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Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India

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Abstract. The Advanced Very High Resolution Radiometer (AVHRR) onboard the National Oceanic and Atmospheric Administration (NOAA) series of satellites has been used for mapping vegetation cover and classification employing the Normalized Difference Vegetation Index (NDVI). Recently, this technique has been improved by converting NDVI with radiation measured in one of the thermal channels and converting brightness temperature into the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI). These indices are being used for estimation of vegetation health and monitoring drought. The present study shows the application of vegetation and temperature condition indices for drought monitoring in India.

1. Introduction

The vegetation index has been considered by numerous scientists as one of the important parameters for the mapping of agricultural fields, rainfall monitoring, estimating weather impacts, calculating biomass, crop yield and pasture production, drought conditions and determining the vigour of the vegetation (Tucker *et al.* 1982, Justice *et al.* 1985, Hielkema *et al.* 1986, Kogan 1987a,b, 1990, 1995, 1998, Dabrowska-Zielinska *et al.* 2002). Scientists have suggested numerous vegetation indices. Kogan (1995) has developed the Temperature Condition Index (TCI) using Advanced Very High Resolution Radiometer (AVHRR) thermal bands to determine the temperature-related vegetation stress and also stress caused by excessive wetness. The Vegetation Condition Index (VCI) and TCI are found to be dependent on the region and also weather and ecological conditions. In the present paper, we discuss the VCI and TCI for drought monitoring in different regions of India.

2. NOAA AVHRR data

National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) records radiations in five spectral bands:

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visible (Ch 1), near-infrared (Ch 2) and three thermal (Ch 3, Ch 4 and Ch 5). Global Vegetation Index (GVI) data is a standard NOAA product resulting from processing of the Global Area Coverage (GAC) satellite sensor data. GVI is produced by sampling and mapping of 4 km daily radiance, measured from NOAA polar orbiting satellites to a 16 km map. The daily maps of GVI parameters (radiance, NDVI, satellites and Sun angles) are composite over a 7-day period by saving those values that have the largest difference between Ch 2 and Ch 1 during the 7 days for each map cell. This procedure has the effect of minimizing cloud contamination in the weekly composite (except in areas that are cloudy for all 7 days). By using only the maximum value, atmospheric effects have been reduced. The GVI data have been collected for two polar orbiting satellites NOAA-9 and NOAA-11.

3. NDVI

Green and healthy vegetation reflects much less solar radiation in the visible (Ch 1) compared to those in near-infrared (Ch 2). More importantly, when vegetation is under stress, Ch 1 values may increase and Ch 2 values may decrease. The Normalized Difference Vegetation Index (NDVI) is defined as

$$\mathrm{NDVI} = (\mathrm{Ch}\,2 - \mathrm{Ch}\,1)/(\mathrm{Ch}\,2 + \mathrm{Ch}\,1) \qquad (1)$$

where Ch 2 and Ch 1 are the radiation measured in channels 2 and 1, respectively. The healthy and dense vegetation show a large NDVI. In contrast, clouds, water and snow have larger visible reflectance than those of near-infrared (NIR). Thus, those features yield negative index values. Rock and bare soil covered areas have similar reflectances in the VIS/NIR bands and result in vegetation indices near zero. Because of these properties, NDVI has become the primary tool for mapping changes in vegetation cover and analysis of the impacts of environmental phenomena. The NDVI can be used not only for accurate description of continental land cover, vegetation classification and vegetation phenology (Tucker *et al.* 1982, Tarpley *et al.* 1984, Justice *et al.* 1985) but it is also effective for monitoring rainfall and drought, estimating net primary production of vegetation, crop growth conditions and crop yields, detecting weather impacts and other events important for agriculture, ecology and economics (Kogan 1987a, Dabrowska-Zielinska *et al.* 2002).

The technique of compositing data for 7 days considerably reduces noise in the surface reflection signal but data can still be contaminated. Noise in AVHRR data creates fundamental constraints to the remote sensing of vegetation. The sources of noise in GVI datasets are summarized by Gutman (1991). The largest noise arises from clouds, which considerably reduce NDVI. Other constituents of the atmosphere also influence NDVI. Numerous algorithms have been developed for correction of noise due to different sources (Kogan 1995). However, complete physical ground corrections for all the effects and for various land surfaces are not yet available.

The NDVI has been used successfully to identify stressed and damaged crops and pastures but interpretive problems may arise when these results are extrapolated over non-homogeneous areas. In these areas, differences between level of vegetation can be related to differences in environmental resources (i.e. climate, soil, vegetation, relief). For example, under similar vegetation conditions, a region with abundant resources shows NDVI values twice as large as compared to adjacent regions with insufficient resources (Kogan 1987a). Therefore, it can be said that NDVI has two components: ecology and weather. For vegetated regions, the integrated area of the weather component is smaller than the ecosystem component. So the weather-related NDVI fluctuations are not easily detectable. Therefore, when NDVI is used for analysis of weather impact on vegetation, the weather component must be separated from the ecosystem component. The VCI and TCI, given by Kogan (1995), have been used to estimate the weather impact on vegetation.

4. VCI

VCI quantifies the weather component. The weather-related NDVI envelope is linearly scaled to 0 for minimum NDVI and 100 for the maximum for each grid cell and week. It is defined as

$$VCI = 100(NDVI - NDVI_{min})/(NDVI_{max} - NDVI_{min}) \quad (2)$$

where NDVI, $NDVI_{max}$ and $NDVI_{min}$ are the smoothed weekly NDVI, multi-year maximum NDVI and multi-year minimum NDVI, respectively, for each grid cell. VCI changes from 0 to 100, corresponding to changes in vegetation condition from extremely unfavourable to optimal.

5. TCI

TCI is based on the thermal band (Ch 4) of AVHRR converted to brightness temperature (BT). TCI is used to determine temperature-related vegetation stress and also stress caused by excessive wetness. The TCI algorithm is similar to the VCI algorithm, and is given as

$$TCI = 100(BT_{max} - BT)/(BT_{max} - BT_{min}) \quad (3)$$

where BT, BT_{max} and BT_{min} are the smoothed weekly brightness temperature, multi-year maximum and multi-year minimum, respectively, for each grid cell. The conditions are estimated relative to the maximum and minimum temperature envelopes. The above formula reflects different response of vegetation, to temperature. High temperatures in the middle of the growing season indicate unfavourable conditions for drought, whilst low temperatures indicate mostly favourable conditions.

For the present study, NDVI and BT data of 12 years from 1985 to 1996 have been used. Both indices characterize the status of crop development. The first index (VCI) is based on the relation between the actual weekly value of NDVI and the values of NDVI that represent the best ($NDVI_{max}$) and the worst ($NDVI_{min}$) crop growing conditions for 12 years (1985–1996). The second index (TCI) represents the relation between the actual weekly value of brightness temperature and the temperature that occurred for the potential (BT_{min}) and stress (BT_{max}) crop conditions within the same period.

6. AVHRR data as an indicator of environmental resources

The gridded NDVI, VCI, BT and TCI data have been deduced from AVHRR data during 1985–1996 over various Indian regions. The NDVI has two components: the ecology and the weather. The estimate of the impact of weather on vegetation is possible only after separating the variability of NDVI, which is related to the contribution of geographic resources (ecology). The ecosystem component is mainly controlled by such slow changing environmental factors: climate, soil, topography and vegetation type, which determine the amount and distribution of vegetation on Earth. The weather component of NDVI is controlled by weather parameters (rainfall, temperature, wind) which reflect the vegetation state and greenness in the annual cycle. The weather component of NDVI is superimposed on the ecosystem component. Maximum vegetation is developed in years with optimal weather, since such weather stimulates efficient use of ecosystem resources (for example, an increase in the rate of soil nutrition uptake). In contrast, minimum vegetation is developed in years with extremely unfavourable (mostly dry) weather, which suppresses vegetation growth both directly and through a reduction in the rate of ecosystem resources. For example, lack of water in drought years reduces considerably the amount of soil nutrition uptake. The absolute maximum and minimum NDVI calculated from several years of data that contain the extreme weather events can be used as criteria for quantifying these extreme conditions. Each location on the Earth has a certain amount of ecosystem resources which determines the ecosystem potential or 'carrying capacity' of a geographic region. This carrying capacity can be expressed in the amount of vegetation measured directly or indirectly through the NDVI value. Therefore, in the present study NDVI values have been used. The highest and the lowest NDVI values during 1986–1996 (excluding year 1994 as data are not complete) for each of the 52 weeks in a year and for each pixel have been calculated. The resulting maximum and minimum NDVI have been used as the criteria for estimating the upper (favourable weather) and the lower (unfavourable weather) limits of ecosystem resources.

The NDVI plots for 10 years from 1986 to 1996 (excluding year 1994 as data was not complete) for each of 52 weeks of a year for one pixel of Eastern Rajasthan (figure 1(*a*)) and Western Uttar Pradesh (figure 1(*c*)) are shown. In figure 1(*b*) and (*d*), the multi-year maximum, minimum and 1987 NDVI curves are shown, respectively, for Eastern Rajasthan and Western Uttar Pradesh. The largest mid-season (July–September) NDVI was during 1991 in Eastern Rajasthan and during 1992 in Western Uttar Pradesh. The 1987 mid-season (July–September) NDVI has been found to be lowest due to less precipitation or failure of monsoon. The year 1987–1988 was a year of drought with precipitation levels much below the normal. The difference in the mid-season (July–September) maximum and minimum NDVI values has been found to be 0.26 in Eastern Rajasthan and 0.28 in Western Uttar Pradesh.

Figure 1(*b*) shows that the minimum curve for multi-year composites for Eastern Rajasthan will be from 1988, 1986 and week 30 onwards from 1987 values, and the maximum curve for multi-year composites will be from years 1992, 1995 and 1991 for early, mid and late season, respectively. Figure 1(*d*) shows that the minimum curve for Western Uttar Pradesh will be from 1995 and from week 36 onwards from 1987 values and the maximum curve from the years 1989 and 1995 for the early and mid-season, respectively, and 1992 and 1996 for late season. Since the minimum and maximum NDVI curves delineate the contribution of the ecosystem component into the NDVI value for the cases with the most extreme weather, the area between these curves approximates primarily the weather-driven component of the NDVI. The highest NDVI of 0.27 in figure 1(*a*) suggests excellent vegetation conditions in a less productive Eastern Rajasthan ecosystem whereas in a more

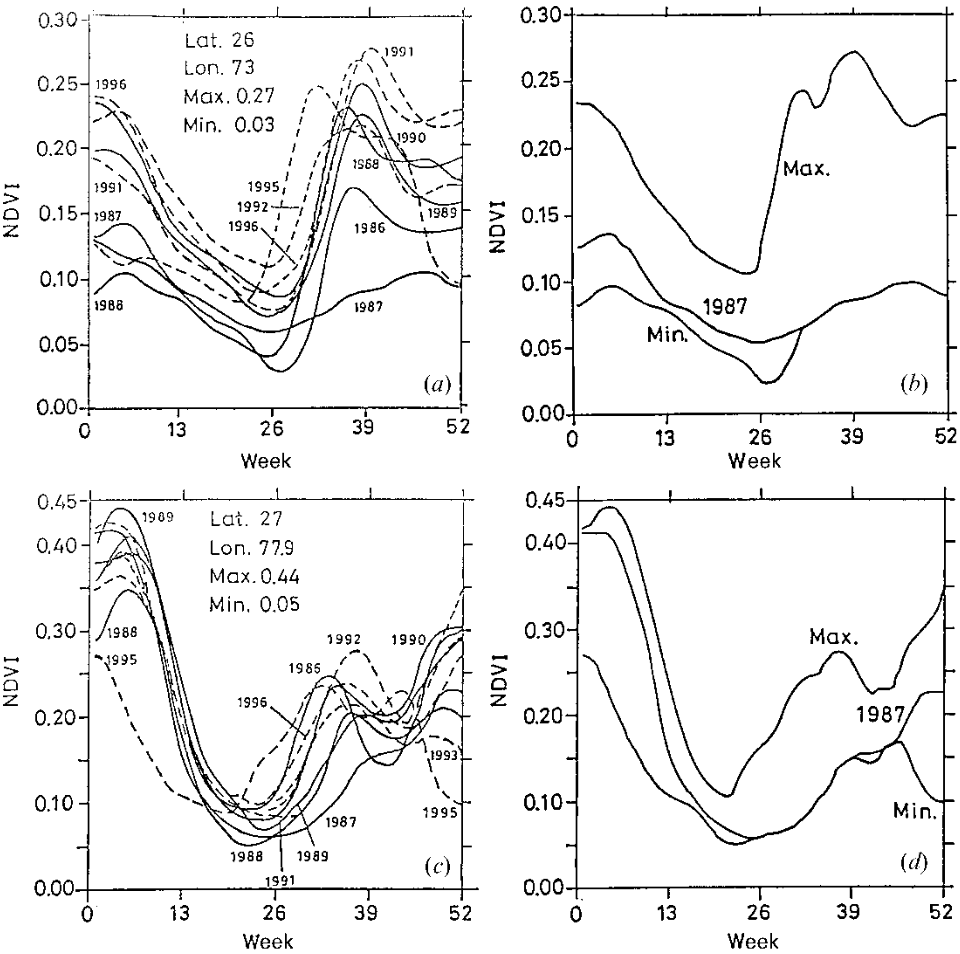

Figure 1. (*a*). Multi-year NDVI curves for Eastern Rajasthan. (*b*) Multi-year maximum, minimum and 1987 NDVI curve for Eastern Rajasthan. (*c*) Multi-year NDVI curves for Western Uttar Pradesh. (*d*) Multi-year maximum, minimum and 1987 NDVI curve for Western Uttar Pradesh.

productive Western Uttar Pradesh ecosystem it shows fair vegetation conditions, where the highest NDVI is found to be 0.44 (figure 1(*c*)). Figure 1 shows that NDVI quantifies both spatial differences between productivity of ecosystem (ecosystem component) and year-to-year variations in each ecosystem due to weather fluctuations (weather component). The eastern part of Rajasthan where the surface temperature is higher compared to the western Uttar Pradesh, which is a more productive region.

In figure 2(*a*), the weekly maximum and minimum NDVI curves compiled from several years of data 1985–1996 are shown for nine types of natural vegetation regions of India (Roy 1999). These nine regions (figure 2(*b*)) are characterized by different types of vegetation and also by different amounts of annual rainfall. One pixel per region has been selected and within a single type of natural vegetation, more than one pixel has been taken to account for the variations in rainfall,

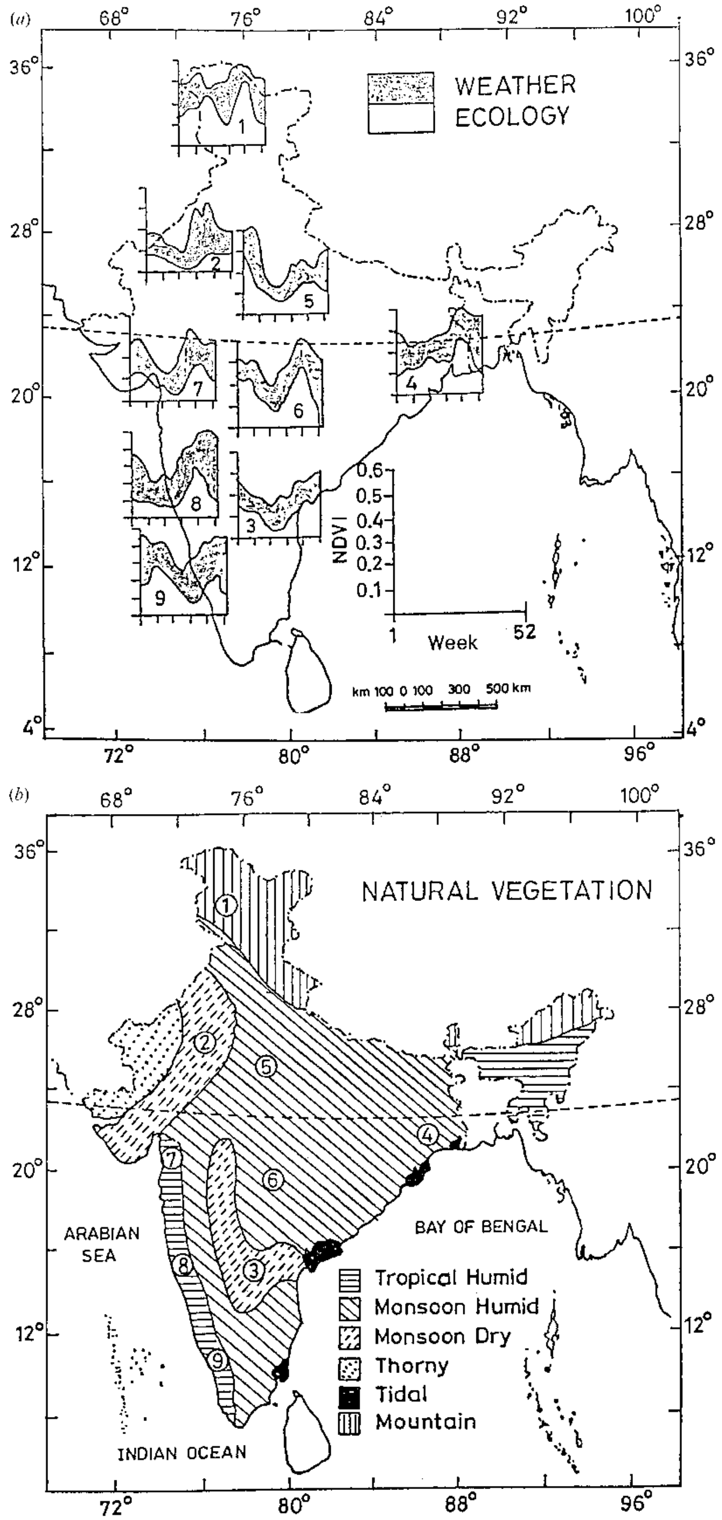

Figure 2. (*a*) NDVI maximum and minimum curves during 1985–1996 for nine different types of vegetation regions. (*b*) Natural vegetation regions of India.

geographic location, etc. Each ecosystem has its own NDVI signature in terms of NDVI value, shape of the curve, rate of NDVI change during leaf appearance and senescence and partitioning of NDVI value into weather and ecosystem components.

In figure 2(*a*), curve 1 represents mountain subtropical vegetation with rainfall of 0–100 cm and cold and moist climate. The NDVI curve shows distinctive seasonal dynamics with a maximum value of 0.4 and minimum value of 0.12. The ecology component (green envelope) is greater than those of the weather component (blue envelope). Curves 2 and 3 represent monsoon dry deciduous type vegetation with rainfall in the range of 20–60 cm per year. The difference in the shape of the two curves are due to different geographic locations; climate type 2 lies in a hot and dry climate, whereas type 3 lies in a warm and low moisture climate. These curves have small NDVIs with a maximum value of 0.3 and minimum value of 0.03. The NDVI values show no distinctive seasonal dynamics, with the contribution of the weather component being equal to or greater than those of the ecology component.

Curves 4, 5 and 6 represent monsoon humid deciduous forests (figure 2(*a*)). Curve 4 represents a region with rainfall of 100–200 cm and hot and moist climate. Curves 5 and 6 represent a region with rainfall of 60–100 cm. Curve 5 has an extremely warm and moist climate and curve 6 has a warm and less moist climate. In these regions, the NDVI values represent crops since only a small area of forest cover is present. All the three curves show distinctive seasonal dynamics with the ecology contribution more than those of the weather. Curve 4 shows a minimum value of 0.1 and maximum value of 0.4. The NDVI values are highest from week 26 to 42, i.e. during the Kharif season, since rice is the principal crop here. Curve 5 shows a minimum value of 0.13 and maximum value of 0.42. The NDVI values are maximum from around week 5 (Rabi) and week 38 (Kharif), the peak at week 5 is higher than the peak at week 38. These peaks represent wheat of high productivity (Rabi) and rice of low productivity (Kharif). Wheat being the principal crop grown here, the high in the NDVI during the Rabi season is more than NDVI peak in the Kharif season. Curve 6 shows a minimum value of 0.2 and a maximum value of 0.42. It is in a region where Jowar and Bajra (Kharif) are the principal crops. Curves 7, 8 and 9 represent Tropical Humid evergreen forests having hot and wet climates but varying amounts of rainfall, curve 7, 100–200 cm; curve 8, over 400 cm; and curve 9, 200–400 cm. All the three curves show distinctive seasonal dynamics. Curve 7 shows a minimum value of 0.1 and a maximum of 0.35. Curves 8 and 9 show high NDVI values with a minimum value of 0.25 and a maximum value of 0.5, signifying excellent vegetation condition.

7. VCI and TCI as a tool for drought detection

VCI and TCI have been successfully used in recent years to detect drought and vegetation stress due to excessive wetness. The drought and vegetation stress are mapped when VCI is less than 35 and TCI is greater than 95. They can be used for both localized/short-term and widespread/long-term droughts (Kogan 1987a,b, 1995). The ability to detect drought can be verified with *in situ* data, e.g. crop yield and precipitation data. During 1987–1988 large parts of India have faced drought conditions, parts of Uttar Pradesh province in India also came under the spell of drought. An area in eastern Uttar Pradesh has been chosen to verify the relation

Table 1. Weekly VCI and TCI.

	1986		1987		1988	
Weeks	TCI	VCI	TCI	VCI	TCI	VCI
20	51	88	4	0	100	29
21	48	100	0	0	96	34
22	47	98	0	0	96	32
23	50	92	0	0	95	28
24	46	88	0	0	88	28
25	25	84	20	0	80	26
26	20	82	50	0	64	25
27	11	84	50	0	57	30
28	7	84	53	0	58	38
29	8	85	62	0	57	49
30	9	80	74	0	56	54
31	15	76	78	0	59	56
32	13	63	81	0	59	57
33	10	45	95	9	62	44
34	8	34	100	24	57	43
35	0	14	100	26	38	44
36	0	8	100	52	26	50
37	0	0	100	62	18	55
38	10	0	100	63	10	67

between VCI and TCI values and drought conditions. For verification, *in situ* data of crop yield and precipitation have been collected. The drought in 1987–1988 was due to the late arrival of the monsoon in most parts, while in some parts the monsoon failed to arrive. So, VCI and TCI data during June–September have been considered for the drought detection. Table 1 shows weekly VCI and TCI values for three consecutive years from 1986 to 1988 for a part of Eastern Uttar Pradesh. The VCI values show a low value (0) for the weeks 20–32 in year 1987, showing that the vegetation of this part of Uttar Pradesh was highly under stress. Earlier case studies have shown that a value of VCI below 35 is an indication of drought (Kogan 1995).

One may notice that for September 1987 the precipitation is about 144% and VCI is above 62 and 63, respectively, for weeks 37 and 38, therefore the VCI criterion was not met. In July 1987, precipitation was observed to be about 90% but the TCI criterion was not met—TCI was in the range 50–74 in weeks 27–30. In July 1986, the precipitation was observed to be about 96% but the TCI varies only in the range 80–84. One may also note that there is no direct relationship as such between VCI, TCI and precipitation. VCI shows cumulative environmental impact on vegetation while precipitation is not related with TCI. During 1987, a deficit in precipitation in June (and probably before) caused the VCI to be below 25 during June–August, while precipitation in July and August was normal.

8. Rainfall and crop yield data

Rice is one of the major Kharif crops of Uttar Pradesh. It is sown during May–June and harvested during September–October. Table 2 shows a substantial decrease of rice yield in years 1986–1987 and 1987–1988 as compared with other years. This decrease is due to a short-term and localized drought, which occurred due to insufficient precipitation in the beginning of crop-sowing season. In Uttar

Table 2. Rice yield for different years ($\times 10^3$ Kg ha^{-1}).

Year	1985–1986	1986–1987	1987–1988	1988–1989
Rice yield	14.88	13.55	13.54	17.52

Table 3. Average rainfall, and rainfall for years 1986, 1987, 1988 for the months of June–September.

	June		July		August		September	
Month/Year	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
1986	178.6	108.5	324.6	96.36	254.1	77.98	149	71
1987	70.2	42.65	303.2	90.01	297	91.14	302.2	144.04
1988	175.7	106.74	308.3	91.52	351.7	107.93	135.4	64.53
Avg. rainfall	164.6		336.85		325.87		209.84	

Pradesh, monsoon showers start around 20 June. Table 3 shows that in the month of June the rainfall was much below the average monthly rainfall. Fifty-five districts of Uttar Pradesh suffered with drought conditions in this month, which has affected Kharif crops severely. Due to further lack of precipitation in the month of August, crops could not be sown and those sown have been badly affected by lack of water. About 45×10^5 ha of Kharif crop could not be sown and 56×10^5 ha have been adversely affected. In the month of September, most of the districts of Eastern Uttar Pradesh received more than normal rainfall. Table 3 shows excess rainfall in September 1987 (Kharif season), which lead to flooding that affected around 3.21×10^5 ha of agricultural area. This was another reason for the damage of Kharif crops.

9. Conclusion

The VCI variations show that in the months of June, July, August and September the crop is stressed and conditions for drought have developed. Since the rainfall was less than normal, temperatures remain high, as a result low TCI values are found during June and July. In these months, crop data shows a decrease in yield and these months were hot due to summer and absence of precipitation, which is reflected also by the VCI and TCI values. Therefore, VCI and TCI can be used for drought detection and mapping. When there is excessive soil moisture due to heavy rainfall or long cloudiness, NDVI is depressed and VCI values are low, which can be interpreted erroneously as drought. In such cases, the TCI values are used to distinguish drought from non-drought events. In September, an excess of normal rainfall occurred and TCI values show favourable conditions, but VCI values are low. This is because after being affected by droughts for the first 3 months, excess of normal rainfall (table 3) in September damaged the crops, and agricultural fields were wet and flooded. This led to a substantial decrease in crop yield. Due to stressed vegetation, VCI is found to be unfavourable in September, while TCI due to wetting of land and flooding shows a favourable condition, under such a condition VCI can not be used alone to predict droughts. TCI provides the reason for vegetation stress whether stress is due to dryness or excessive wetness. The present results show that VCI coupled with TCI should be employed as a tool to monitor both drought and excessive wetness.

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