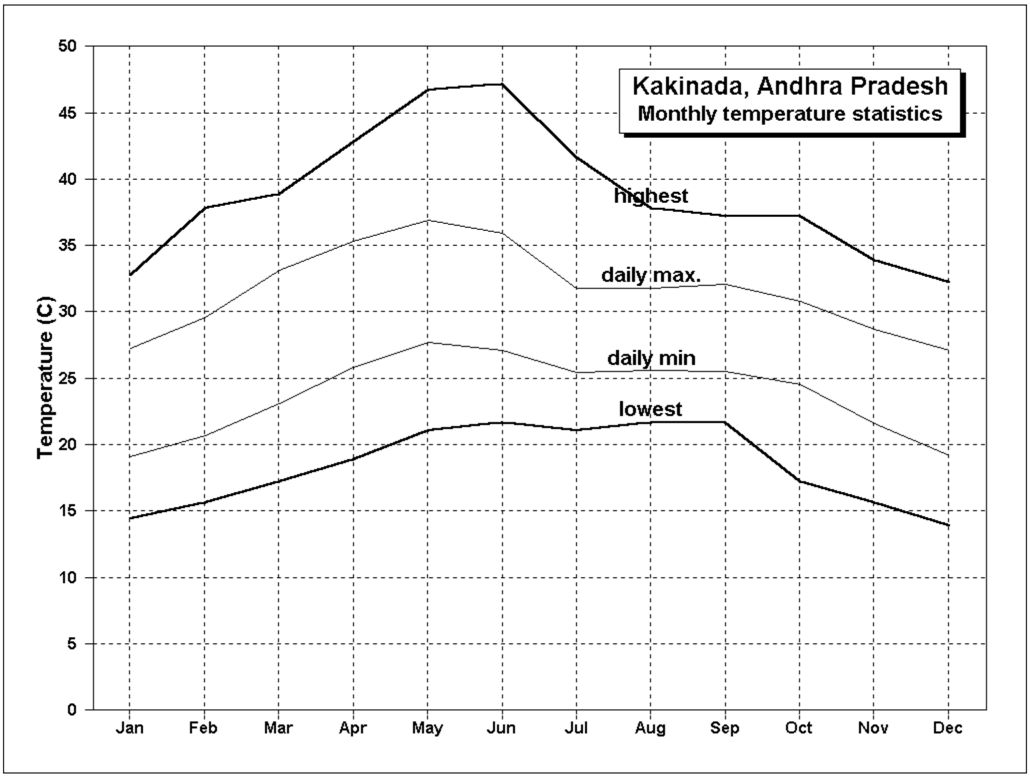

Figure 3.3: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Kakinada

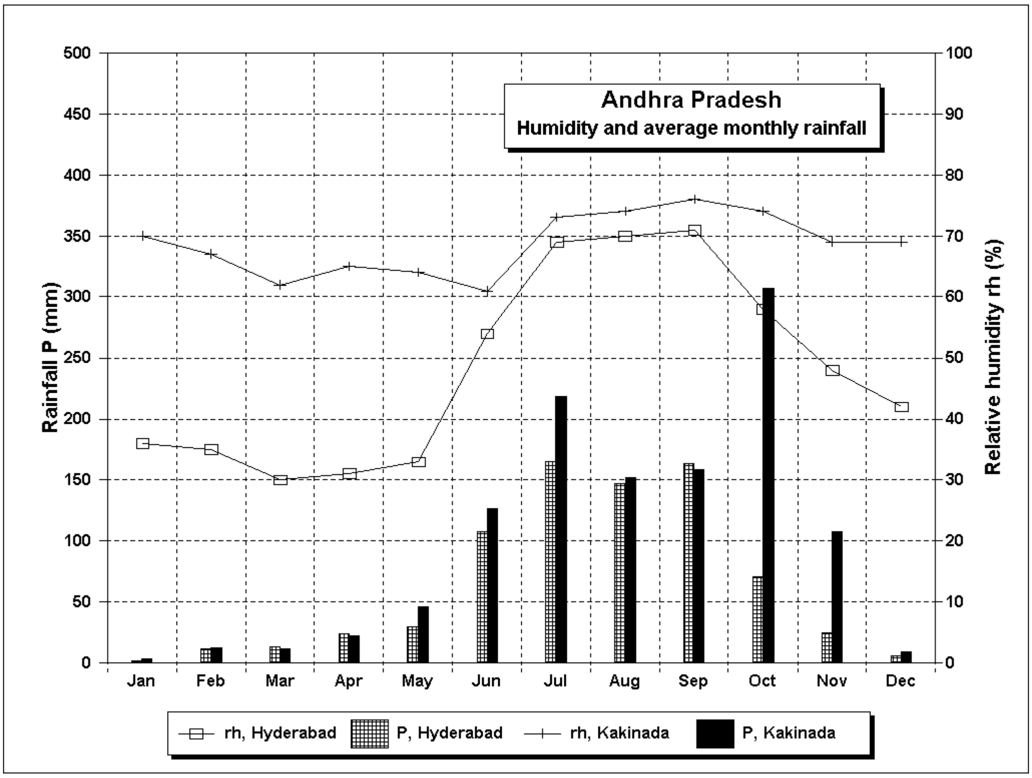

Figure 3.4: Monthly rainfall totals and humidity for Hyderabad and Kakinada

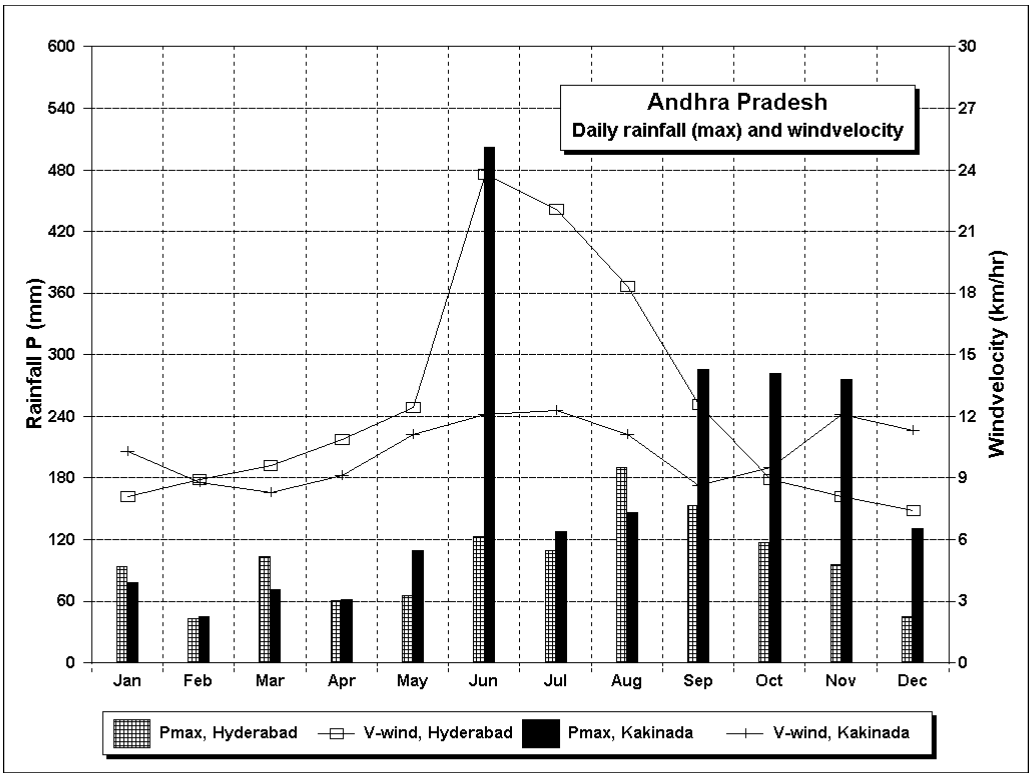

Figure 3.5: Monthly highest 24 hour rainfall and average windspeed for Hyderabad and Kakinada

3.3 CHHATTISGARH

The monthly and annual statistics of selected climatic variables for Raipur and Jagdalpur are presented in the Tables 3.3 and 3.4 and Figures 3.6 to 3.9.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Chhattisgarh	Raipur	January	27.7	13.5	35.0	5.0	39	12.2	55.4	5.0
		February	30.3	16.2	37.8	5.0	31	20.4	57.4	6.0
		March	34.7	20.5	43.3	8.3	24	23.3	55.9	6.9
		April	39.2	25.1	46.1	15.0	21	15.1	38.3	8.4
		May	42.3	28.8	47.2	14.4	22	16.8	80.3	10.7
		June	37.5	26.8	47.2	16.1	49	193.6	197.6	12.1
		July	30.3	24.1	38.9	20.0	78	391.8	213.1	11.8
		August	30.1	24.1	36.7	20.0	78	393.6	370.3	10.4
		September	31.0	24.1	37.2	18.3	74	249.4	148.6	7.4
		October	31.2	21.5	37.8	13.9	60	62.4	148.6	6.0
		November	29.1	16.0	35.6	8.3	46	7.8	70.4	4.1
		December	27.3	13.2	32.2	3.9	43	1.8	52.1	4.4
		ANNUAL	32.6	21.2	47.2	3.9	47	1388.2	370.3	7.8

Table 3.3: Summary statistics of climatic variables for Raipur

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Chhattisgarh	Jagdalpur	January	28.5	11.0	33.1	2.8	41	5.3	40.6	2.8
		February	31.0	14.3	36.7	5.0	36	14.5	120.4	3.9
		March	34.7	18.4	40.6	9.4	28	17.1	45.7	4.5
		April	36.9	22.2	43.3	13.9	31	51.1	54.4	5.7
		May	38.3	24.6	46.1	17.2	37	65.6	64.3	6.6
		June	33.5	23.9	44.4	17.2	61	211.8	133.1	7.2
		July	28.1	22.2	35.6	18.3	82	397.9	180.9	9.1
		August	28.4	22.2	33.9	16.7	81	381.2	203.2	7.8
		September	29.5	22.3	35.0	17.8	80	245.5	163.8	5.6
		October	29.8	19.9	34.4	11.1	67	115.8	136.9	3.7
		November	28.1	14.7	33.3	5.6	56	24.4	102.9	3.0
		December	27.4	11.3	32.2	3.9	50	3.9	38.3	2.5
		ANNUAL	31.2	18.9	46.1	2.8	54	1534.1	203.2	5.2

Table 3.4: Summary statistics of climatic variables for Jagdalpur

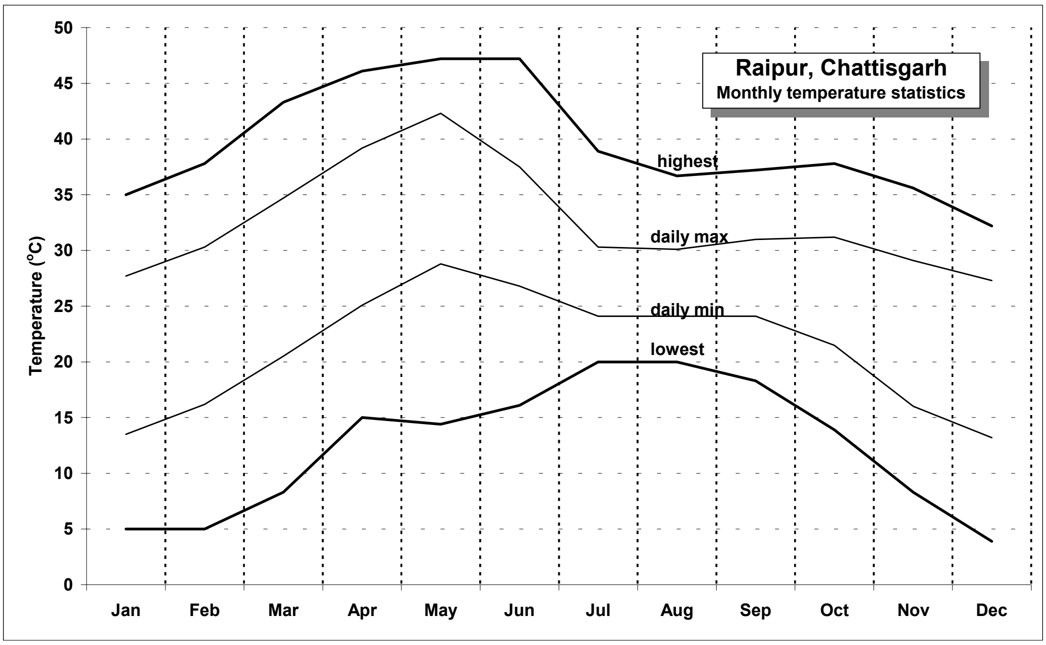

Figure 3.6: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Raipur

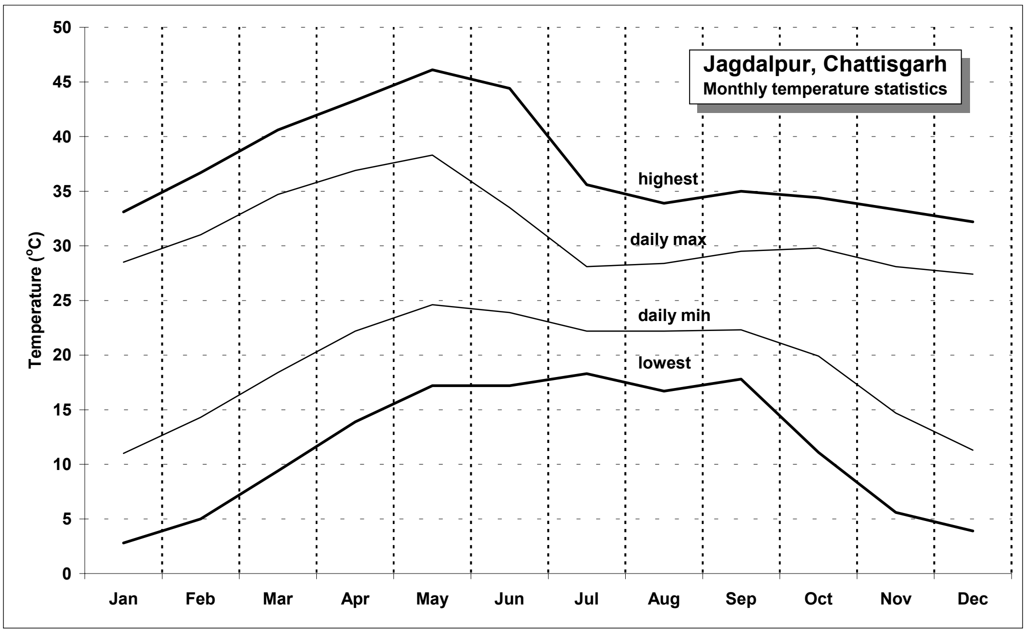

Figure 3.7: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Jagdalpur

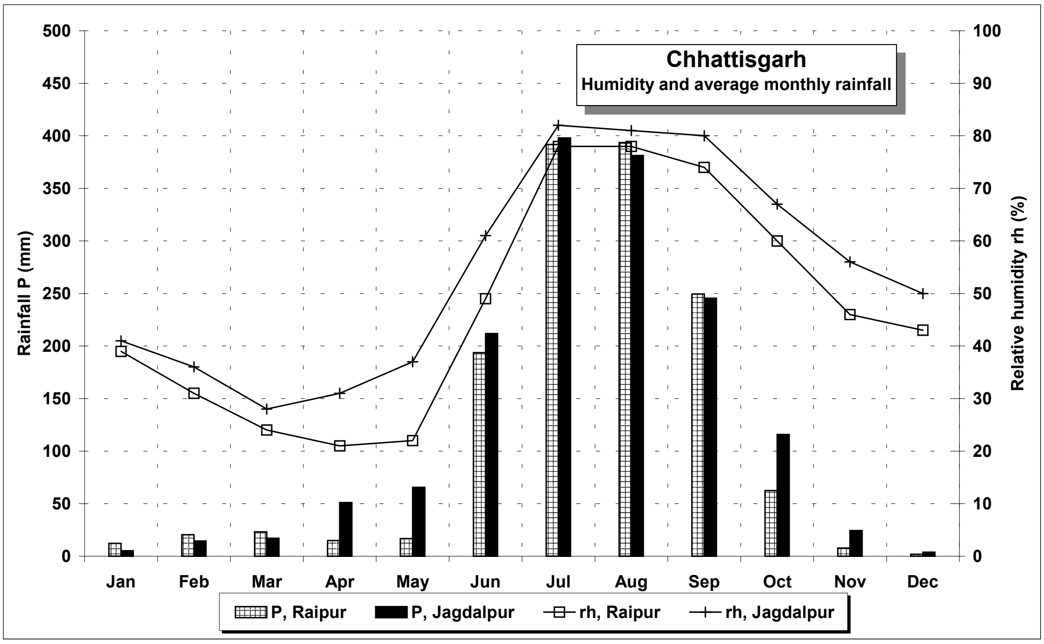

Figure 3.8: Monthly rainfall totals and humidity for Raipur and Jagdalpur

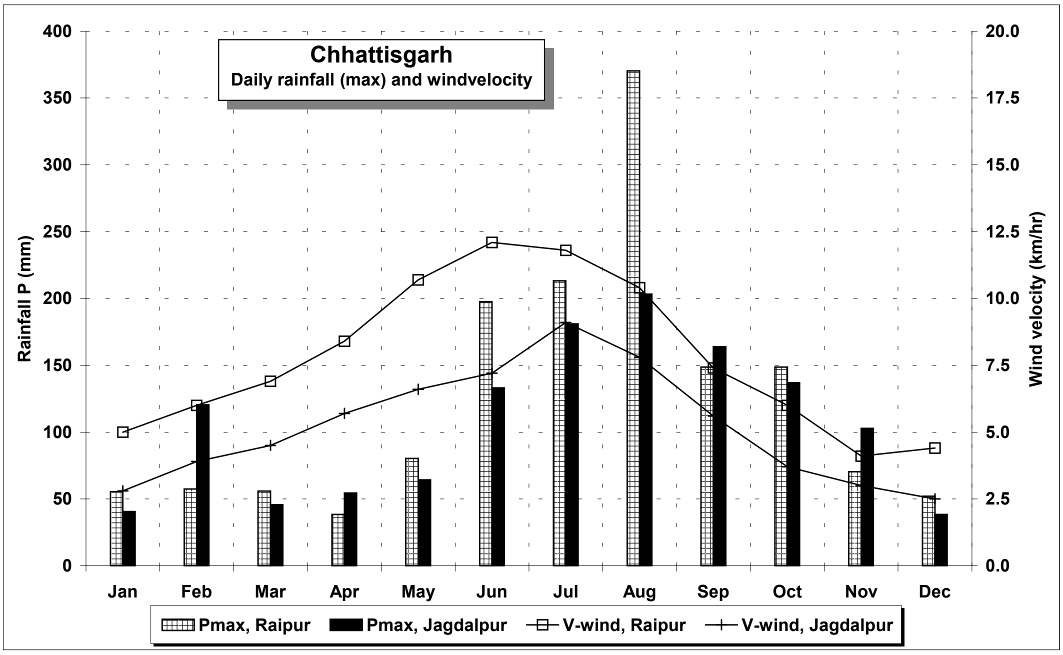

Figure 3.9: Monthly highest 24 hour rainfall and average windspeed for Raipur and Jagdalpur

3.4 GUJARAT

The monthly and annual statistics of selected climatic variables for Ahmedabad and Surat are presented in the Tables 3.5 and 3.6 and Figures 3.10 to 3.13.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Gujarat	Ahmedabad	January	28.7	11.9	36.1	3.3	28	3.9	30.7	5.4
		February	31.1	14.5	40.6	2.2	24	0.3	26.4	5.1
		March	35.7	18.6	43.9	9.4	20	0.9	12.2	7.3
		April	39.7	23.1	46.2	12.8	18	1.9	21.6	7.8
		May	40.7	26.3	47.8	19.4	21	4.5	46.2	9.5
		June	38.1	27.4	47.2	19.4	41	100.1	130.8	10.8
		July	33.2	25.7	42.2	21.1	68	316.3	414.8	10.8
		August	31.8	24.6	38.9	21.7	69	213.3	150.6	8.3
		September	33.1	24.2	41.7	21.6	60	162.8	257.8	7.1
		October	35.6	21.2	42.8	14.4	35	13.1	52.8	4.6
		November	33.1	16.1	38.9	9.4	29	5.4	53.3	4.1
		December	29.6	12.6	35.6	6.1	29	0.7	14.1	2.6
		ANNUAL	34.2	20.5	47.8	2.2	37	823.1	414.8	6.9

Table 3.5: Summary statistics of climatic variables for Ahmedabad

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Gujarat	Surat	January	31.4	14.8	38.3	4.4	41	0.6	43.7	6.1
		February	33.1	16.4	41.7	8.6	35	1.1	38.1	6.1
		March	36.1	20.1	43.9	10.6	33	0.7	8.1	6.6
		April	37.3	23.7	45.6	15.1	40	5.1	97.8	7.6
		May	36.2	26.6	45.6	19.4	57	5.5	48.8	11.1
		June	33.7	27.1	45.6	21.8	70	209.8	260.1	12.2
		July	30.5	25.7	38.9	20.6	81	448.1	459.2	11.8
		August	30.3	25.4	37.2	21.1	79	254.1	228.9	10.7
		September	31.6	24.1	41.1	20.6	72	217.9	389.4	7.3
		October	35.5	23.1	41.1	14.4	48	43.1	257.1	5.9
		November	34.9	19.2	39.4	10.6	40	15.7	148.3	6.2
		December	32.8	16.1	38.9	6.7	41	2.1	42.2	6.1
		ANNUAL	33.6	21.9	45.6	4.4	53	1203.5	459.2	8.1

Table 3.6: Summary statistics of climatic variables for Surat

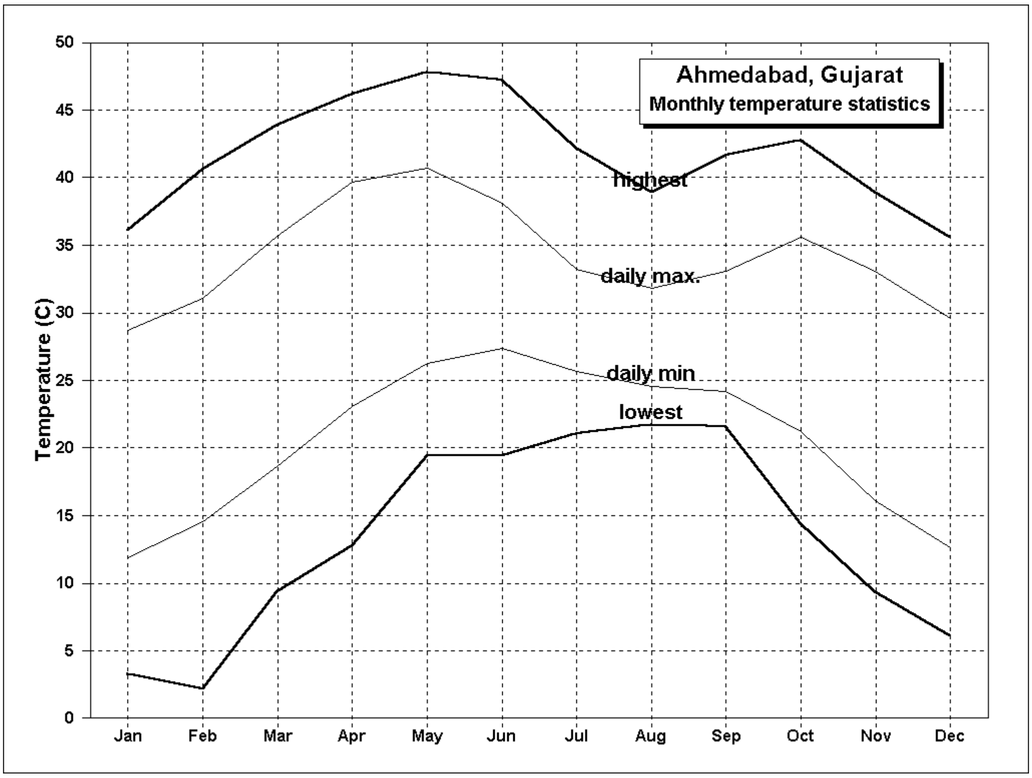

Figure 3.10: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Ahmedabad

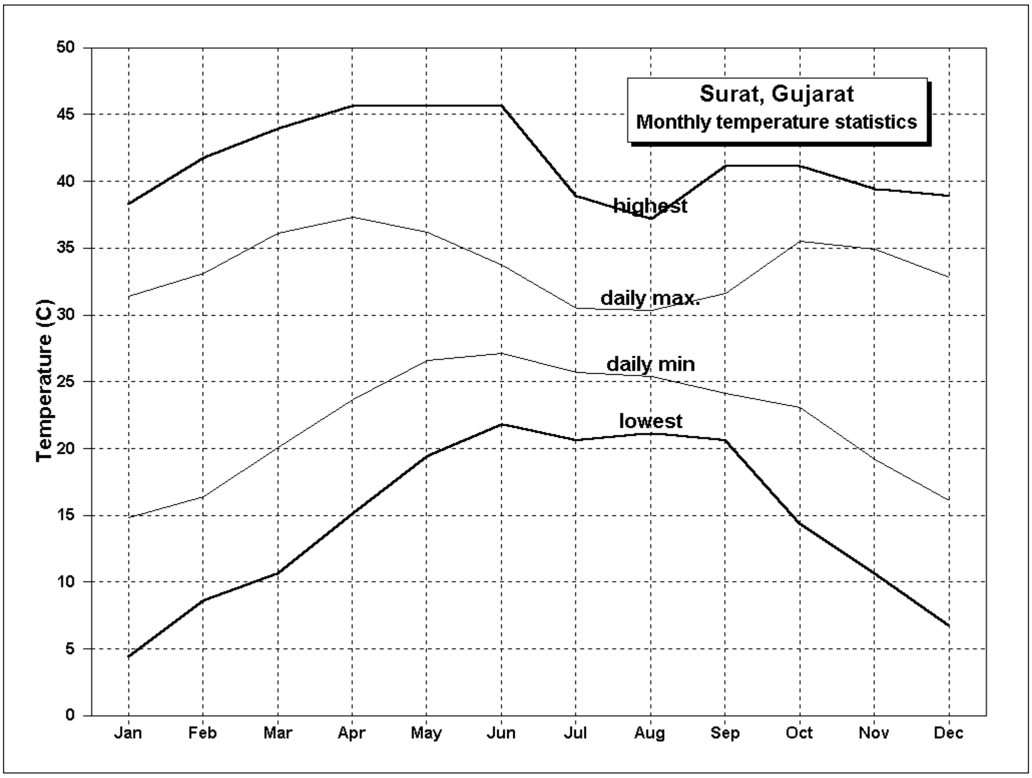

Figure 3.11: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Surat

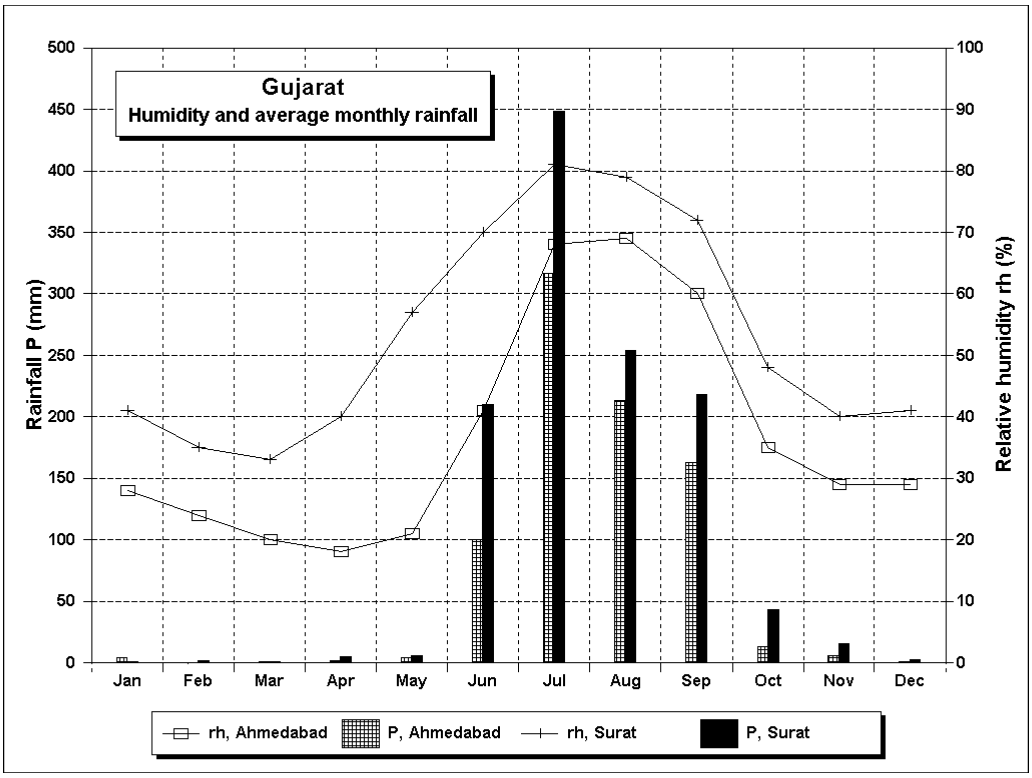

Figure 3.12: Monthly rainfall totals and humidity for Ahmedabad and Surat

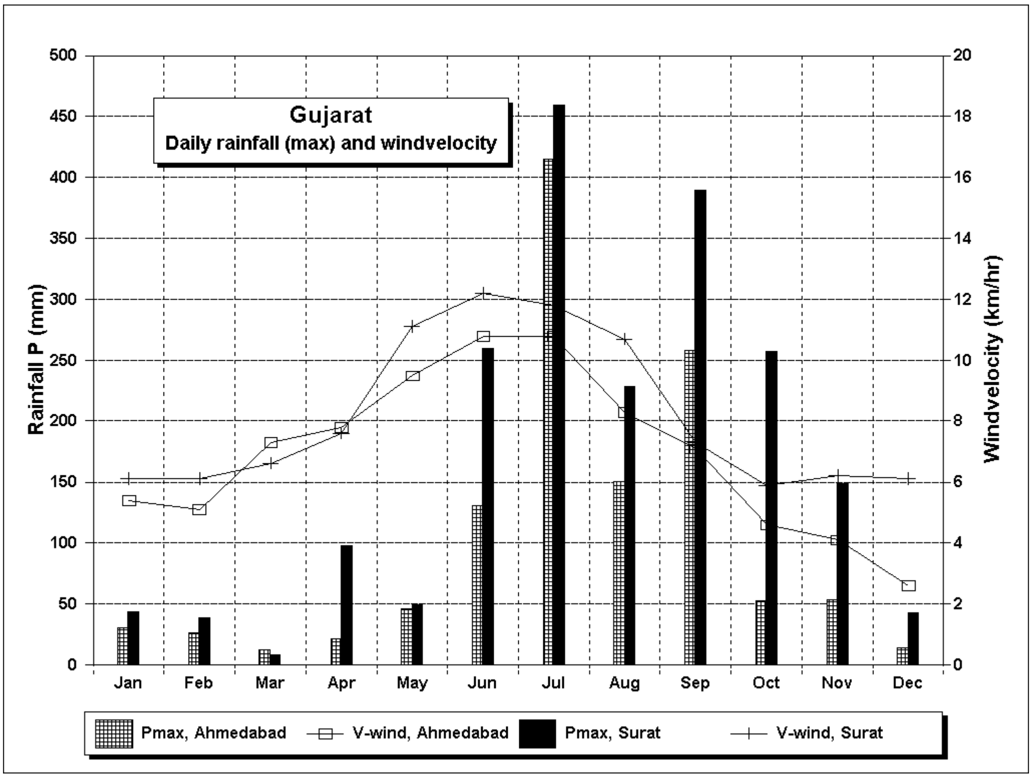

Figure 3.13: Monthly highest 24 hour rainfall and average windspeed for Ahmedabad and Surat

3.5 KARNATAKA

The monthly and annual statistics of selected climatic variables for Bangalore and Honavar are presented in the Tables 3.7 and 3.8 and Figures 3.14 to 3.17.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Karnataka	Bangalore	January	26.9	15.1	32.2	7.8	40	3.3	65.8	10.4
		February	29.7	16.5	34.4	9.4	29	10.2	67.3	7.9
		March	32.3	19.1	37.2	11.1	24	6.1	50.8	9.4
		April	33.4	21.2	38.3	14.4	34	45.7	90.7	9.1
		May	32.7	21.1	38.9	16.7	46	116.5	153.9	11.8
		June	28.9	19.7	37.8	16.7	62	80.1	101.6	17.1
		July	27.2	19.2	33.3	16.1	68	116.6	105.4	17.5
		August	27.3	19.2	33.3	14.4	66	147.1	162.1	15.2
		September	27.6	18.9	33.3	15.1	62	142.7	124.7	12.1
		October	27.5	18.9	32.2	13.3	64	184.9	116.8	8.2
		November	26.3	17.2	31.1	10.6	59	54.3	114.5	8.5
		December	25.7	15.3	31.1	8.9	51	16.2	67.3	9.6
		ANNUAL	28.8	18.4	38.9	7.8	50	923.7	162.1	11.5

Table 3.7: Summary statistics of climatic variables for Bangalore

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Karnataka	Honavar	January	31.9	20.1	36.1	15.6	57	1.4	20.3	5.1
		February	31.3	20.5	37.2	14.2	64	0.1	36.3	5.2
		March	31.9	22.7	37.8	17.8	67	1.1	29.2	5.1
		April	32.4	25.2	35.1	20.6	70	24.1	107.9	5.4
		May	32.3	25.8	35.1	20.6	72	137.5	238.5	6.3
		June	29.3	24.1	33.9	21.1	86	1038.6	378.5	6.8
		July	28.2	23.5	32.2	21.1	90	1176.2	330.2	7.2
		August	28.3	23.5	31.8	19.4	88	638.5	282.5	6.1
		September	28.8	23.2	32.2	20.6	84	349.3	181.1	4.4
		October	30.6	23.2	35.6	18.3	79	174.7	209.1	4.2
		November	32.5	21.9	36.7	15.6	66	47.4	118.4	4.4
		December	32.7	20.9	37.2	16.1	59	7.4	102.6	5.2
		ANNUAL	30.9	22.9	37.8	15.6	74	3596.3	378.5	5.4

Table 3.8: Summary statistics of climatic variables for Honavar

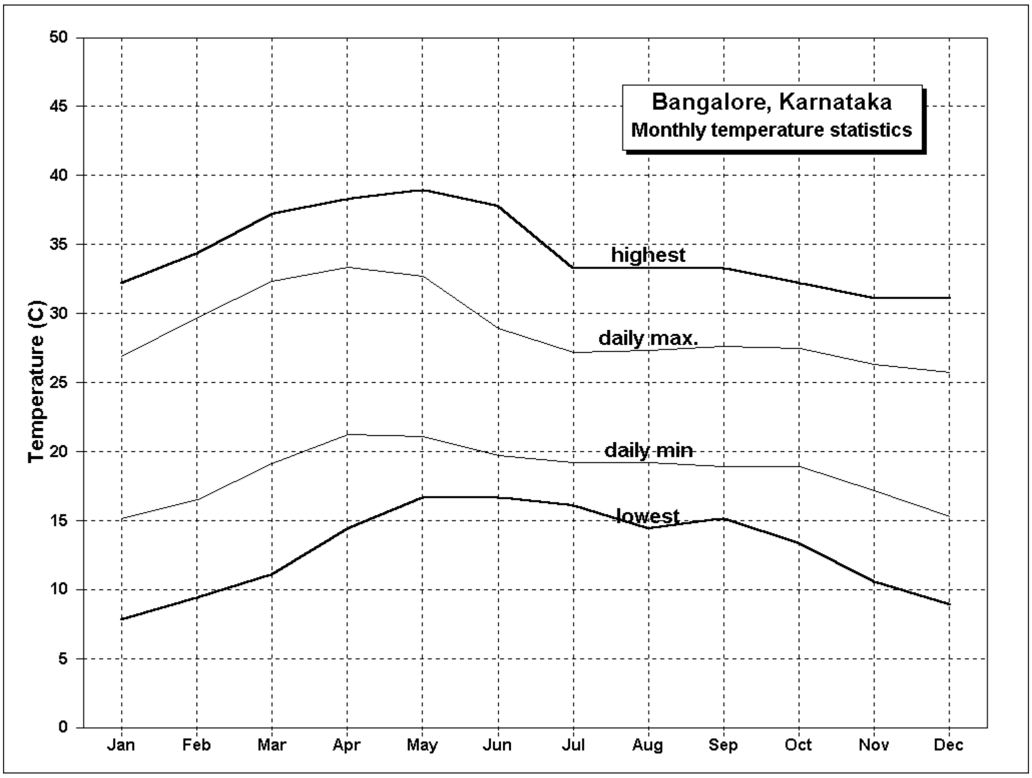

Figure 3.14: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Bangalore

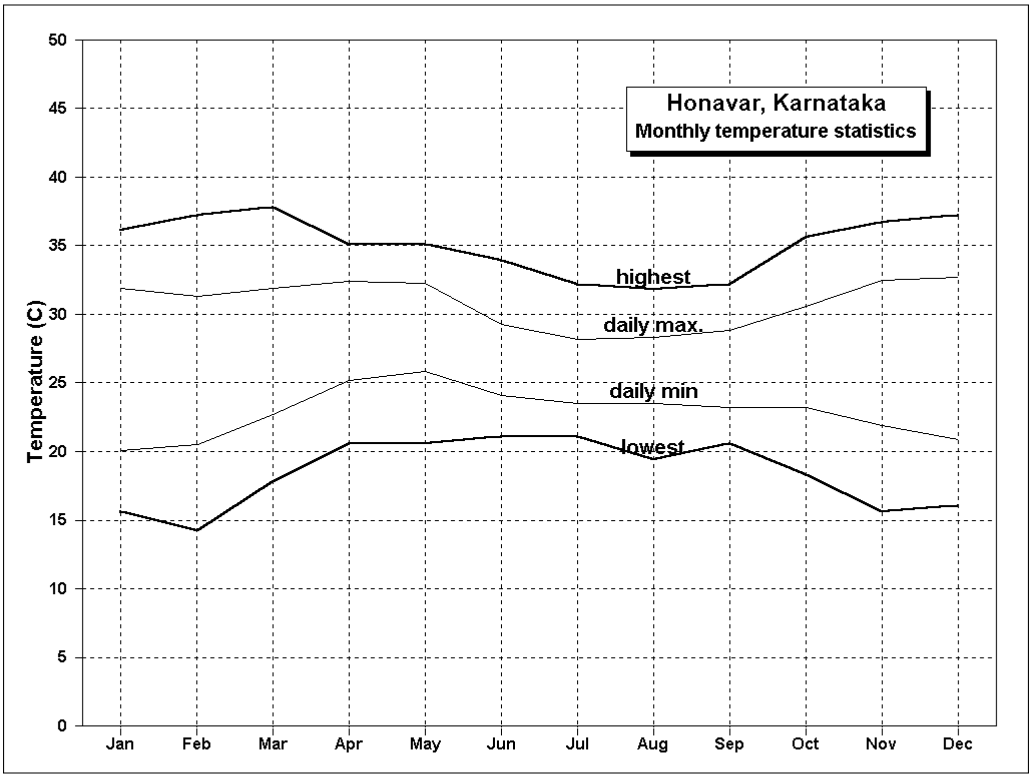

Figure 3.15: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Honavar

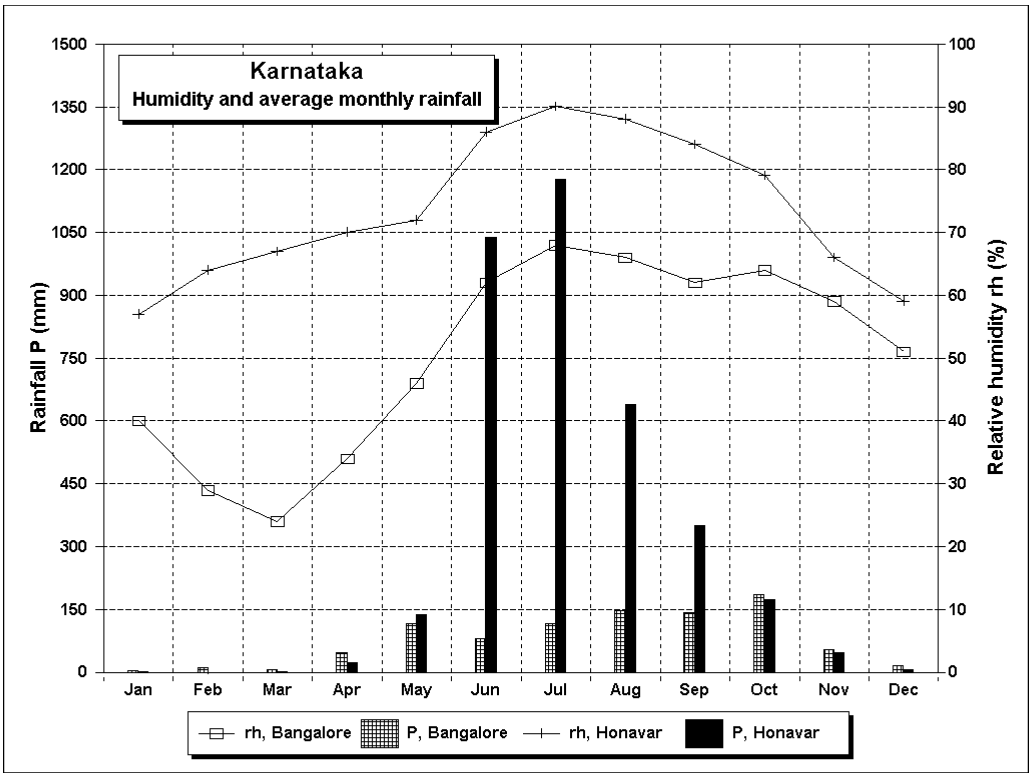

Figure 3.16: Monthly rainfall totals and humidity for Bangalore and Honavar

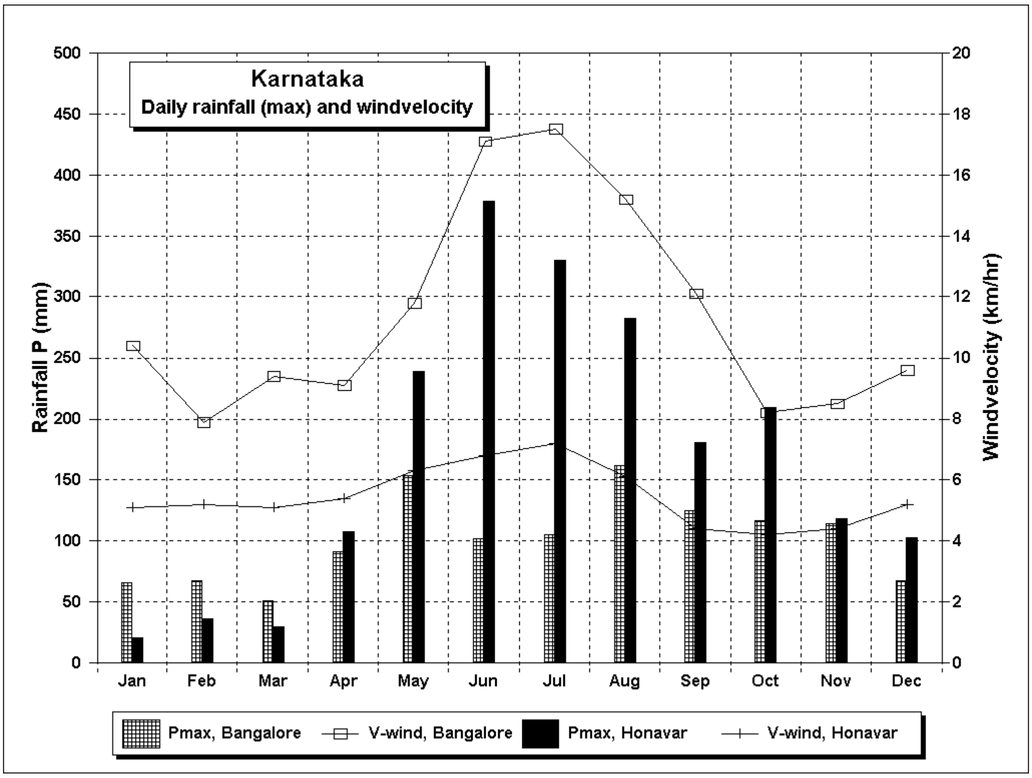

Figure 3.17: Monthly highest 24 hour rainfall and average windspeed for Bangalore and Honavar

3.6 KERALA

The monthly and annual statistics of selected climatic variables for Trivandrum and Calicut are presented in the Tables 3.9 and 3.10 and Figures 3.18 to 3.21.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Kerala	Trivandrum	January	31.3	22.3	35.5	18.9	63	20.1	52.1	5.1
		February	31.7	22.9	35.1	18.9	63	20.3	88.1	5.9
		March	32.5	24.2	36.2	20.6	66	43.5	80.1	6.6
		April	32.4	25.1	35.3	21.7	73	122.1	129.8	7.8
		May	31.6	25.1	35.2	21.2	77	248.6	277.9	9.2
		June	29.4	23.6	34.4	20.1	82	331.2	154.7	9.6
		July	29.1	23.2	31.7	21.1	81	215.4	151.6	10.9
		August	29.4	23.3	32.8	20.6	78	164.1	102.4	11.2
		September	29.9	23.3	33.3	21.1	77	122.9	125.5	10.4
		October	29.9	23.4	32.8	21.1	80	271.2	215.9	7.3
		November	30.1	23.1	33.9	18.9	78	206.9	162.8	5.5
		December	30.9	22.5	34.4	18.9	69	73.1	148.8	4.8
		ANNUAL	30.7	23.5	36.2	18.9	74	1839.3	277.9	7.9

Table 3.9: Summary statistics of climatic variables for Trivandrum

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Kerala	Calicut	January	31.7	22.1	35.6	17.2	64	5.9	104.4	9.4
		February	31.9	23.1	35.6	16.1	66	11.1	150.1	11.4
		March	32.6	24.7	35.1	19.4	69	21.1	83.3	12.3
		April	32.9	25.8	35.6	21.1	71	111.1	143.3	12.6
		May	32.5	25.6	37.2	20.1	76	322.5	268.5	12.5
		June	29.5	23.8	33.9	20.6	85	870.9	250.2	9.8
		July	28.2	23.3	32.2	21.1	89	860.1	264.2	9.2
		August	28.7	23.6	32.2	20.6	86	404.9	204.5	8.9
		September	29.5	23.7	33.9	21.1	82	215.1	179.1	8.7
		October	30.4	23.8	34.4	20.1	78	290.4	189.2	8.8
		November	31.1	23.4	34.4	16.1	72	140.1	192.3	8.1
		December	31.6	22.2	34.8	16.1	64	29.9	115.1	8.3
		ANNUAL	30.9	23.7	37.2	16.1	75	3282.7	268.5	10.1

Table 3.10: Summary statistics of climatic variables for Calicut

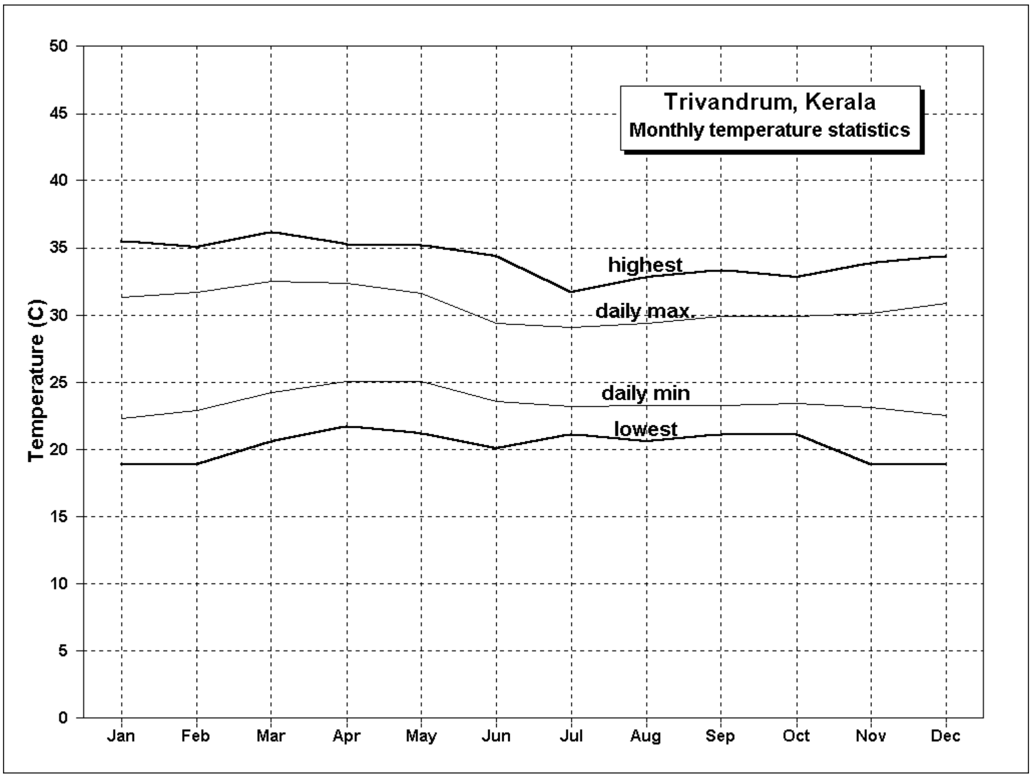

Figure 3.18: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Trivandrum

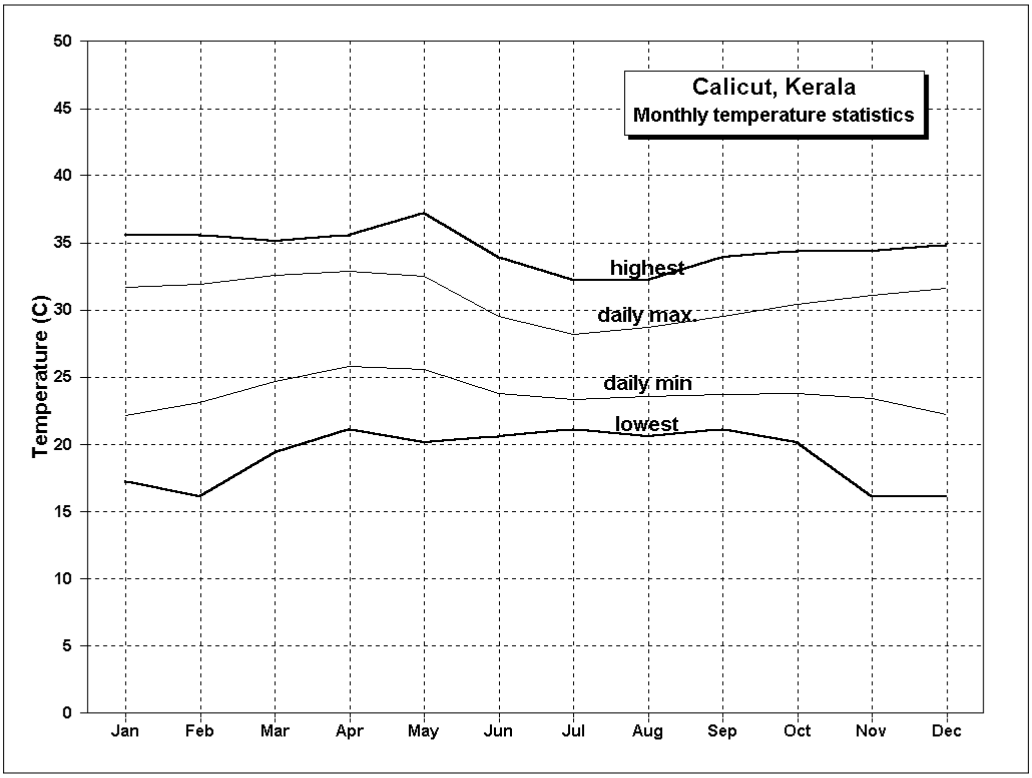

Figure 3.19: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Calicut

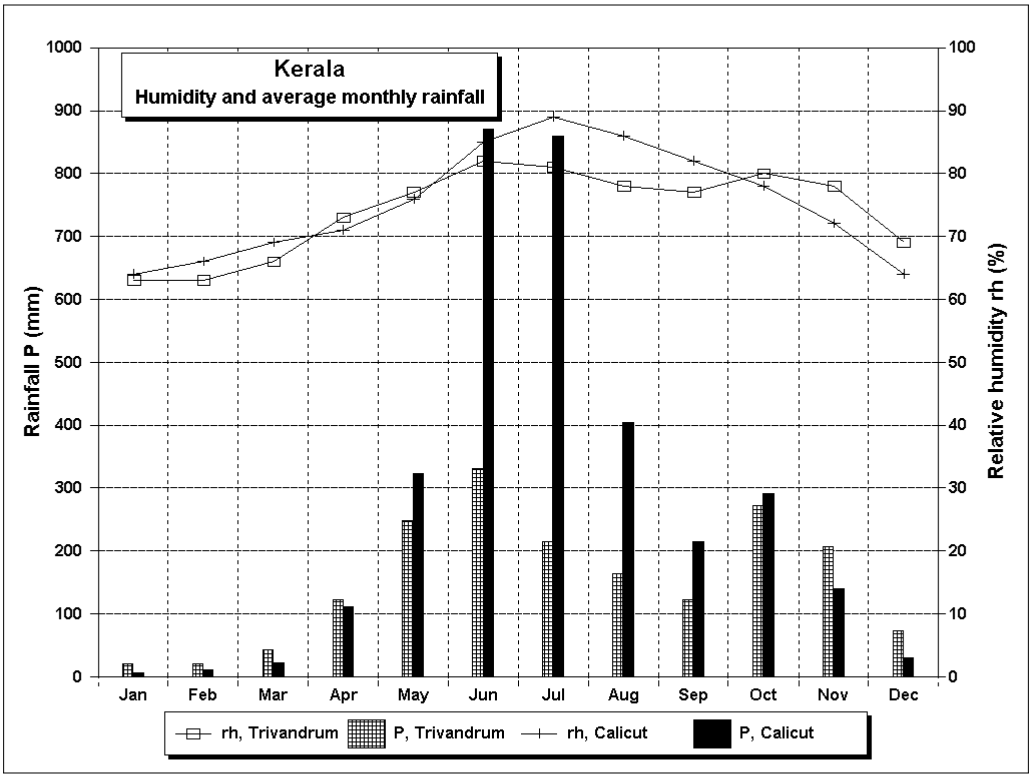

Figure 3.20: Monthly rainfall totals and humidity for Trivandrum and Calicut

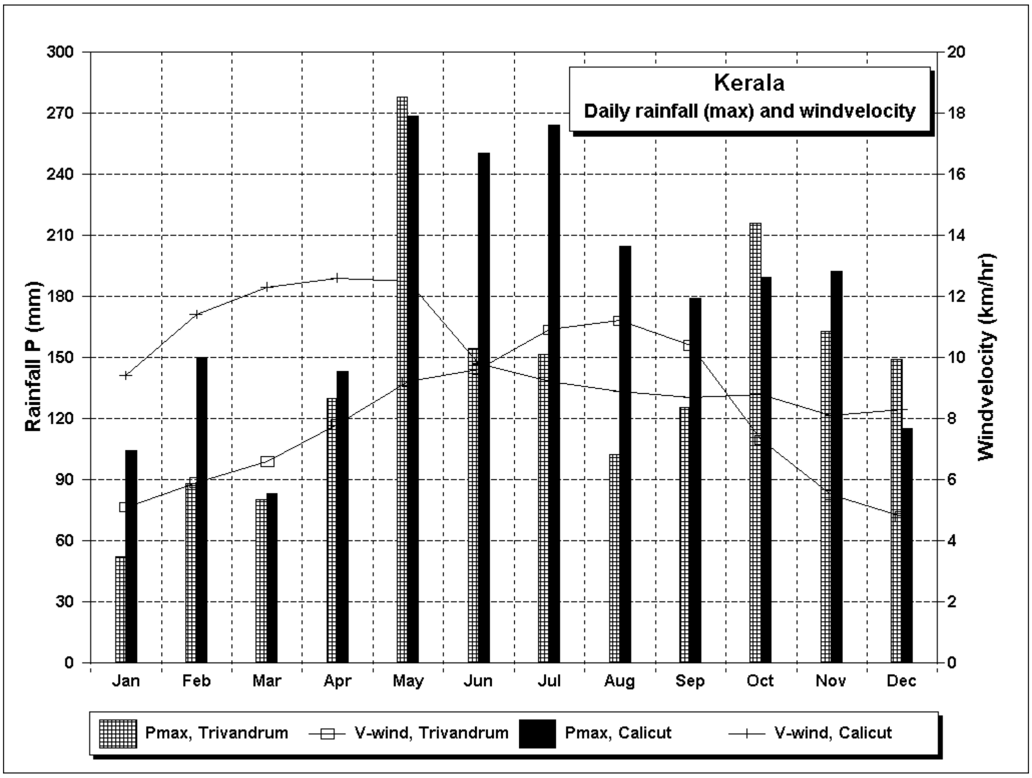

Figure 3.21: Monthly highest 24 hour rainfall and average windspeed for Trivandrum and Calicut

3.7 MADHYA PRADESH

The monthly and annual statistics of selected climatic variables for Bhopal and Pachmarhi are presented in the Tables 3.11 and 3.12 and Figures 3.22 to 3.25.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Madhya Pradesh	Bhopal	January	25.7	10.4	32.2	0.6	35	16.8	34.3	5.8
		February	28.5	12.5	36.1	1.7	23	4.5	15.5	6.4
		March	33.6	17.1	40.1	7.8	17	9.8	35.1	7.2
		April	37.8	21.2	44.2	12.2	14	3.3	13.5	8.6
		May	40.7	26.4	45.6	19.4	16	11.1	72.6	11.9
		June	36.9	25.4	43.9	19.5	41	136.6	120.9	13.1
		July	29.9	23.2	40.6	19.1	72	428.5	218.2	13.2
		August	28.6	22.5	35.1	19.4	76	307.7	188.5	11.3
		September	30.1	21.9	36.1	17.2	66	232.1	233.2	9.1
		October	31.3	18.1	37.8	11.7	41	36.9	123.7	5.1
		November	28.5	13.3	33.3	6.1	33	14.7	68.3	4.3
		December	26.1	10.6	32.8	3.3	39	7.1	31.7	4.4
		ANNUAL	31.5	18.5	45.6	0.6	39	1208.9	233.2	8.3

Table 3.11: Summary statistics of climatic variables for Bhopal

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Madhya Pradesh	Pachmarhi	January	22.4	8.7	27.8	-1.1	49	27.9	94.2	3.3
		February	24.7	10.4	31.7	-0.6	37	25.3	52.1	4.2
		March	28.9	14.8	36.1	3.3	25	13.3	55.1	4.5
		April	33.4	20.1	40.1	8.9	22	10.4	38.6	5.1
		May	36.1	24.3	40.6	15.1	23	15.8	35.3	6.8
		June	31.4	22.5	40.6	15.6	55	201.9	201.9	7.2
		July	24.3	19.9	37.4	16.1	87	753.4	338.3	9.1
		August	23.8	19.6	30.1	15.1	88	646.7	458.7	8.3
		September	25.2	19.1	35.6	12.8	82	435.7	350.3	6.2
		October	26.2	14.8	31.7	6.7	56	84.1	164.1	3.6
		November	24.1	9.6	28.3	2.2	50	26.1	99.1	2.8
		December	22.6	7.5	27.8	-1.1	47	4.2	63.1	2.7
		ANNUAL	26.9	15.9	40.6	-1.1	52	2244.6	458.7	5.3

Table 3.12: Summary statistics of climatic variables for Pachmarhi

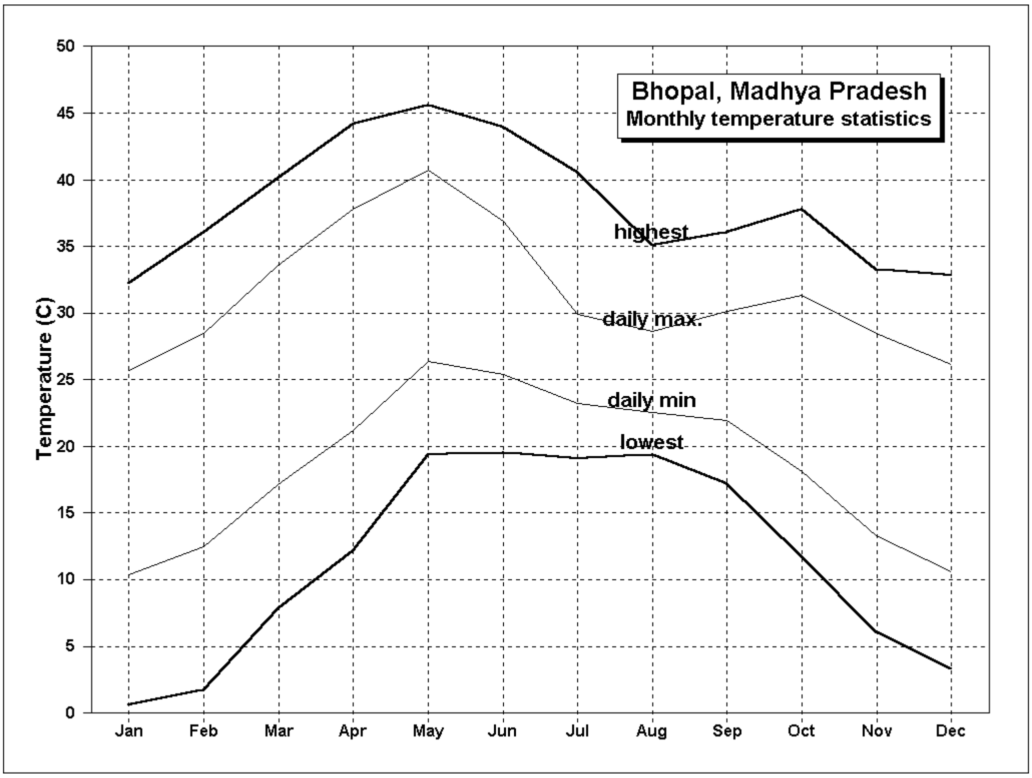

Figure 3.22: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Bhopal

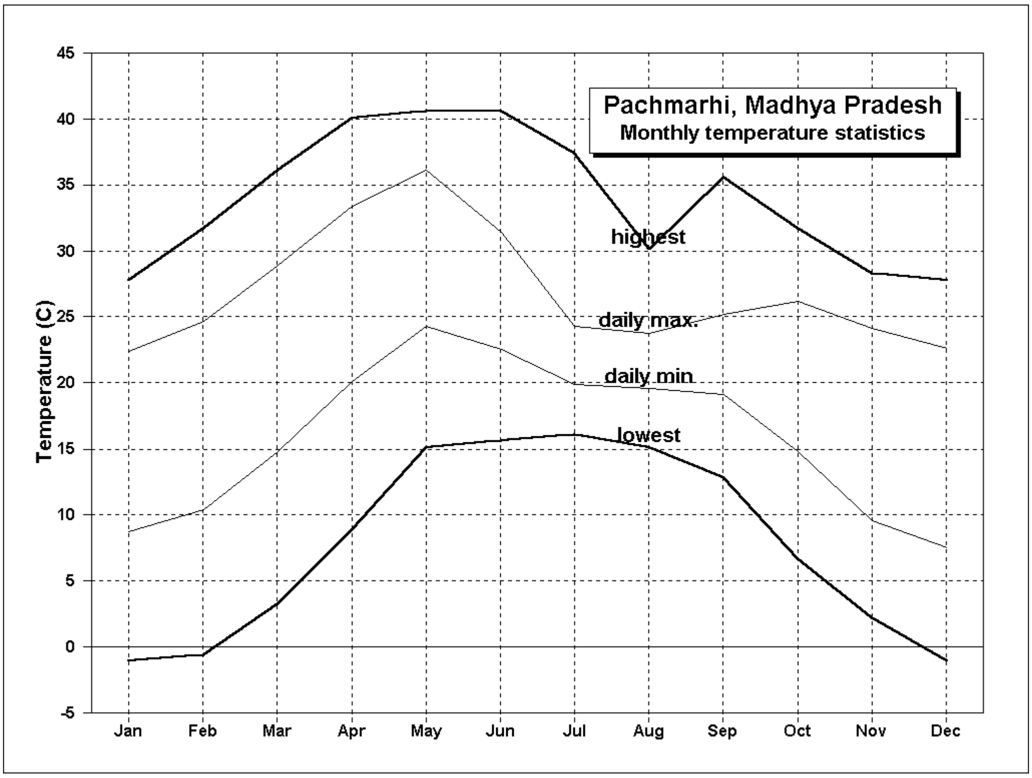

Figure 3.23: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Pachmarhi

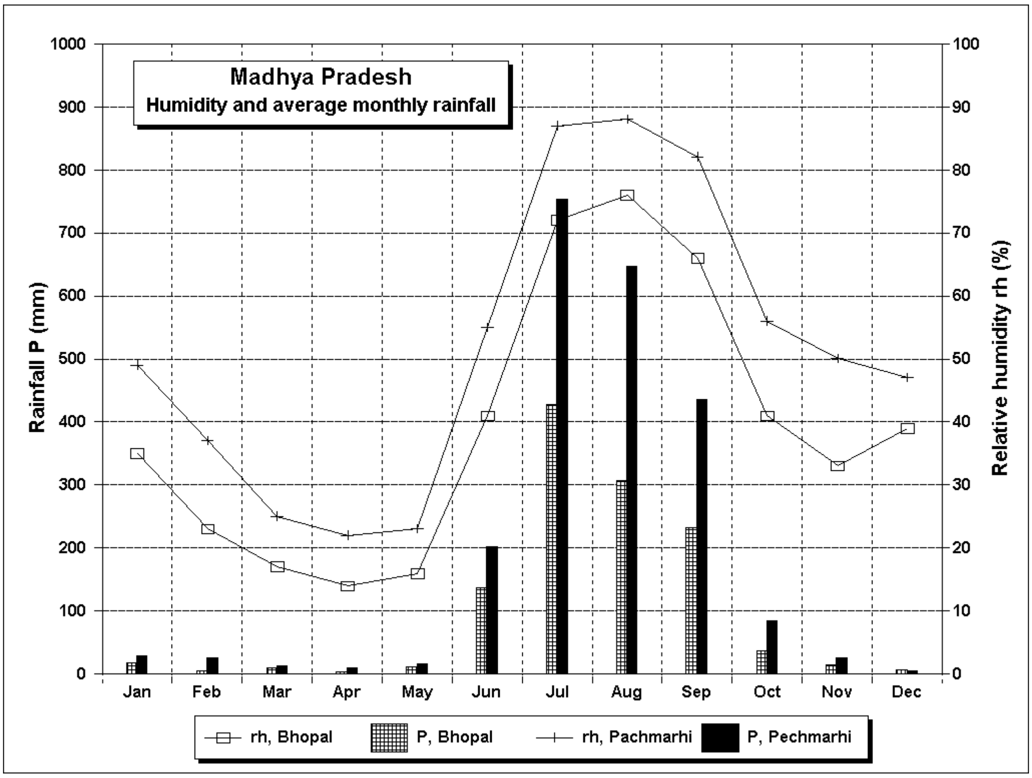

Figure 3.24: Monthly rainfall totals and humidity for Bhopal and Pachmarhi

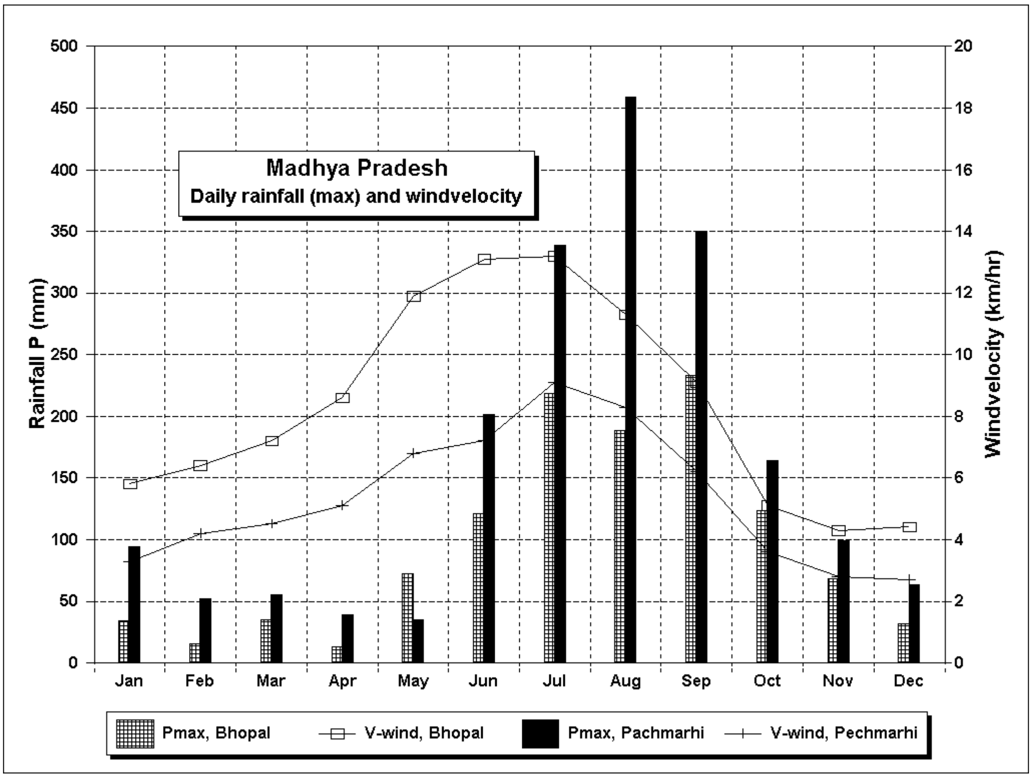

Figure 3.25: Monthly highest 24 hour rainfall and average windspeed for Bhopal and Pachmarhi

3.8 MAHARASHTRA

The monthly and annual statistics of selected climatic variables for Mumbai and Mahabaleshwar are presented in the Tables 3.13 and 3.14 and Figures 3.26 to 3.29.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Maharashtra	Mumbai	January	29.1	19.4	35.1	11.7	63	2.1	49.3	9.1
		February	29.5	20.3	38.3	11.7	62	1.1	41.7	9.3
		March	31.1	22.7	39.7	16.7	63	0.4	34.3	10.4
		April	32.3	25.1	40.6	20.1	66	2.8	37.3	10.5
		May	33.3	26.9	36.2	22.8	68	16.1	126.2	10.1
		June	31.9	26.3	37.2	21.1	78	520.3	408.9	12.8
		July	29.8	25.1	35.6	21.7	85	709.5	304.8	14.8
		August	29.5	24.8	32.2	21.7	84	439.3	287.1	13.4
		September	30.1	24.7	35.1	20.1	80	297.1	548.1	10.1
		October	31.9	24.6	36.6	20.6	74	88.1	148.6	8.5
		November	32.3	22.8	36.2	17.8	67	20.6	122.7	8.2
		December	30.9	20.8	35.1	12.8	64	2.2	24.4	8.5
		ANNUAL	31.1	23.6	40.6	11.7	71	2099.2	548.1	10.5

Table 3.13: Summary statistics of climatic variables for Mumbai

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Maharashtra	Mahabaleshwar	January	24.1	13.8	28.9	6.1	49	3.1	22.1	7.7
		February	26.1	14.9	31.1	3.9	40	1.8	29.1	8.1
		March	28.8	17.4	33.9	9.4	43	6.8	33.1	9.7
		April	29.3	18.8	36.1	11.1	55	29.6	95.1	10.7
		May	28.8	18.2	34.4	13.9	67	55.4	62.2	11.6
		June	21.9	16.9	32.2	12.8	94	898.3	310.4	14.8
		July	19.1	16.7	25.9	13.9	100	2521.3	381.2	20.1
		August	18.9	16.3	26.7	13.9	100	1714.7	339.9	17.3
		September	20.3	15.7	27.8	12.2	98	709.2	327.1	11.8
		October	24.1	16.1	30.6	11.1	78	179.3	191.5	10.3
		November	24.1	14.9	28.9	10.1	62	56.7	148.6	10.3
		December	23.5	13.9	28.2	8.3	52	6.1	39.6	9.7
		ANNUAL	24.1	16.1	36.1	3.9	70	6182.3	381.2	11.8

Table 3.14: Summary statistics of climatic variables for Mahabaleshwar

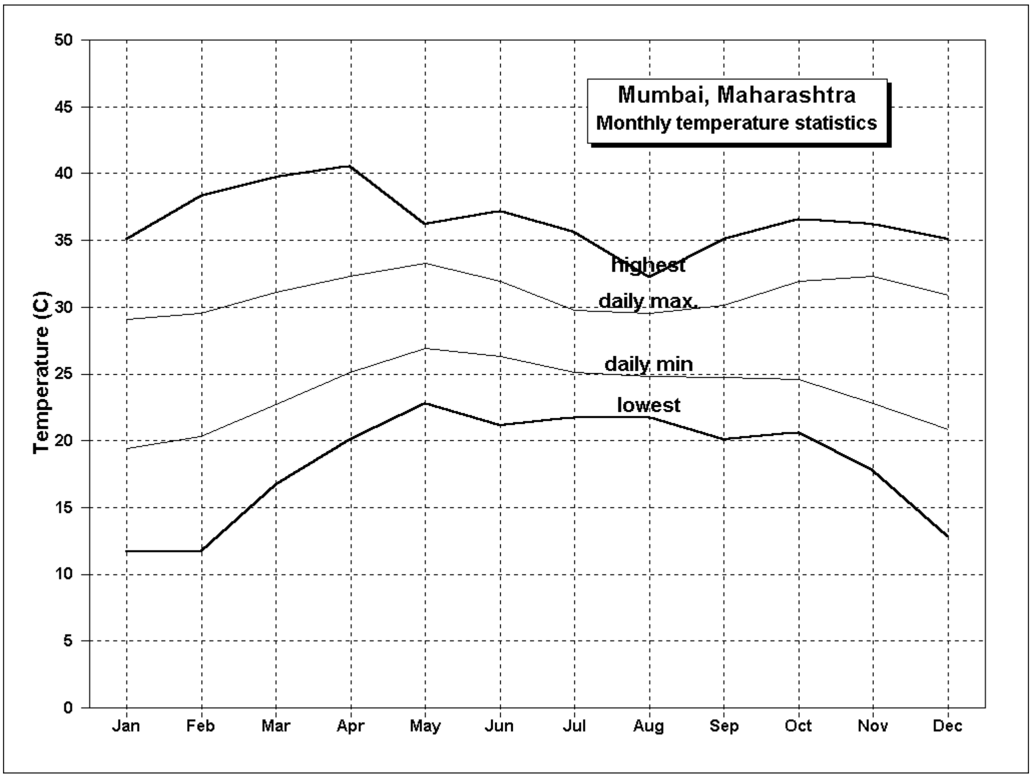

Figure 3.26: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Mumbai

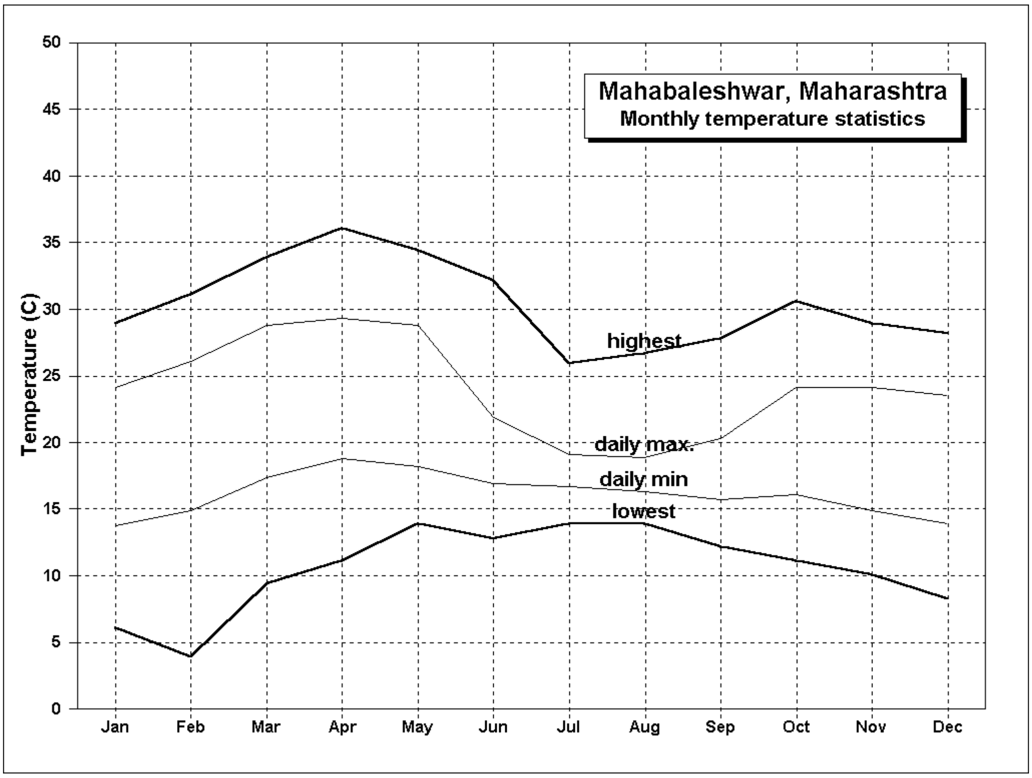

Figure 3.27: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Mahabaleshwar

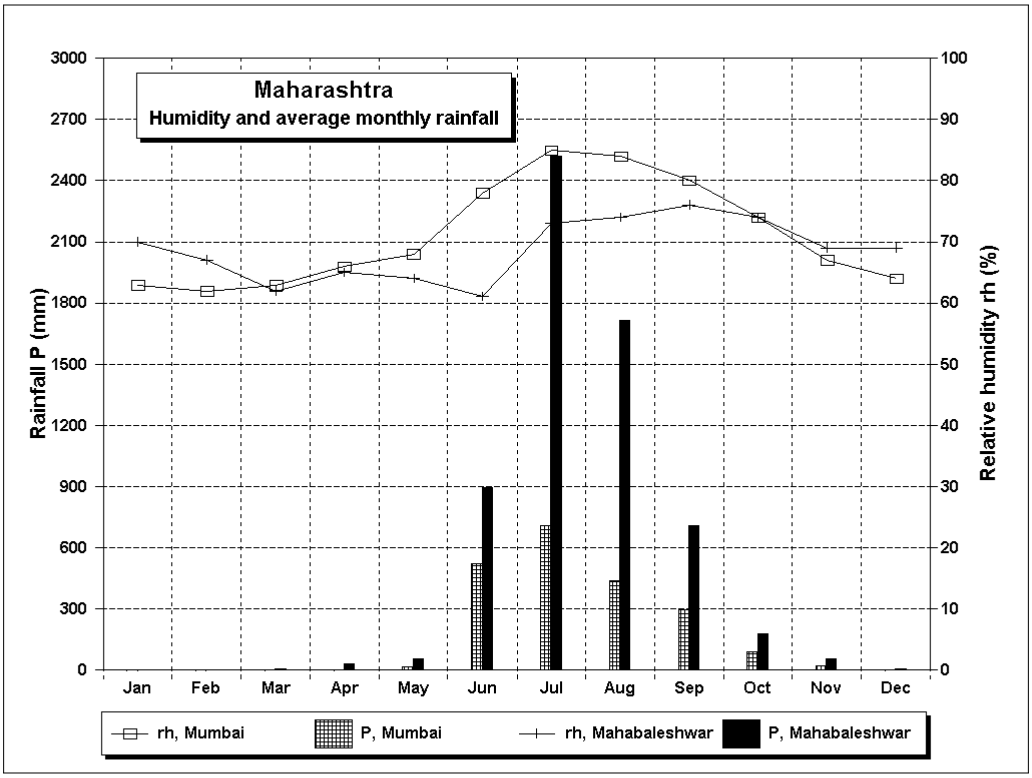

Figure 3.28 Monthly rainfall totals and humidity for Mumbai and Mahabaleshwar

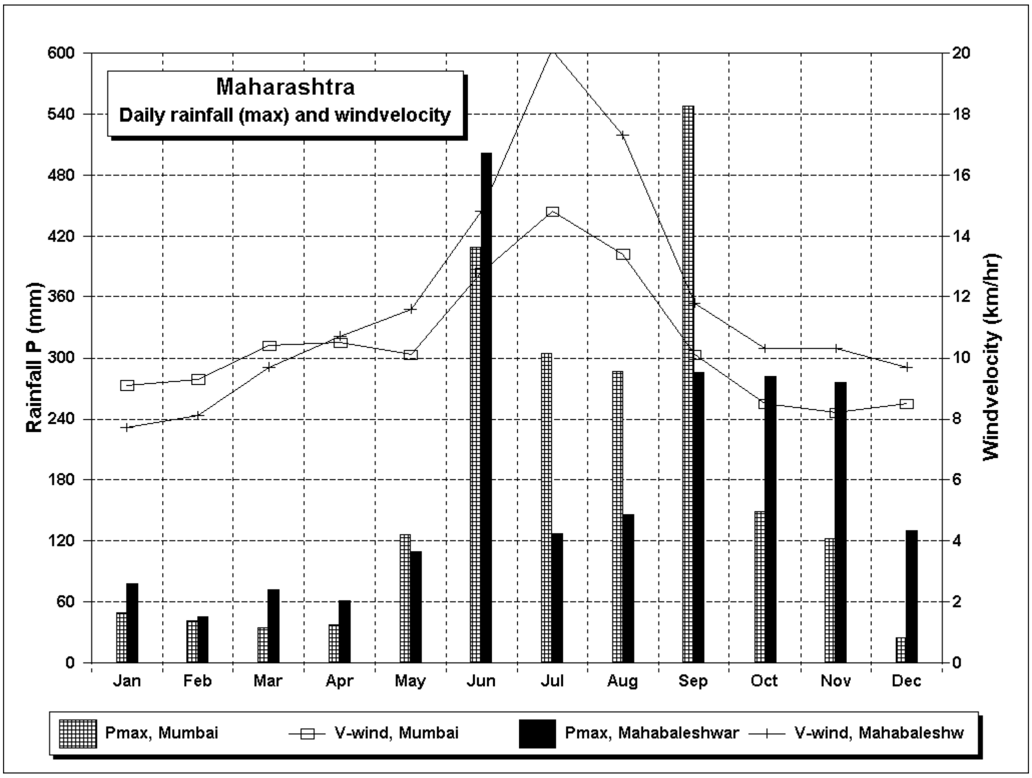

Figure 3.29: Monthly highest 24 hour rainfall and average windspeed for Mumbai and Mahabaleshwar

3.9 ORISSA

The monthly and annual statistics of selected climatic variables for Cuttack and Sambalpur are presented in the Tables 3.15 and 3.16 and Figures 3.30 to 3.33.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Orissa	Cuttack	January	28.9	15.7	35.6	7.8	48	10.4	61.1	2.9
		February	31.5	18.2	38.9	10.6	43	28.5	98.1	3.8
		March	35.9	22.1	42.8	14.4	41	19.5	99.1	5.6
		April	38.3	25.3	45.1	17.2	50	27.1	94.5	7.7
		May	38.8	26.9	47.7	20.6	58	71.8	142.7	9.1
		June	35.8	26.5	47.2	21.7	69	214.6	205.7	7.2
		July	31.6	25.6	40.1	21.1	81	355.1	210.8	6.7
		August	31.6	25.6	37.2	21.7	81	364.5	320.8	6.1
		September	32.2	25.5	36.7	21.7	80	252.1	249.2	4.8
		October	32.1	23.7	38.9	16.7	72	167.6	292.6	4.3
		November	30.1	18.8	35.1	10.6	59	41.4	195.6	3.3
		December	28.4	15.5	33.3	8.9	52	4.7	54.9	2.6
		ANNUAL	32.9	22.5	47.7	7.8	61	1557.2	320.8	5.3

Table 3.15: Summary statistics of climatic variables for Cuttack

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Orissa	Sambalpur	January	28.2	12.6	33.9	4.4	45	18.8	90.7	3.1
		February	30.5	14.9	37.8	5.6	38	24.7	55.1	3.7
		March	35.4	18.7	43.3	11.1	29	23.1	46.2	4.3
		April	39.6	23.8	45.6	14.4	27	11.7	45.2	5.3
		May	42.1	27.6	47.2	20.6	29	24.5	107.9	6.7
		June	37.2	26.9	46.7	19.4	57	237.6	254.5	8.1
		July	30.7	24.9	40.6	18.3	82	503.1	401.3	8.3
		August	30.7	24.9	35.1	21.1	83	476.5	290.7	7.4
		September	31.5	24.8	36.1	20.6	79	262.4	200.9	5.5
		October	31.5	22.1	36.1	12.8	67	67.7	173.7	3.8
		November	29.3	15.8	33.9	7.8	55	9.5	106.2	3.1
		December	27.7	12.2	32.2	4.4	49	2.1	39.1	2.6
		ANNUAL	32.9	20.8	47.2	4.4	53	1661.5	401.3	5.1

Table 3.16: Summary statistics of climatic variables for Sambalpur

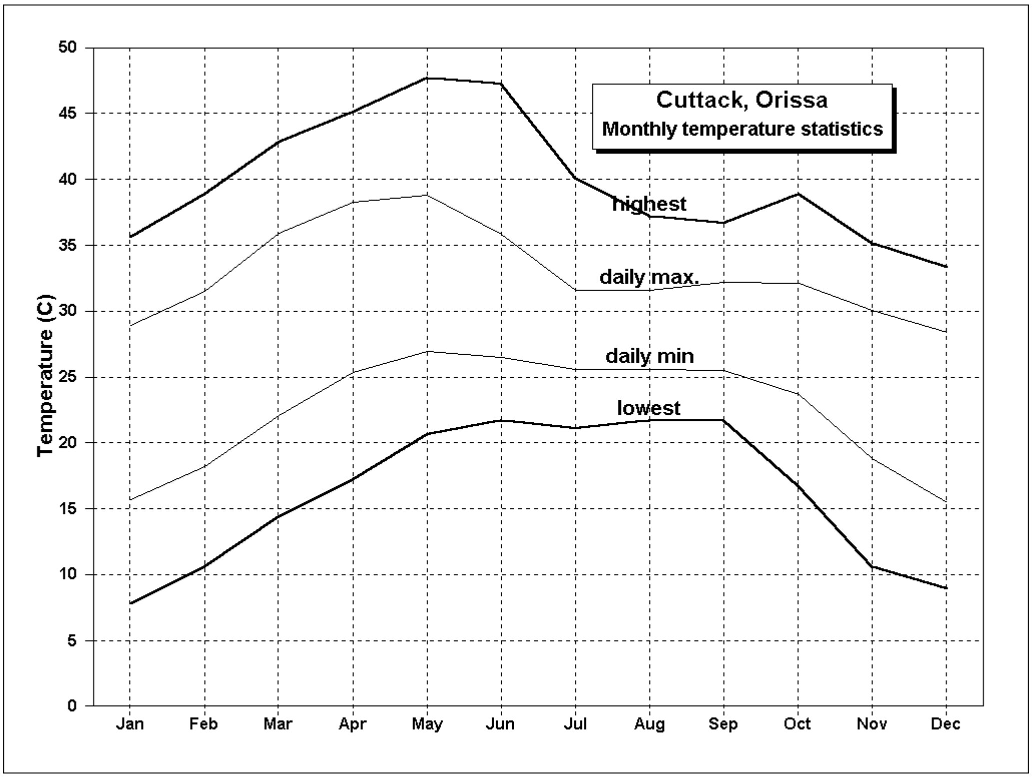

Figure 3.30: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Cuttack

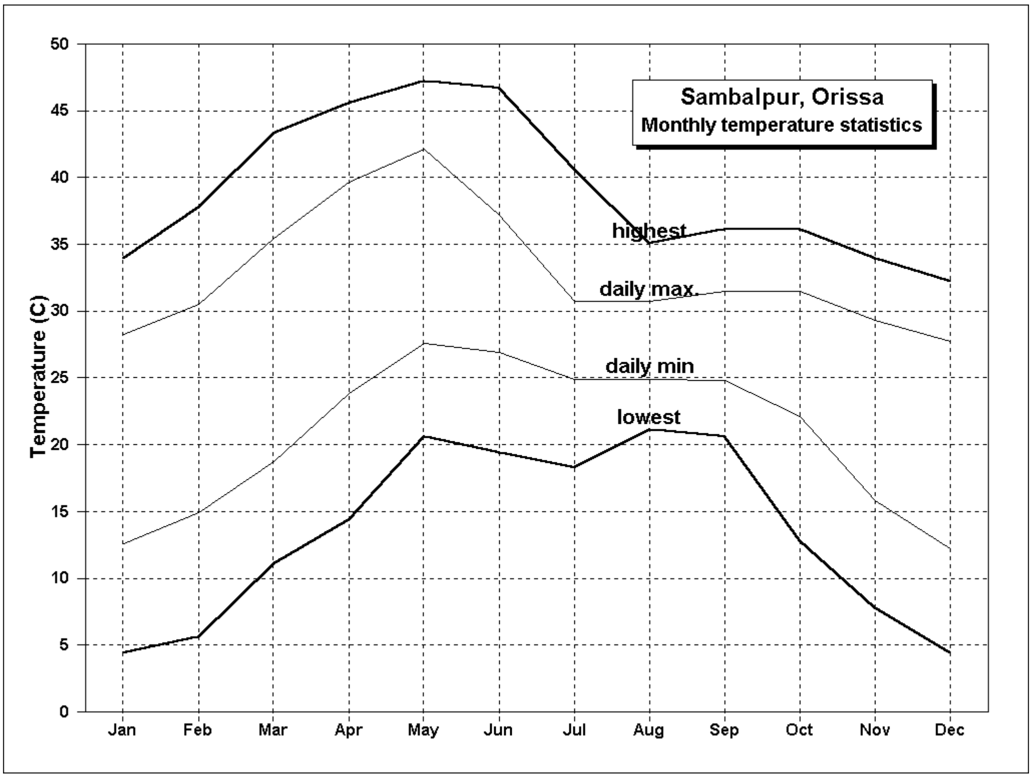

Figure 3.31: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Sambalpur

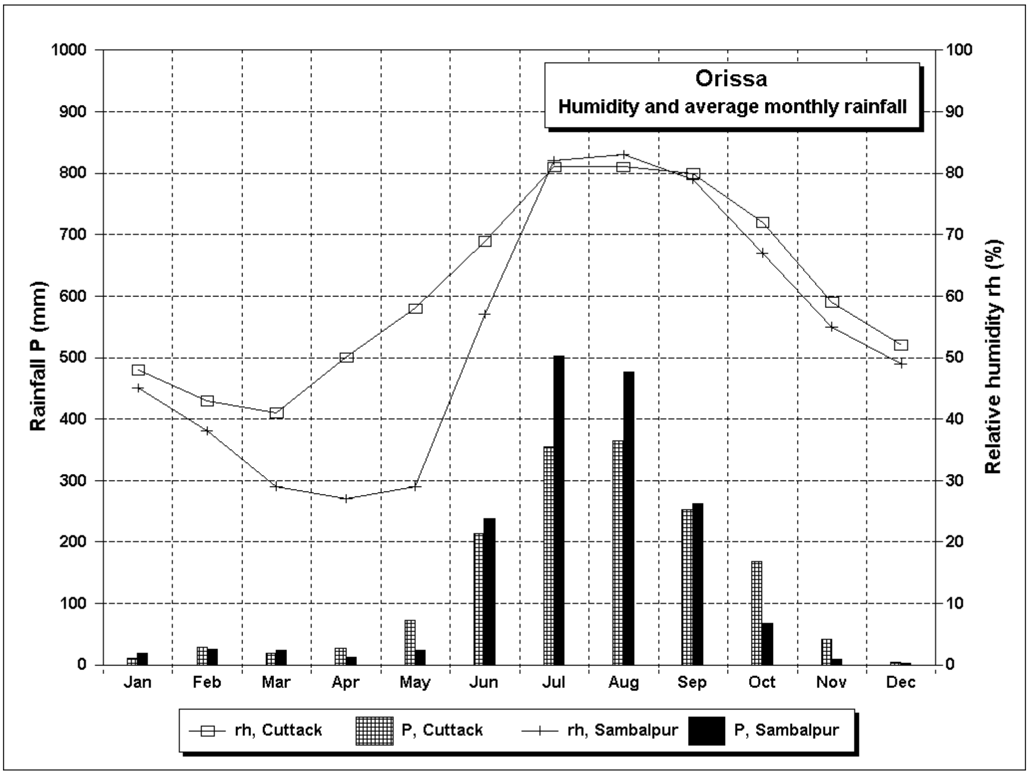

Figure 3.32: Monthly rainfall totals and humidity for Cuttack and Sambalpur

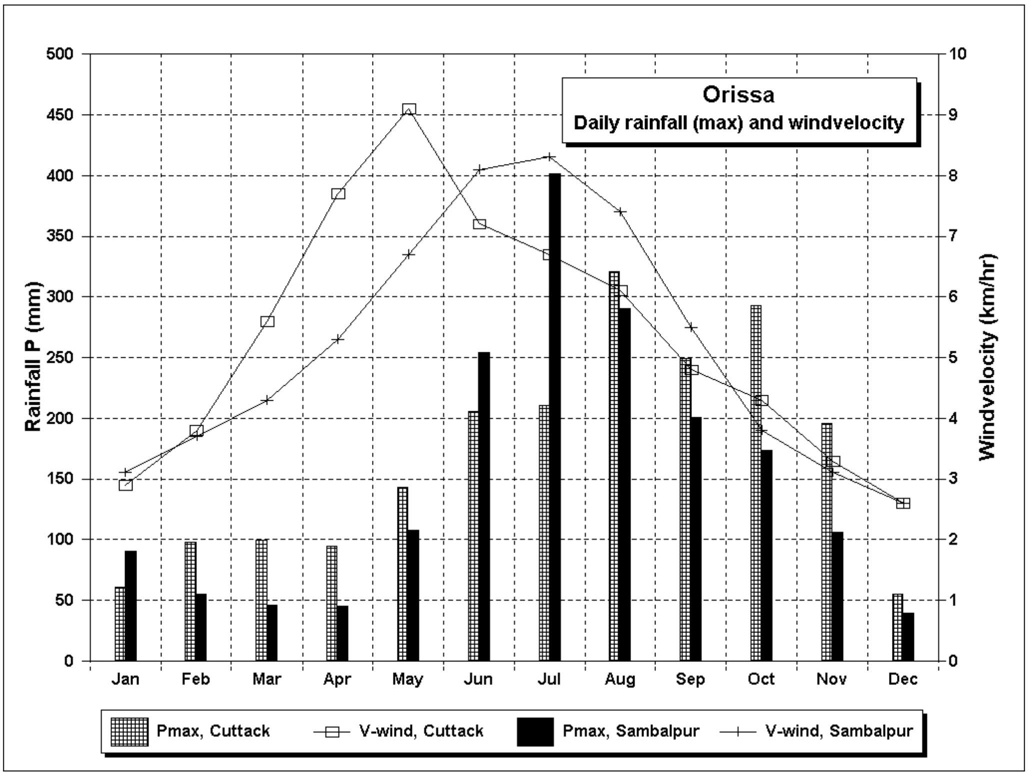

Figure 3.33: Monthly highest 24 hour rainfall and average windspeed for Cuttack and Sambalpur

3.10 TAMIL NADU

The monthly and annual statistics of selected climatic variables for Chennai and Madurai are presented in the Tables 3.17 and 3.18 and Figures 3.34 to 3.37.

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Tamil Nadu	Chennai	January	28.8	20.3	32.8	13.9	67	23.8	212.9	9.1
		February	30.6	21.1	36.7	15.1	63	6.8	123.2	9.2
		March	32.7	23.1	40.6	16.7	64	15.1	88.1	10.2
		April	34.9	26.1	42.8	20.1	68	24.7	96.3	10.5
		May	37.6	27.8	45.1	21.1	66	51.7	214.9	13.1
		June	37.3	27.6	43.3	20.6	59	52.6	59.2	16.4
		July	35.2	26.3	41.1	21.7	61	83.5	116.3	14.6
		August	34.5	25.8	40.1	20.6	64	124.3	91.7	13.6
		September	33.9	25.4	38.9	20.6	69	118.1	100.3	11.1
		October	31.8	24.4	39.4	16.7	76	267.1	233.7	9.2
		November	29.2	22.5	34.4	13.1	76	308.7	236.2	11.7
		December	28.2	21.1	32.8	13.9	71	139.1	261.6	12.6
		ANNUAL	32.9	24.3	45.1	13.9	67	1215.3	261.6	11.8

Table 3.17: Summary statistics of climatic variables for Chennai

State	Station	Month	Temperature				Humidity	Rainfall		Wind speed
			Daily maximum °C	Daily minimum °C	Highest °C	Lowest °C	%	Total mm	Highest 24 hr mm	Km/ h
Tamil Nadu	Madurai	January	30.2	20.9	34.4	15.6	54	26.2	152.4	7.3
		February	32.4	21.6	38.3	16.1	44	16.1	188.1	6.6
		March	35.1	23.4	41.7	17.2	37	21.3	100.3	5.8
		April	36.3	25.4	41.7	19.4	46	80.8	166.4	5.1
		May	37.5	26.3	41.7	17.8	47	58.9	99.6	6.3
		June	36.7	26.3	42.2	17.8	45	30.9	105.4	9.6
		July	35.7	25.7	40.6	19.4	45	47.8	124.5	9.3
		August	35.3	25.2	40.1	20.6	50	117.1	112.3	7.1
		September	35.1	24.8	39.4	20.1	51	122.7	154.2	6.4
		October	33.1	24.1	38.3	18.9	63	179.2	128.8	4.5
		November	30.6	23.1	36.1	17.2	68	161.2	169.7	5.2
		December	29.7	21.6	35.1	16.7	62	42.8	165.6	6.9
		ANNUAL	33.9	24.1	42.2	15.6	51	904.9	188.1	6.7

Table 3.18: Summary statistics of climatic variables for Madurai

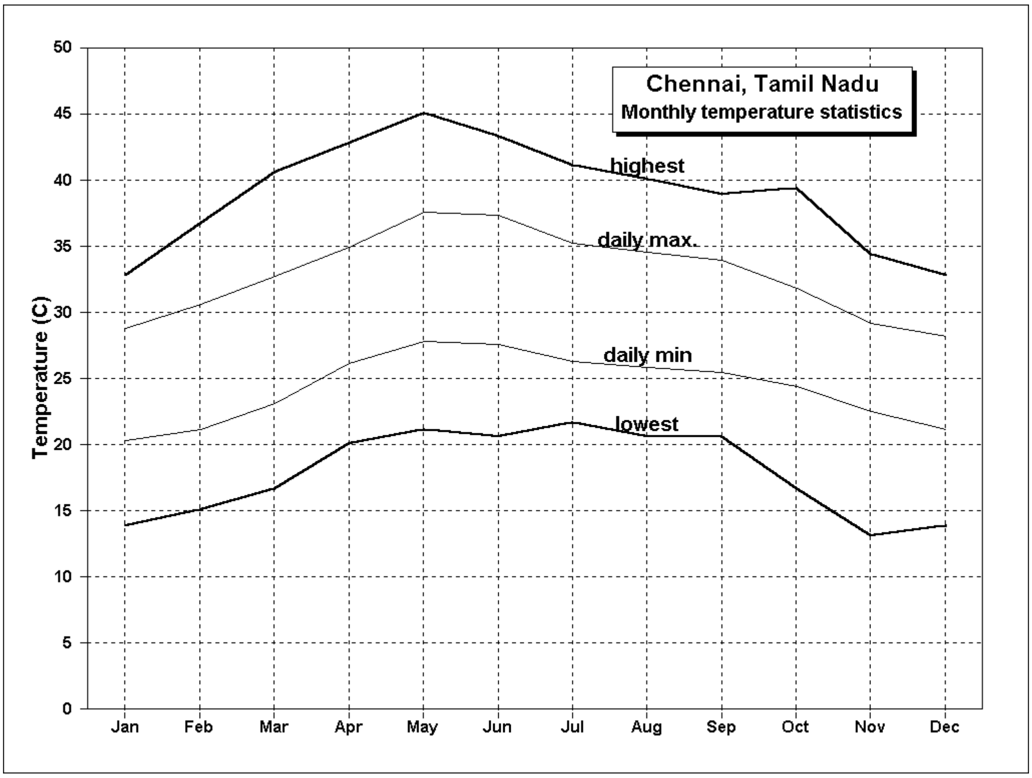

Figure 3.34: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Chennai

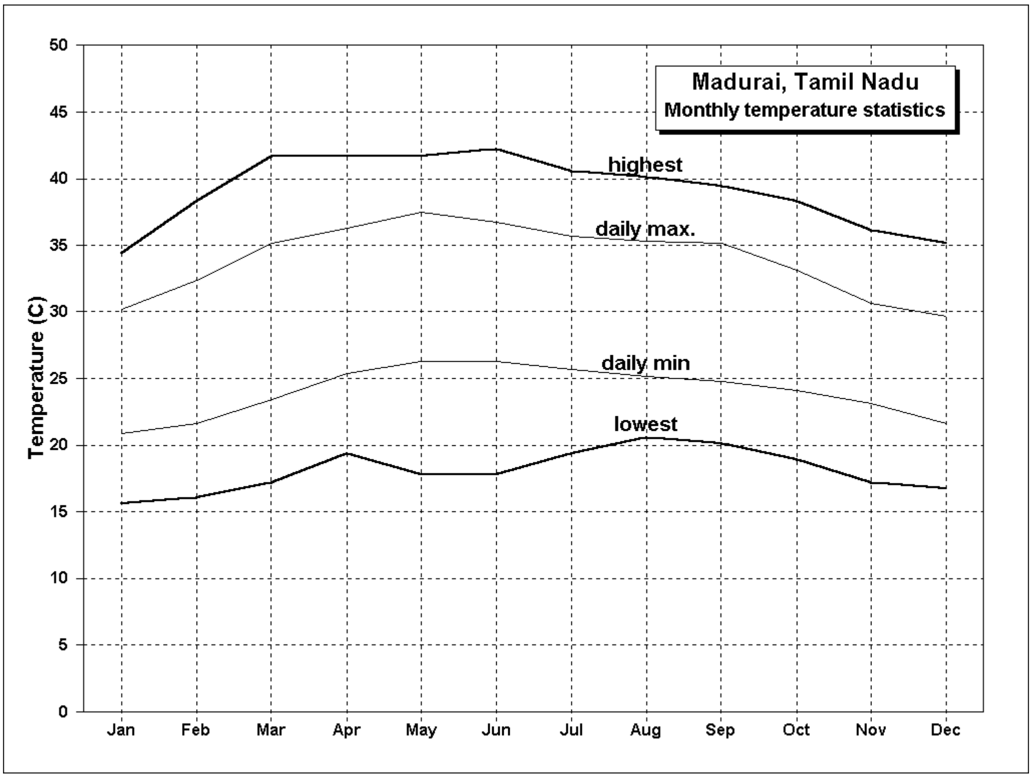

Figure 3.35: Monthly daily maximum and minimum temperatures and highest and lowest temperatures for Madurai

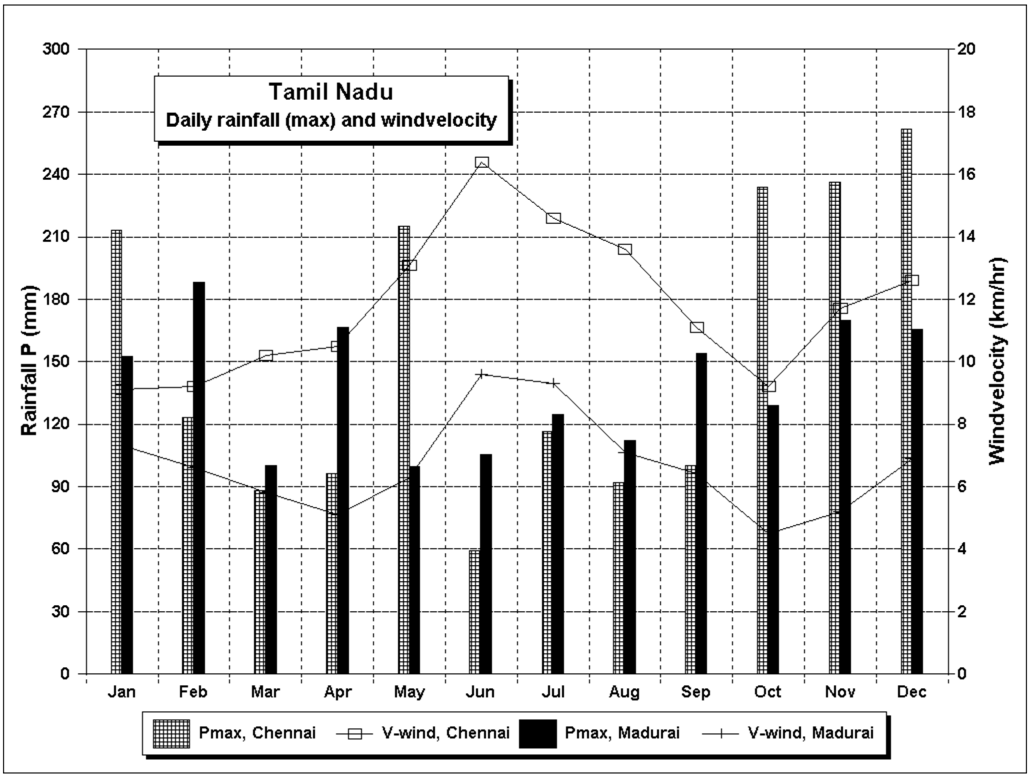

Figure 3.36: Monthly rainfall totals and humidity for Chennai and Madurai

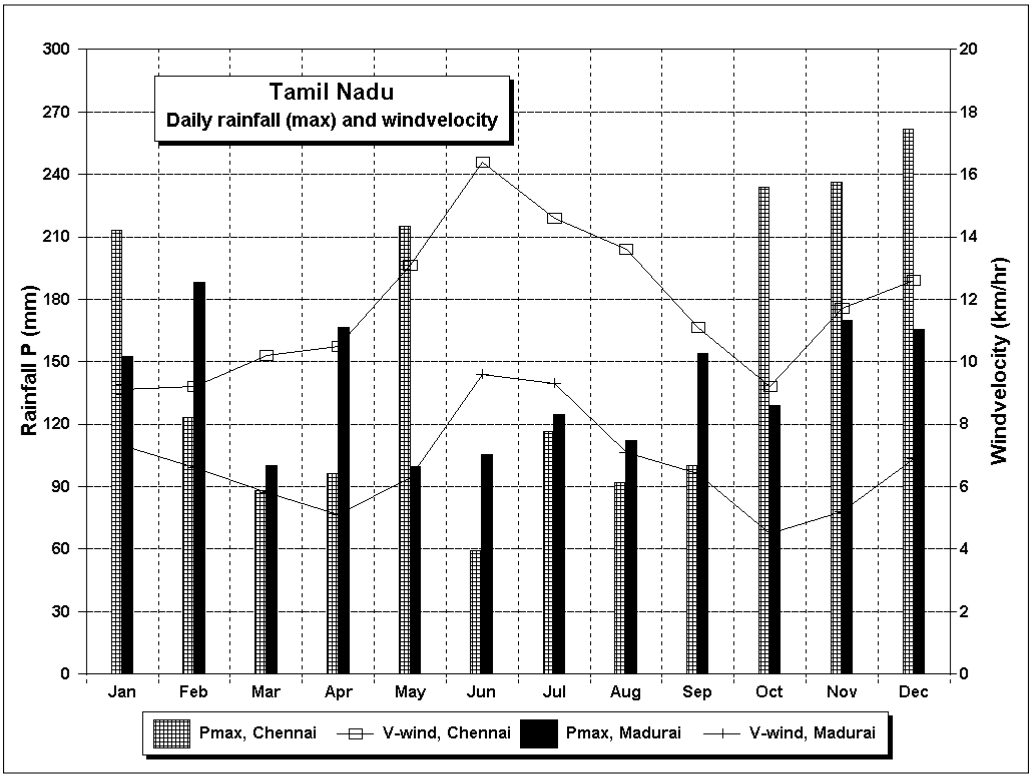

Figure 3.37: Monthly highest 24 hour rainfall and average windspeed for Chennai and Madurai

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