Interannual variability of summer monsoon rainfall over Orissa in relation to tropospheric circulation features

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The summer monsoon rainfall over Orissa shows large-scale interannual variability due to variation in the characteristics of meteorological parameters like temperature, pressure/geopotential height and wind at surface and in the troposphere. A study was therefore undertaken to find out the characteristic features of surface and upper air meteorological parameters in the troposphere and their relationship with summer monsoon rainfall over Orissa. For this purpose, rainfall data over 31 uniformly distributed stations in Orissa along with the surface meteorological parameters at seven stations and upper air parameters at different standard isobaric levels up to 200 hPa over four stations in Orissa and its neighbourhood during summer monsoon season over a period of 19 years (1980–98) have been considered. The principal objective of this study is to find out the contribution of different meteorological parameters in the spatio-temporal variability of summer monsoon rainfall over Orissa.

The interannual variability of rainfall mostly depends on the interannual variation of wind over Orissa and its neighbourhood. Strong northeasterlies over north coastal Orissa along with the southeasterly winds over Gangetic West Bengal and northwesterlies over northwest Orissa, south Orissa and north coastal Andhra Pradesh at the lower and mid-tropospheric levels are favourable for good rainfall over Orissa as a whole. They are also favourable for good rainfall over the western side of the Eastern Ghats and over the central zone, extending from the central part of coastal Orissa to western Orissa. This pattern of wind is also associated with the synoptic disturbances over northwest Bay of Bengal. Hence, the higher/lower number of days of synoptic disturbances over the NW Bay causes excess/deficient rainfall over Orissa. The stronger gradient of mean sea-level pressure and geopotential over the region to the south of the monsoon trough passing through north coastal Orissa at lower and mid-tropospheric level, is favourable for good rainfall over Orissa. Divergence at the upper troposphere (200 hPa) due to a trough in the upper tropospheric westerlies to the right of Visakhapatnam and an east-west ridge to the south of Visakhapatnam and over the NW Bay is favourable for rainfall over Orissa. There is no significant trend in both zonal and meridional winds at the upper troposphere (200 hPa) over the region, supporting insignificant trend in summer monsoon seasonal rainfall over Orissa during 1980–98.

Keywords: Meteorological parameters, monsoon, Orissa, rainfall variability, troposphere.

THE Indian summer monsoon rainfall (ISMR) shows large-scale spatial and temporal variability due to changes in surface and upper air meteorological fields like temperature, pressure, geopotential height, wind, etc. Hence, an understanding of the characteristics of surface and upper air meteorological fields is essential for a complete understanding of the Indian monsoon and its variability. Investigators[1–16] have tried to study the characteristics of surface and upper air meteorological fields over India and adjacent seas in relation to Indian monsoon activity. However, the studies are limited considering the spatio-temporal variability of rainfall over Orissa in relation to these field parameters.

Orissa, a meteorological sub-division of India, lies adjacent to the north Bay of Bengal. The eastern end of the monsoon trough passes through the northernmost parts of Orissa[17]. Hence, the basic monsoon flow over Orissa is westerly at lower levels. According to Pathan[17], maximum rainfall occurs to the south of the monsoon trough and the line of maximum rainfall passes through Orissa. The meteorological parameters over Orissa and its neighbourhood change significantly with respect to location and intensity of the monsoon trough and embedded synoptic disturbances. As most of the synoptic disturbances, including cyclonic circulations extending up to mid-tropospheric level, lows, depressions and cyclonic storms develop over the northwest (NW) Bay and move along the monsoon trough across the Gangetic West Bengal (GWB) or Orissa[18], meteorological parameters and hence rainfall are largely influenced by these disturbances. With a synoptic disturbance over NW Bay and the monsoon trough extending from the disturbance in a west-northwesterly

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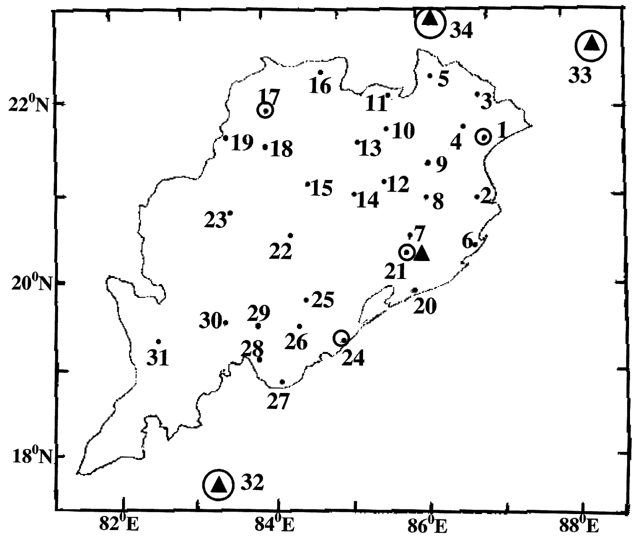
direction, the meteorological parameters are modified. There is maximum low-level convergence and vertical motion of moist air in the left front quadrant or southwest sector of disturbance. As Orissa lies in the left front quadrant or southwest sector of this disturbance, it gets heavy to very heavy rainfall due to such a disturbance. In the absence of any such disturbance over the north Bay of Bengal and adjoining land areas of Orissa and GWB along the monsoon trough, the basic monsoon flow is generally westerly. The westerlies do not yield good rainfall over Orissa, as they are relatively continental in nature due to their movement from the west coast of India to Orissa.

Broadly, Orissa consists of four physiographical regions, viz. (i) coastal plain, (ii) northern upland, (iii) central river basin and (iv) southwest hilly region. Some of the hill peaks in the northern upland and southwest hilly region are as high as 1000–2000 m. Though the Eastern Ghats of India extends from Tamil Nadu in the southwest to north Orissa in the northeast, it is more prominent in the north Andhra Pradesh and south Orissa region. Hence modification of rainfall intensity and distribution over Orissa is due to interaction of basic monsoon flow with the synoptic disturbances and orography of the Eastern Ghats and other hill peaks in Orissa and its neighbourhood.

Due to the above-mentioned reasons, the relationship of rainfall over Orissa with the meteorological fields is highly complex in nature. Hence, a study was undertaken to find out the spatio-temporal variability of summer monsoon rainfall over Orissa in relation to the meteorological parameters over Orissa and its neighbourhood. In this study, the significant relationships of seasonal monsoon rainfall over Orissa with the meteorological parameters over Orissa and its neighbourhood at surface and different levels of the troposphere are brought out and analysed based on data from 31 uniformly distributed rain gauge stations in Orissa along with seven surface observatory stations and four upper air radiosonde and radio wind stations in Orissa and its neighbourhood during 1980–98. The principal objective of this study was to understand the contribution of different meteorological parameters over Orissa and its neighbourhood in the spatio-temporal variability of monsoon rainfall over Orissa. This study will help in understanding the physical processes and development of appropriate models for prediction of rainfall over Orissa.

Data and methodology

The spatio-temporal variability of summer monsoon rainfall over Orissa in relation to the meteorological parameters over Orissa and its neighbourhood is analysed based on the data of daily rainfall recorded at 0830 Indian Standard Time (IST) over 31 uniformly distributed rain gauge stations in Orissa during monsoon months (June–September) for the period 1980–98. The daily values of surface parameters recorded at 0830 IST and upper air parameters recorded at 0530 IST over the stations in Orissa and its neighbourhood during the monsoon season for the same period have also been considered. Rainfall values and the surface and upper air meteorological parameters are collected from India Meteorological Department (IMD). The rain gauge stations selected for the study are shown in Figure 1. The data are quality-checked and the missing values, though rare, are filled up by considering the average rainfall recorded over the surrounding stations. The time series of seasonal rainfall over the selected stations in Orissa and Orissa as a whole is prepared from the daily rainfall values. Different surface observatory stations considered in the study (Figure 1) are Visakhapatnam (VSK) in north coastal Andhra Pradesh (NCAP), Kolkata (CAL) in GWB, Ranchi (RNC) in Jharkhand (JKD), Balasore (BLS), Bhubaneswar (BWN), Gopalpur (GPL) and Jharsuguda (JRG) in Orissa. The upper air stations selected for the study include VSK, BWN, CAL and RNC (Figure 1). Different meteorological parameters considered in the study include maximum temperature, minimum temperature, dry bulb temperature, dew point, mean sea level pressure (MSLP), geopotential, zonal wind, meridional wind and vector wind at the surface and different standard isobaric levels in the troposphere (Table 1). The actual



● Rain gauge stations
○ Observatory for surface observation
▲ Radiosonde and radio wind observatory for upper air observation

1. Balasore	10. Keonjhar	19. Ambobhona	28. Gunupur
2. Chandabali	11. Champua	20. Puri	29. Gudari
3. Baripada	12. Kamakshyanagar	21. Bhubaneswar	30. Bisam Cuttack
4. Udala	13. Pallahara	22. Phulbani	31. Nawarangapur
5. Rairangapur	14. Anugul	23. Bolangir	32. Visakhapatnam
6. Paradeep	15. Rajkishorenagar	24. Gopalpur	33. Kolkata
7. Cuttack	16. Panposh	25. Sorada	34. Ranchi
8. Jenapur	17. Jharasuguda	26. Mohana	
9. Anandapur	18. Sambalpur	27. Paralakhemundi	

Figure 1. Selected rain gauge stations, surface observatory stations and radiosonde and radio wind observatory stations in Orissa and its neighbourhood.

Table 1. Meteorological parameters under consideration in the study

Meteorological parameter	Station	Meteorological subdivision	Observation level
Maximum temperature	Visakhapatnam (VSK)	North coastal Andhra Pradesh (NCAP)	Surface
Minimum temperature	Gopalpur (GPL)	Orissa	
Mean sea-level pressure	Bhubaneswar (BWN)	Orissa	
Dry bulb temperature	Balasore (BLS)	Orissa	
Dew point	Kolkata (CAL)	Gangetic West Bengal (GWB)	
Wind speed and direction	Jharsuguda (JRG)	Orissa	
	Ranchi (RNC)	Jharkhand (JKD)	
Geopotential height	VSK	NCAP	850, 700, 500, 400, 300 and 200 hPa
Dry bulb temperature	BWN	Orissa	
Dew point	CAL	GWB	
Wind speed and direction	RNC	JKD	

wind is resolved into zonal and meridional components. The mean vector wind is calculated from the mean values of zonal and meridional components. The time series of the seasonal mean values of all the above meteorological parameters over different stations under consideration have been prepared for the period of 1980–98.

Different statistical characteristics like average and coefficients of variation (CV) of the meteorological parameters over different stations under consideration are calculated and analysed for the summer monsoon season as a whole. The CV is a measure of interannual variation with respect to average and is defined as standard deviation of the parameter from its average value per unit value of average. The spatial patterns of average rainfall and the standard deviation of rainfall over Orissa based on data from the same 31 stations during the period 1980–99 for the monsoon season has been analysed by Mohapatra *et al.*[19]. The linear correlation coefficients (CC)[20] between rainfall over the selected stations under consideration and the mean values of different meteorological parameters over the selected stations as shown in Figure 1, has been calculated for the monsoon season as a whole and analysed to find out their degree of association. The significance of the CC has been tested at 95% level of confidence[20]. The linear trend coefficients of mean values of different meteorological parameters over different selected stations during the monsoon season as a whole, over the period 1980–98, have been calculated to find out the changes in recent years. The significance of the trend coefficients have been tested at 95% level of confidence and significant trends are analysed and discussed.

Results and discussion

The mean pattern and interannual variation of rainfall and meteorological parameters during summer monsoon season are analysed and discussed. The relationship of surface and upper air parameters with rainfall during summer monsoon season is presented and discussed. Also recent trends in rainfall and field parameters during the summer monsoon season have been analysed and discussed. The relationship of upper air parameters with rainfall and recent trends in the upper air parameters has been presented only for three representative levels, viz. (i) 850 hPa for lower level, (ii) 500 hPa for middle level and (iii) 200 hPa for upper level of the troposphere.

Average pattern of mean sea-level pressure and geopotential height

From Figure 2, the mean sea-level pressure (MSLP) is minimum near GPL followed by BLS along the coast against the normal pattern of lowest pressure between BLS and CAL. Comparison of the mean number of low-pressure system (LPS) days over west central (WC) Bay off NCAP, as calculated by Mohapatra and Mohanty[18] during 1980–99, with that calculated by Jadhav[21] for the period 1891–90, shows an increase in the number of LPS days over WC Bay off NCAP during 1980–99. Hence, the lower MSLP over GPL may be attributed to increased tendency of the monsoon trough to lie over south coastal Orissa and adjoining NCAP (near GPL) in association with the increased number of LPS days over the WC Bay off NCAP in recent years. The increased number of LPS days over the WC Bay might have contributed to the decrease in rainfall over most parts of Orissa, except the eastern side of the Eastern Ghats and adjoining south coastal Orissa during 1980–98. In association with the LPS over WC Bay off NCAP, the basic westerly flow over the Eastern Ghats region changes to easterly. Hence, the eastern side of the Eastern Ghats and south coastal Orissa lies on the windward side and hence gets more rainfall. The central zone and north Orissa do not get good rainfall as rainfall occurs in the southwest sector, mainly due to the westward-moving LPS over WC Bay off NCAP. Orissa as a whole has received 111.7 cm of average seasonal rainfall during 1980–99 against the long period average of 117 cm, as calculated by Parthasarathy *et al.*[22] from fixed network of rain gauge stations during 1871–90 and against 116 cm during 1901–90 according to IMD[23]. Decrease in rainfall in recent years compared to the long period average[22] based on 1871–90 is statistically significant at 90% level of confidence according to Student's *t* test[20]. While the geopotential height is minimum near CAL at 850 hPa, it is minimum near VSK at 500 hPa level, indicating southward tilting of the monsoon trough with height up to mid-tropospheric level. The higher geopotential height to the north of Orissa at higher levels, supports the climatological pattern[24]. The geopotential height gradient is fairly weak over the region at all levels.

Average pattern of temperature and dew point

Distribution of maximum temperature, minimum temperature and dry bulb temperature at surface level indicates weak north-south gradient over the region (Table 2 and Figure 2). Also, all these temperatures are higher over the coastal regions than in the interiors. The pattern is almost

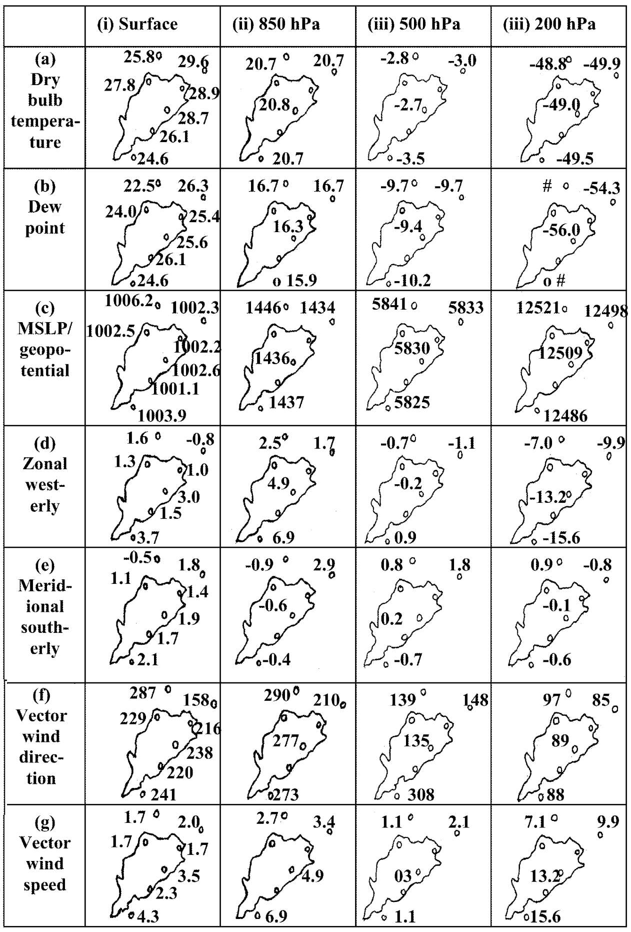


Figure 2. Average values of (a) dry bulb temperature (°C), (b) dew point (°C), (c) surface pressure (hPa)/geo-potential height (m), (d) zonal westerlies (m/s), (e) meridional southerlies (m/s), (f) mean vector wind direction (deg) and (g) mean vector wind speed (m/s) of tropospheric parameters over different selected stations in Orissa and its neighbourhood at (i) surface, (ii) 850 hPa, (iii) 500 hPa and (iv) 200 hPa levels during summer monsoon season. #, Data insufficient.

the same as that found by Kothwale and Rupa Kumar[7]. The region of higher dew point along the coast shifts southward from CAL to BWN with increase in height as the dew point remains higher along the position of the monsoon trough and the monsoon trough tilts southward with height[25].

Average pattern of wind

At the surface level, the zonal easterlies prevail over north of Orissa and westerlies cover the whole of Orissa, extending further south. The zonal westerlies change to easterlies over most parts of Orissa, except over the southern part at 500 hPa; and the easterlies further penetrate to the south with increase in speed as the height increases. It also indicates a southward tilt of monsoon trough with height up to mid-tropospheric level. The zonal wind is stronger than the meridional wind over the region, except the northern part (CAL and RNC), at all levels. This leads to the exchange of heat, momentum, etc. between different latitudes. All the observations confirm the earlier findings of Sharma and Paliwal[12], Prasad *et al.*[13] and Saha and Saha[25].

The meridional wind is southerly over the whole region, except the northernmost part where it is northerly at the surface. It changes to northerly over the whole region barring the north-eastern part at 850 hPa. It again becomes southerly over the whole region, except the southernmost part at 500 hPa. At 200 hPa, the flow further changes to northerly leaving the extreme northern part. Rao[26], while studying mean meridional circulation over India in July, has found that this flow is from south in the lower troposphere up to 32°N. Aloft, the flow is from the north excluding northwest India. According to Rao, to the south of 25°N, there is a meridional monsoon circulation with southerlies below and northerlies aloft. However, to the north of 25°N, monsoon circulation is confined to the lower troposphere with Hadley cell circulation aloft. Fluctuation in the meridional wind flow that depends on the strength of the Hadley circulation over the Asian region is known to have significant influence on the performance of the summer monsoon. The southerly meridional winds flowing in the upper troposphere during July–August over India in times of large-scale monsoon failure, exhibit considerable persistence[16]. Comparison of the mean vector wind with that based on National Centre for Environmental Prediction (NCEP) reanalysis data (Figure 3), shows that the pattern of wind has remained almost the same.

Interannual variation of meteorological parameters

The interannual variations of different parameters excluding wind have been less (< 3%) and hence are not presented here. The CV of zonal westerly and meridional southerly wind components at surface and lower, middle and upper

Table 2. Mean, coefficient of variation and linear trend coefficients of maximum and minimum temperature over the region under consideration. Linear trend coefficients significant at 95% level of confidence are shown in bold.

Statistical parameter	Meteorological parameter	Stations under consideration						
		VSK	GPL	BWN	BLS	CAL	JRG	RNC
Mean (°C)	Maximum temperature	31.5	32.0	32.7	32.4	33.0	32.6	30.2
	Minimum temperature	26.5	26.3	25.2	25.6	26.1	24.9	22.8
Trend coefficient (°C per 10 years)	Maximum temperature	–0.1	0.0	0.1	–0.1	**0.4**	0.0	**0.5**
	Minimum temperature	0.1	0.0	0.2	0.1	–0.1	0.2	**0.6**

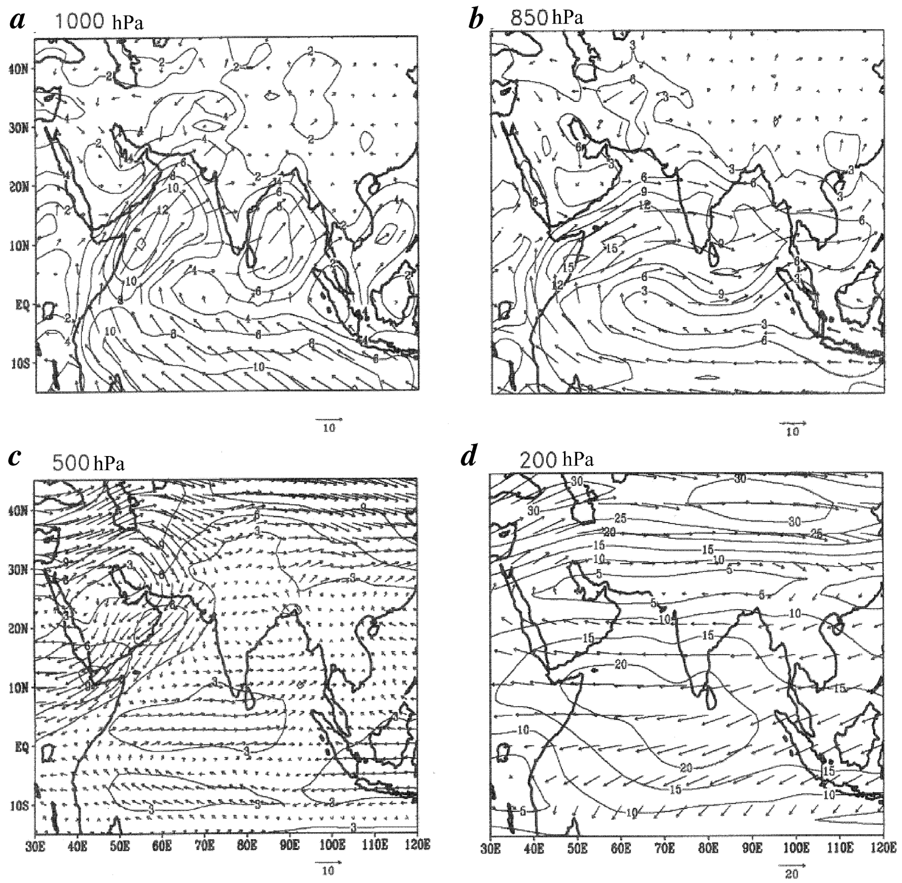


Figure 3. Spatial patterns of mean vector wind (m/s) at (***a***) 1000 hPa, (***b***) 850 hPa, (***c***) 500 hPa and (***d***) 200 hPa over India and its neighbourhood during summer monsoon season based on NCEP data of 1958–99.

troposphere is shown in Figure 4. Comparatively, the variability of meridional wind is more than that of zonal wind over the region, barring the northeastern part (CAL) at lower levels (850 hPa). It may be due to the fact that most of the synoptic disturbances develop over NW Bay during the monsoon season and move westwards across Orissa/GWB. In association with these disturbances, the winds over Orissa and adjoining NCAP become northerly to northwesterly. In the absence of synoptic disturbances, the winds over these regions are generally westerly to southwesterly at lower levels (Figure 3). As a result, the meridional component undergoes significant changes due to frequent occurrences of synoptic disturbances. The large interannual variability in the frequency of formation, intensity, region of occurrence and movement of synoptic disturbances leads to large interannual variability of the meridional component of the wind. Variability of zonal and meridional wind is more at 500 and 200 hPa respectively. As there is a large interannual variation of wind and that of other parameters under consideration is negligible, the interannual variation of rainfall may significantly depend on the interannual variation of wind apart from local and remote factors. Variation of wind determines the region of occurrence and intensity of convergence/

divergence of wind and moisture fields. It also determines the region of occurrence and intensity of low-level jet, tropical easterly jet, cross-equatorial flow, Tibetan high, etc. which significantly influence monsoon rainfall over the Indian region. The interannual variation of wind may be attributed to large-scale processes in the coupled land, ocean and atmosphere.

Correlation of rainfall with maximum and minimum temperature

The higher maximum temperature to the south of Orissa latitude (VSK) and lower maximum temperature over the region extending from north coastal Orissa to west-north-westward through RNC (JKD) are associated with more rainfall over Orissa as a whole (Table 4). The lower minimum temperature over the above region with higher minimum temperature to its south and north are also associated with good rainfall over Orissa as a whole. According to Kothwale and Rupa Kumar[7], the seasonal summer monsoon rainfall over India is inversely correlated to average temperature at the surface during the monsoon season. Considering the spatial pattern of CC (Figure 5), the rainfall significantly increases over coastal Orissa and over the region extending from coastal Orissa to western Orissa, with an increase in maximum temperature at VSK. The maximum temperature over other places is inversely correlated with rainfall over north Orissa and western side of the Eastern Ghats. It may be due to the fact that the higher rainfall activity leads to higher evaporational cooling and hence less maximum temperature. North Orissa and western side of the Eastern Ghats get good rainfall due to synoptic disturbance over NW Bay. The non-existence of monsoon trough in the normal position and less frequency of such disturbances adversely affect rainfall over these regions, and hence may cause increase in maximum temperature over them. Higher rainfall over the central zone extending from east to west is associated with higher minimum temperature (Figure 5) over the southern latitude (GPL–VSK to JRG). Rainfall is adversely affected with the zone of higher minimum temperature passing through north coastal Orissa (BLS) to JKD (RNC). Higher minimum temperature is associated with more cloudiness and high moisture content. The maximum cloud zone lies in the southwest sector of the monsoon disturbance and to the south of the monsoon trough. Hence, the higher minimum temperature zone over GPL–VSK to JRG is possible only with synoptic disturbance over NW Bay, with the monsoon trough extending west-northwestwards.

Correlation of rainfall with dry bulb temperature

The lower dry bulb temperature at surface level (Table 4) over north coastal Orissa to northwest Orissa is associated with higher rainfall activity over Orissa as a whole. The higher temperature over CAL at 850 hPa level is associated with higher rainfall over Orissa as a whole (Table 3).

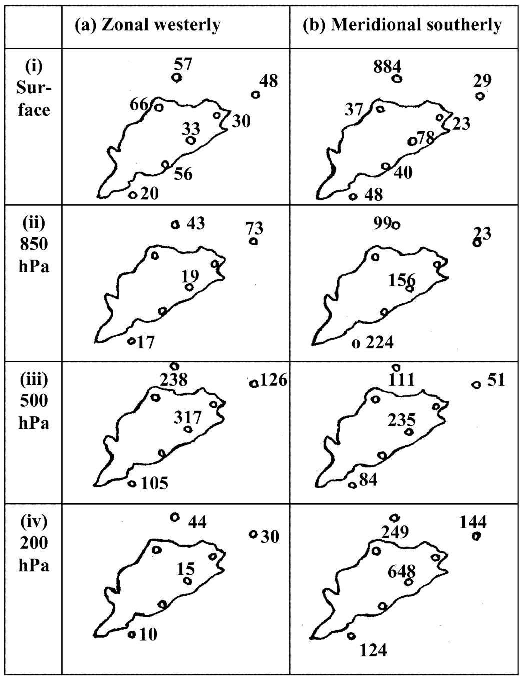


Figure 4. Coefficient of variation (%) of (a) zonal westerly and (b) meridional southerly components of wind (m/s) over different selected stations in Orissa and its neighbourhood at (i) surface, (ii) 850 hPa, (iii) 500 hPa and (iv) 200 hPa levels during summer monsoon season.

Table 3. Correlation coefficient of seasonal monsoon rainfall over Orissa as a whole with different upper air parameters over Orissa and its neighbourhood during 1980–98

		Height of the atmosphere (hPa)		
Parameter	Station	850	500	200
Geopotential height	VSK	0.33	–0.08	–0.12
	BWN	0.04	–0.01	–0.18
	CAL	**–0.40**	0.11	0.12
	RNC	0.15	0.23	0.15
Dry bulb temperature	VSK	–0.07	–0.09	–0.16
	BWN	–0.17	–0.09	–0.16
	CAL	**0.54**	0.35	0.13
	RNC	0.03	0.23	0.17
Dew point	VSK	–0.29	0.25	#
	BWN	0.08	0.10	#
	CAL	–0.24	–0.27	#
	RNC	–0.08	0.05	#
Zonal westerly wind	VSK	**0.68**	**0.75**	**0.82**
	BWN	**0.69**	**0.53**	0.24
	CAL	**0.52**	**0.62**	**0.74**
	RNC	–0.18	0.19	**0.85**
Meridional southerly wind	VSK	**–0.45**	**–0.97**	**–0.87**
	BWN	**–0.73**	**–0.55**	**0.69**
	CAL	**–0.43**	–0.30	**0.47**
	RNC	**–0.81**	–0.24	0.31

Linear correlation coefficients significant at 95% level of confidence are shown in bold. # Data on dew point are insufficient.

Table 4. Correlation coefficient of seasonal monsoon rainfall over Orissa as a whole with different surface parameters over Orissa and its neighbourhood during 1980–98

	Station under consideration						
Surface parameter	VSK	GPL	BWN	BLS	CAL	JRG	RNC
Maximum temperature	**0.68**	–0.23	**–0.50**	**–0.56**	–0.06	–0.09	**–0.47**
Minimum temperature	0.10	**0.56**	**–0.52**	**–0.76**	**0.53**	**0.64**	–0.38
Dry bulb temperature	–0.02	–0.13	0.13	**–0.57**	0.14	**–0.40**	0.31
Dew point	**–0.75**	0.25	**–0.50**	**0.48**	–0.29	0.11	0.21
Mean sea-level pressure	**0.43**	0.09	**0.47**	–0.20	–0.16	0.30	**–0.58**
Zonal westerly wind	0.37	0.24	**0.81**	**–0.77**	–0.32	**0.62**	0.16
Meridional southerly wind	–0.29	**0.46**	–0.22	**–0.77**	**0.39**	–0.19	**–0.50**

Linear correlation coefficients significant at 95% level of confidence are shown in bold.

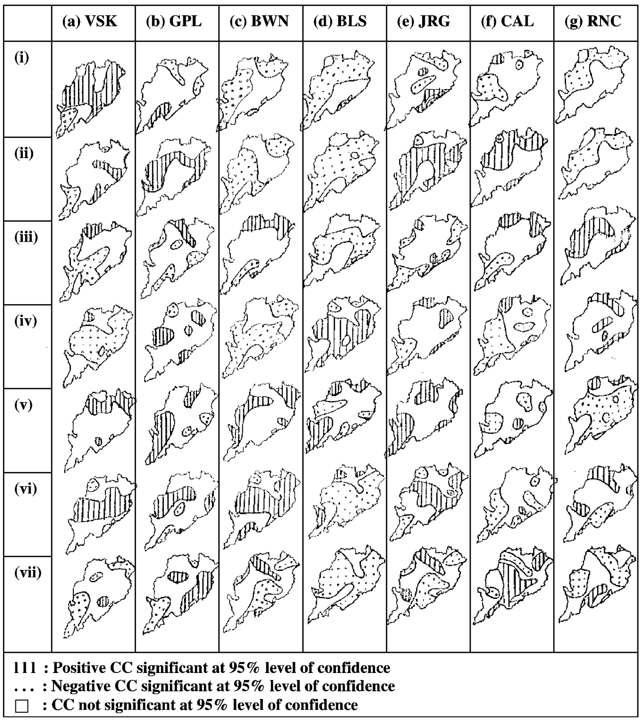


Figure 5. Spatial patterns of correlation coefficient (CC) of seasonal summer monsoon rainfall over different stations in Orissa with (i) maximum temperature, (ii) minimum temperature, (iii) dry bulb temperature, (iv) dew point, (v) MSLP, (vi) zonal westerly wind and (vii) meridional southerly wind recorded over (a) Visakhapatnam, (b) Gopalpur, (c) Bhubaneswar, (d) Balasore, (e) Jharsuguda, (f) Kolkata and (g) Ranchi at surface level.

The higher temperature at CAL and lower temperature over the southern part (VSK) at 850 hPa indicates the monsoon trough to pass through the latitude near CAL and the maximum rainfall zone lies to the south of CAL latitude and hence across Orissa. It is supported by the fact that lower temperature over BWN and BLS at the surface and 850 hPa levels is associated with higher rainfall over the central zone of Orissa (Figures 5 and 6). According to Srinivasan and Sadasivan[27], the air is slightly cooler in the lower levels (surface to 700 hPa) and slightly warmer in the upper levels (500–200 hPa) during active monsoon than under weak monsoon condition. The central zone extending from east to west, normally gets maximum rainfall due to the monsoon trough passing close to BLS, with embedded synoptic disturbance over NW Bay. According to Kothwale and Rupa Kumar[7], the ISMR is significantly and directly related with the average seasonal monsoon temperature at all standard isobaric levels between 700 and 150 hPa. There is significant negative correlation between ISMR and all-India mean seasonal monsoon temperature at surface and 850 hPa levels. Higher rainfall over the central zone from east to west is associated with the lower temperature to the south of Orissa (over VSK) at upper tropospheric levels (200 hPa) and higher temperature over the region to the north of Orissa (over CAL and RNC) at mid-tropospheric levels (500 hPa). Lower temperature over VSK and BWN and higher temperature over CAL and RNC at upper levels confirm higher upper-level divergence over the monsoon trough region in association with warm Tibetan high. According to Raju *et al.*[28], an intense warming at the upper level (500 hPa and above) over the monsoon trough zone is associated with excess rainfall over the Indian region and vice versa.

Correlation of rainfall with dew point

Rainfall over Orissa as a whole increases with increase in dew point at surface level over north coastal Orissa (BLS) and fall in dew point to the south (Table 4). The rise in dew point over BLS at surface level, which confirms the location of monsoon trough close to BLS and possible existence of disturbance over NW Bay with centre close to BLS, is also associated with higher rainfall activity over central Orissa (Figure 5) extending from east to west (zone lying to the south of the monsoon trough). Rainfall significantly decreases over this zone and its neighbourhood, with increase in dew point over south coastal Orissa and NCAP at surface level, as the rise indicates the shifting of monsoon trough to the south with formation of more disturbances over southern latitude like WC Bay/WC and adjoining NW Bay. The shifting of zone of dew point maxima to the north (CAL to JRG) has most adverse impact on the western side of the Eastern Ghats, as it indicates shifting of monsoon trough and maximum rainfall zone to the north. Also due to northward shifting of the monsoon trough, the interaction between basic westerly monsoon flow and orography due to the Eastern Ghats decreases. From Figure 7, rainfall over the eastern side of the Eastern Ghats increases with increase in dew point over south coastal Orissa (BWN) and over VSK up to 500 hPa level. It may be due to the fact that higher dew point over this region occurs in association with the monsoon trough and the embedded synoptic disturbances lying southward, e.g. over/across WC Bay and adjoining NW Bay, south Orissa and NCAP. With this system, basic flow over the Eastern Ghats becomes easterly and the eastern side of the Eastern Ghats becomes the windward region to get more moisture and rainfall.

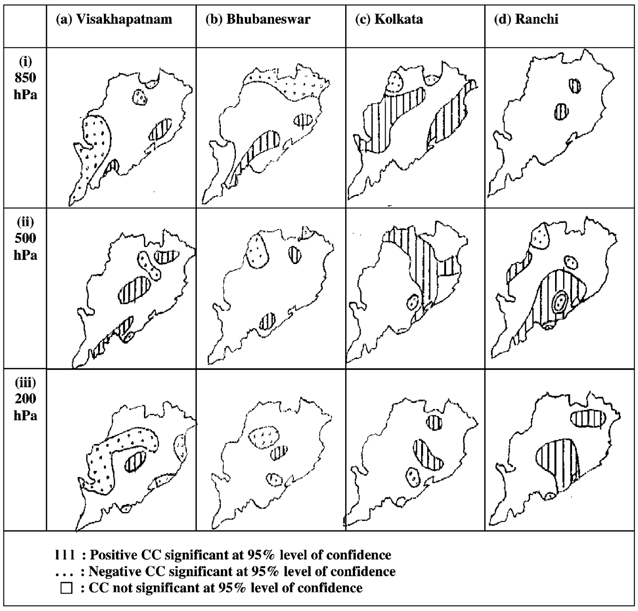


Figure 6. Spatial patterns of correlation coefficient (CC) of seasonal summer monsoon rainfall over different stations in Orissa with dry bulb temperature recorded over (a) Visakhapatnam, (b) Bhubaneswar, (c) Kolkata and (d) Ranchi at (i) 850 hPa, (ii) 500 hPa and (iii) 200 hPa levels.

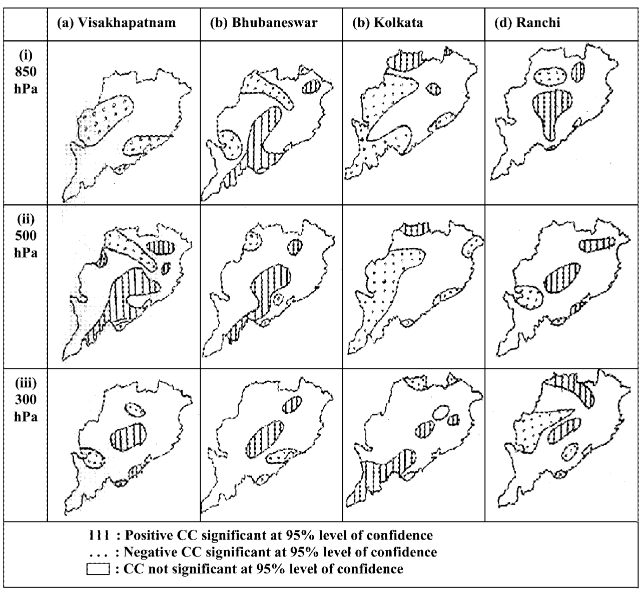


Figure 7. Same as in Figure 6, but with respect to dew point at (i) 850 hPa, (ii) 500 hPa and (iii) 300 hPa levels.

Correlation of rainfall with MSLP

Rainfall over Orissa as a whole (Table 4) increases with increase in MSLP over south Orissa and further to the south and decrease in MSLP to north, as it ascertains the trough to pass through north coastal Orissa and JKD with higher pressure gradient to the south. Considering the spatial pattern (Figure 5), the rise in MSLP over southern latitude (BWN, GPL, JRG and VSK) and fall in pressure over northern latitude (RNC and CAL) are favourable for good rainfall over different parts of Orissa. This condition confirms the monsoon trough (line of lowest pressure) to pass through JKD and GWB near to CAL–RNC latitude, and increase in pressure gradient to the south of the monsoon trough over Orissa. Higher pressure gradient leads to increase in wind velocity to the south of the monsoon trough and hence higher positive horizontal vorticity and convergence of moist air to the south of monsoon trough at lower levels. The rise in pressure over JKD (RNC) has most adverse impact over most parts of Orissa, especially the central zone, as it indicates the shifting of monsoon trough and hence the maximum rainfall zone from its normal position over Orissa.

Correlation of rainfall with geopotential height

Lower geopotential height over CAL along with higher geopotential height over VSK at lower level (850 hPa) indicates higher potential gradient to the south of the monsoon trough. This strong potential gradient to the south of the monsoon trough gives low-level convergence and hence more rainfall over Orissa. Hence, Orissa as a whole gets good rainfall with lower geopotential height over CAL along with higher geopotential height over VSK (Table 3). For the same reason, decrease in geopotential height over RNC (JKD) and increase of same over VSK at 850 hPa are favourable for rainfall over the central zone (Figure 8). Rainfall over the eastern side of the Eastern Ghats increases with increase in geopotential height over RNC at 200 hPa.

Correlation of rainfall with zonal westerly wind

Figure 3 indicates that the basic monsoon flow over Orissa is westerly. The monsoon trough passes through

JKD and GWB, a little to the north of Orissa at lower levels. It then shifts southward with height up to mid-tropospheric level. The monsoon trough is less marked above the 500 hPa level. Mainly easterlies prevail over Orissa and its neighbourhood at upper tropospheric levels under the influence of Tibetan high and tropical easterly jet.

Considering surface zonal wind (Table 4), rainfall over Orissa as a whole increases with increase in zonal westerly over the region extending from the central part of coastal Orissa (BWN) to northwest Orissa (JRG), along with decrease in westerly/increase in easterly over north coastal Orissa (BLS). Similarly, rainfall over Orissa as a whole increases with increase in the westerly component of the wind over Orissa and increase in easterly component of the wind over JKD (RNC) at 850–500 hPa levels (Table 3). The strong easterly over BLS along with stronger westerly over BWN confirms the passage of monsoon trough through north coastal Orissa to the south of BLS. This type of zonal wind pattern also confirms maximum low-level convergence over central Orissa. This type of pattern, when associated with a synoptic disturbance over NW Bay and adjoining Orissa/GWB, further augments the rainfall over Orissa. The spatial pattern of CC (Figure 5) also confirms the above, as the central zone extending from east to west gets more rainfall with stronger westerly over VSK, BWN, GPL and easterly over BLS, CAL and RNC at surface level. The stronger westerly over the southern latitude indicates stronger monsoon over the region. The strength of the westerlies over the Indian region depends on the strength of the trade wind. A weaker trade wind and a weaker Somali jet during summer over the ocean are associated with weaker rainfall over India and vice versa[28,29]. Rainfall increases over many parts of Orissa, especially over central zone, extending from east to west with increase in westerly over Orissa and to the south (VSK) and increase in easterly over JKD (RNC) at low levels (Figure 9). Rainfall over the central zone and adjoining south Orissa decreases with increase in the westerly at lower levels to the north of Orissa (over RNC). It may be due to the fact that an increase in the westerly over RNC indicates shifting of monsoon trough, to the north of RNC. With this location of monsoon trough, relatively dry continental westerly wind prevails over Orissa, yielding less rainfall over the region. The stronger westerly component over the region, especially to the south (over VSK) and to the north (over CAL and RNC) at 200 hPa is favourable for good rainfall over Orissa, especially over the central zone. The stronger westerly over the region indicates southward shifting of 200 hPa ridge (to the south of VSK). Hence, the southerly location of 200 hPa ridge in association with the Tibetan high is favourable for rainfall over Orissa, especially over the central zone.

Correlation of rainfall with meridional southerly wind

The stronger northerlies at the surface level over north coastal Orissa (BLS) and over RNC along with southerlies over GWB (CAL), are favourable for rainfall over Orissa as a whole (Table 4). From Table 3, the stronger northerly component at lower levels over the region and over south Orissa and NCAP at mid-tropospheric level, has also been favourable for more rainfall over Orissa as a whole. It may be due to the fact that this pattern of meridional

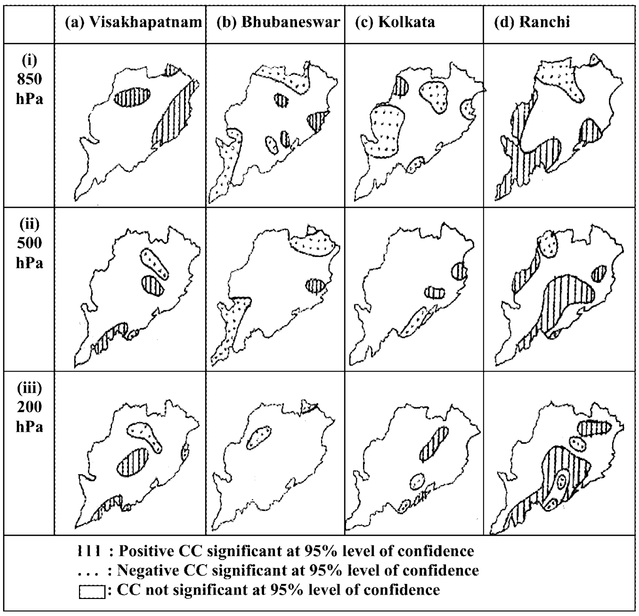


Figure 8. Same as in Figure 6, but with respect to geopotential height.

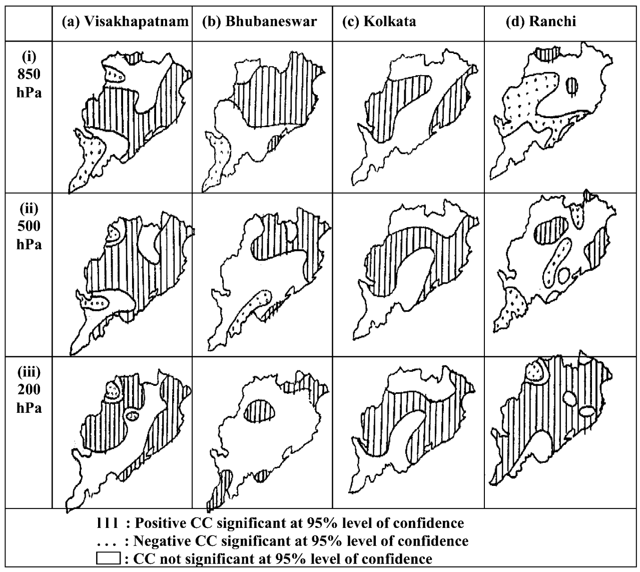


Figure 9. Same as in Figure 6, but with respect to zonal westerly wind.

wind confirms the existence of convergence zone over Orissa and adjoining GWB, which is favourable for good rainfall over Orissa. The spatial pattern of CC also confirms the above findings and shows that the above conditions have been more favourable for rainfall over the central zone (Figure 5). The western side of the Eastern Ghats gets more rainfall (Figure 5), with decrease in southerly or increase in northerly over south coastal Orissa and NCAP (VSK and GPL), as it confirms the existence of the convergence zone over the region. With the monsoon trough and embedded synoptic disturbance to the north of the Eastern Ghats region, the basic flow over the Eastern Ghats region is westerly and the western side of the Eastern Ghats becomes the windward region to get more rainfall. It also lies in the southwest sector (zone of maximum low level convergence) of this synoptic disturbance. Considering the spatial pattern of CC of the upper wind with rainfall, the rainfall over central zone and north Orissa increases with increase in northerly component (Figure 10) at lower levels over all stations, especially over BWN and RNC. The stronger northerly over VSK and BWN at 500 hPa are more favourable for good rainfall over central zone and adjoining north Orissa. At the upper troposphere (200 hPa), the northerlies over VSK and southerlies over other stations are favourable for good rainfall over many parts of Orissa.

Rainfall and mean vector wind

Considering both zonal and meridional winds favourable for good rainfall over Orissa as discussed above, strong northeasterlies over north coastal Orissa (BLS) along with southeasterlies over GWB (CAL), northwesterlies over northwest Orissa (JRG) at surface level cause good rainfall over Orissa as a whole and over most parts of the state, especially over the central zone extending from west to east. Similarly, rainfall over Orissa as a whole increases (Table 3) with increase in northwesterly wind at lower and mid-tropospheric levels over all stations, except RNC and with increase in northeasterly winds over RNC. This type of wind pattern at the surface and lower to mid-tropospheric levels is associated with synoptic disturbance over the NW Bay and the associated monsoon trough extending west-northwestwards from the centre of the disturbance. With the synoptic disturbance like cyclonic circulations extending up to mid-tropospheric level, lows, depressions and cyclonic storms over NW Bay, most parts of Orissa lie in the southwest sector and get maximum rainfall. Hence, the higher/lower number of days with synoptic disturbance over NW Bay may lead to excess/deficient rainfall over Orissa. Rainfall also increases with increase in southwesterly wind over north Orissa, GWB and JKD (BWN, CAL and RNC) and northwesterly wind over south Orissa and NCAP (VSK) at upper tropospheric level (200 hPa). This type of favourable wind pattern at the upper troposphere suggests that the ridge at 200 hPa passes through the latitude to the south of VSK and over Bay. The northwesterly wind over VSK and southwesterly wind over BWN and CAL at 200 hPa indicate an upper tropospheric trough at 200 hPa passing along the longitude to the right of VSK.

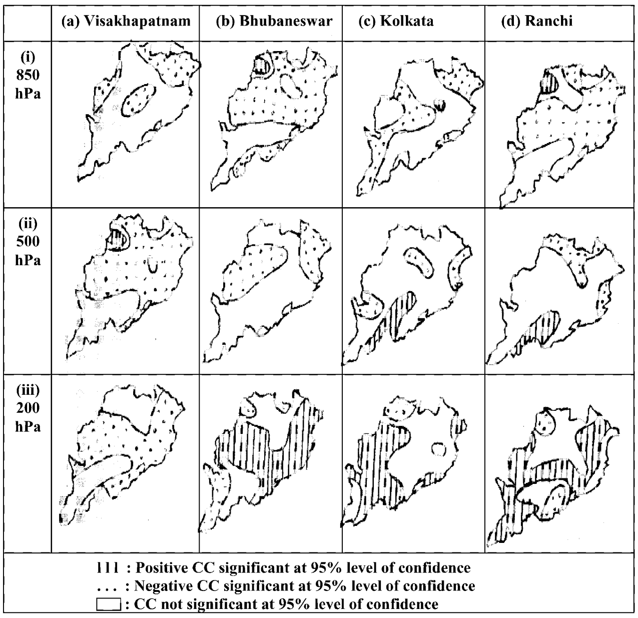


Figure 10. Same as in Figure 6, but with respect to meridional southerly wind.

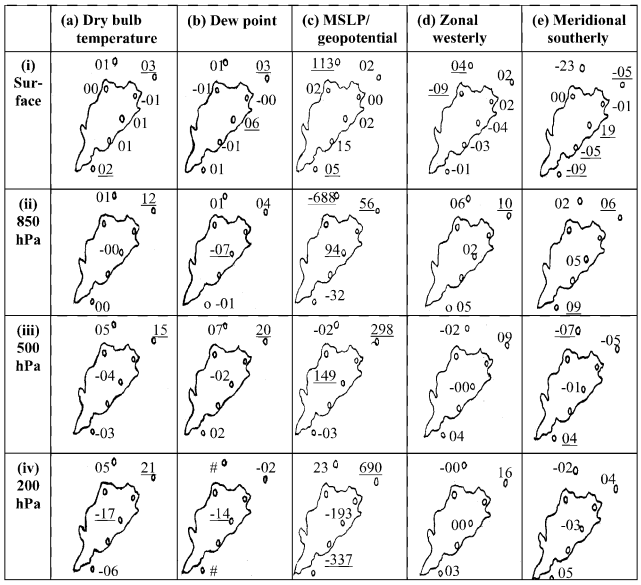


Figure 11. Linear trend coefficients (per 100 years) of (a) dry bulb temperature (°C), (b) dew point (°C), (c) surface pressure (hPa)/geopotential height (m), (d) zonal westerlies (m/s) and (e) meridional southerlies (m/s) over different selected stations in Orissa and its neighbourhood at (i) surface, (ii) 850 hPa, (iii) 500 hPa and (iv) 200 hPa levels during summer monsoon season. Trend coefficients significant at 95% level of confidence are underlined.

Recent trends in meteorological parameters and rainfall over Orissa

The linear trend analysis of seasonal rainfall over Orissa as a whole indicates the decreasing trend during 1980–98, though not statistically significant. From Table 2, the maximum temperature over CAL, RNC and minimum temperature over RNC show a significant rising trend during the same period. While the dry bulb temperature shows significant rising trend over CAL from surface to upper tropospheric levels, dew point over CAL shows rising trend at surface and mid-tropospheric level (Figure 11). MSLP shows rising trend over the region. However, the trend is significant to the north and south of Orissa. It is supported by the significant increasing trend of geopotential height over Orissa (BWN) at 850–500 hPa. Dry bulb temperature, dew point and geopotential at the upper troposphere show increasing trend over the region to the north of Orissa and decreasing trend over Orissa and NCAP. There is significant rising trend in zonal westerlies over RNC at the surface and CAL at 850 hPa and decrease in westerly over JRG at surface level. There is a decreasing trend in southerlies over CAL, south coastal Orissa and NCAP at surface level, increase in southerly both south and north at 850 hPa and south at 500 hPa. Considering the significant CCs of rainfall with different surface and upper air meteorological parameters, it can be summarized that there is a mixed trend in the meteorological parameters at surface, lower and middle troposphere causing insignificant trend in seasonal rainfall over Orissa. However, there is no significant trend in both zonal and meridional winds at the upper troposphere (200 hPa) over the region, supporting insignificant trend in summer monsoon seasonal rainfall over Orissa.

Conclusion

The spatio-temporal variation of rainfall over Orissa largely depends on the spatio-temporal variation of wind over Orissa and its neighbourhood. The interannual variation of wind is high due to large variation in the characteristics of synoptic disturbances developing over the Bay of Bengal.

The strong northeasterly over north coastal Orissa (BLS) along with southeasterly over GWB (CAL) and northwesterly over northwest Orissa (JRG), south Orissa and north coastal Andhra Pradesh at lower and mid-tropospheric levels are favourable for good rainfall over Orissa as a whole, over the western side of Eastern Ghats and over the central zone extending from the central part of coastal Orissa to western Orissa. This type of wind pattern is associated with synoptic disturbance over the NW Bay and the monsoon trough extending west-northwestwards from the centre of the disturbance. Hence, the higher/lower number of days of synoptic disturbances over NW Bay cause excess/deficient rainfall over Orissa.

The stronger gradient of mean sea level pressure and geopotential over the region to the south of the monsoon trough passing through north coastal Orissa at lower and mid-tropospheric level is favourable for good rainfall over Orissa.

Divergence at the upper troposphere due to a trough in the upper tropospheric westerlies at 200 hPa to the right of VSK and an east-west ridge to the south of VSK is favourable for rainfall over Orissa.

There is no significant trend in both zonal and meridional winds at the upper troposphere (200 hPa) over the region supporting insignificant trend in summer monsoon seasonal rainfall over Orissa during 1980–99.

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