DESERT VEGETATION DURING DROUGHTS: RESPONSE AND SENSITIVITY

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ABSTRACT:

Desert ecosystems are characterised by large spatial and temporal variability mainly due to scarcity of moisture owing to insignificant precipitation. Desert vegetation is represented mostly by natural vegetation and least by agricultural crops. Desert plants are naturally adapted to hyper-arid climate where, rainfall is sparse and day-time temperature is very high. However, desert phenology is very sensitive to climatic parameters, particularly rainfall and temperature. Insufficient and erratic rainfall causes moisture-stress, whereas high heatflow imparts thermal-stress to vegetation. Due to higher sensitivity, slight decrease in rainfall and/or increase in temperature impart stresses on desert plants. Therefore, desert-plants suffer severely during intense droughts. Thar, the Great Indian Desert covers 446,000 km^2 area in the north-western part of India and eastern part of Pakistan. The Indian portion of the Thar Desert covers 208,110 km^2 area of which 61% lies in Rajasthan state. The frequent occurrence of drought in this region is due to poor and untimely monsoon, abnormally high temperature especially in the summer and various other unfavourable physico-climatic events such as dust storm. In the present work, multi-sensor satellite data have been used to derive various vegetation parameters together with actual ground data (rainfall and temperature) for detailed drought analysis of the part of Thar Desert falling in the Rajasthan state, for the years 1984–2003. Vegetative drought indices have been calculated using Normalised Difference Vegetation Index (NDVI) values obtained from Global Vegetation Index (GVI) of NOAA AVHRR data. Spatial and temporal variations in rainfall, temperature, and vegetation indices in the Thar Desert have been analysed and correlated for monsoon and non-monsoon seasons. The mean seasonal NDVI, the index representing greenness of vegetation is found to be strongly correlated with seasonal rainfall. The time series of Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) show that in certain years they correspond each other, while in other years one counter the other and their resultant determined the occurrence and severity of drought, which is reflected in the Vegetation Health Index (VHI). The results show that seasonal average of the VCI is directly correlated with cumulative seasonal rainfall, and seasonal average of the TCI shows strong correlation with average seasonal above-ground temperature. The time series of VHI shows that drought developed and affected the desert vegetation mostly when both moisture- and thermal-stress were generated (years 1985, 1986, 1987, 1989, 1990, 1991, 2000, and 2002) and sometimes due to thermal-stress alone (years 1995). In certain years (1993, 1995, 1996, 1997, 1998, 1999), inspite of high thermal-stress the desert vegetation could avoid drought or reduced drought severity due to adequate moisture supply. Opposite were the cases in the years 1988 and 1994, when excellent thermal condition countered moisture-stress and drought was bypassed. The results point out that both moisture-stress and thermal-stress play role in drought development, whereas drought severity is governed by moisture supply, which is directly related to and dependent on rainfall and dew. Therefore, desert phenology during drought is dependent more on moisture than temperature. Since rainfall reduces both moisture-stress and thermal-stress, it is a saviour of vegetation under drought.

1. INTRODUCTION

Vegetation in deserts is sparse and dominated by bushes and scrubs of natural origin. Agricultural crops are rare and limited mostly along streams and river channels. Desert-vegetation is largely xerophytes, and among them the deep-rooted ones collect water from depth, while the shallow-rooted species require less water to survive. Although adopted to survive in hyper-arid condition, desert-vegetation also suffers from drought depending upon its intensity and duration. Both moisture and temperature play crucial roles in vegetation health, and it is difficult to assess the relative importance of them. However, through comparison and correlation it might be possible to evaluate the impact of moisture-stress and thermal-stress on vegetation, particularly during drought. In the present study, an attempt has been made through a time-series analysis to monitor and assess response and sensitivity of desert-vegetation during droughts.

In arid zones, rainfall is irregular and unevenly distributed both temporally and spatially. The seasonal and year-to-year fluctuation of rainfall affects the plant growth of this environment. Arid ecosystems are characterised by a single rainy season with a short growth period followed by a prolonged dry spell of considerable reduction in the amount of green plant material (Schmidt and Karnieli 2002).

In the present paper, spatiotemporal changes in the vigour of desert-vegetation during droughts as monitored through vegetative parameters have been discussed. Since drought in the concerned region is a function of the monsoon rainfall, analysis has been carried out by dividing the year into two periods – the monsoon and the non-monsoon. The monsoon period consists of four months from June to September while non-monsoon period is constituted of the months, intermediate of two successive monsoon periods. Thus, the non-monsoon 1984–85 consists of the months October–December of 1984 and January–May of 1985 and so on. Response of vegetation to rainfall and surface temperature has been monitored through various vegetation indices. Sensitivity of desert-vegetation to moisture deficiency and thermal-stress have been assessed and correlated with rainfall and land surface temperature.

2. THE STUDY AREA

Thar, the Great Indian Desert contains extensive region of sandy landscape, and is located in the north-western part of India and eastern part of Pakistan (Fig.1). In the present study, the Indian part of Thar Desert is considered, which is located in the western part of Rajasthan state in between 24° 71' E to 30° 15' E latitudes and 69° 32' N to 75° 47' N longitudes, covering about 400,000 km^2 area. The desert is bounded on the northwest by the Sutlej River, on the east by the Aravalli range, on the south by the salt marsh known as the Rann of Kachchh, and on the west by the Indus Valley. The largest part of the desert is located in Rajasthan state, India.

Figure 1: Thar – the Great Indian Desert. Red line demarcates the actual physical boundary of Thar beyond the political boundary of India and Pakistan.

The Thar Desert is about 805 km long and about 485 km wide. The terrain consists mainly of rolling sandy hills, which mainly shows scattered growths of shrub and rock outcrops. The altitude ranges from 457 m in the lower reaches of the Aravalli to 61 m near the Rann of Kachchh. Rainfall is sparse, averaging from 127 to 254 mm annually, and temperatures rise as high as 52.8° C in the month of June. Major parts are covered by aeolian and alluvium sand and small isolated drainages that are lost in the surrounding sand dunes or aeolian plains. Luni River is the only stream, which originates from the Aravalli hills in the east and flows towards south-west.

3. INDICES, DATA AND METHOD

The Normalized Difference Vegetation Index (NDVI) developed by Rouse et al. (1974) reflects the vegetation condition through the ratio of responses in near infrared (Ch2) and visible (Ch1) bands of the Advanced Very High Resolution Radiometer (AVHRR) of National Ocean and Administrative Agency (NOAA). It is expressed as:

$$NDVI = (Ch2 - Ch1) / (Ch2 + Ch1) \quad (3)$$

The Vegetation Condition Index (VCI), the Temperature Condition Index (TCI), and the Vegetation Health Index (VHI) have been developed further using the following equations as:

$$VCI = 100*(NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min}) \quad (4)$$

$$TCI = 100*(BT_{max} - BT) / (BT_{max} - BT_{min}) \quad (5)$$

$$VHI = 0.5*VCI + 0.5*TCI \quad (6)$$

where NDVI, $NDVI_{min}$, and $NDVI_{max}$ are the seasonal average of smoothed weekly NDVI, its multiyear absolute minimum and its maximum respectively; BT, BT_{min}, and BT_{max} are similar values for brightness temperature (Kogan, 2001).

Brightness temperature values are obtained from the thermal band (Ch4) of the NOAA-AVHRR. Vegetative and agricultural droughts reflect vegetation stress, and are closely related with weather impacts. However, in the NDVI, the weather component gets subdued by strong ecological component. The VCI separates the short-term weather-related NDVI fluctuations from the long-term ecosystem changes (Kogan, 1990, 1995). Therefore, while the NDVI shows seasonal vegetation dynamics, the VCI rescales vegetation dynamics in between 0 and 100 to reflect relative changes in moisture condition from extremely bad to optimal (Kogan *et al.* 2003). Since favourable weather provides optimal moisture condition, high values of the VCI correspond to healthy and unstressed vegetation. On the other hand, low TCI values correspond to vegetation stress due to high temperature and dryness. The TCI provides opportunity to identify subtle changes in vegetation health due to thermal effect as drought proliferates when moisture shortage is accompanied by high temperature (Kogan, 2002). The VCI and the TCI have been classified following the scheme (Table 1) developed for drought assessment (Bhuiyan 2004). Kogan (1995, 2001) formulated, calculated, and applied these indices based on the smoothed weekly NDVI and BT values. However, in the present study these parameters have been calculated season wise by averaging weekly values.

Drought	**Values**	**VCI**	**TCI**	**VHI**
Extreme	< 10			
Severe	< 20			
Moderate	< 30			
Mild	< 40			
No	≥ 40			

Table 1: VCI, TCI, and VHI classifications and colour schemes for vegetative drought

Ground data of total monthly rainfall have been collected from the Central Ground Water Board, Jaipur. Data of mean monthly maximum temperature are obtained from the NCEP. Seasonal rainfall and temperature have been computed respectively, by summing and averaging the monthly data. Distributed maps of seasonal rainfall and temperature have been generated through GIS based interpolation. Spline technique with a tension and a 0.1 weight has been used for interpolation. The distributed maps of rainfall and temperature have been visually compared with the vegetation indices. Rainfall and surface temperature values of the sample locations have been correlated with the corresponding pixel values of the VCI, TCI, and VHI. The VCI and the TCI values are plotted in the descending order respectively under different ranges of seasonal rainfall and maximum temperature. The relative percentage of pixels with the VCI and the TCI equal to or grater than the stated value P_m was computed as

$$P_m = [m / (N_t + 1)]*100 \quad (7)$$

where m is the order number of a pixel; N_t is the total number of pixels under the range of rainfall or temperature.

To keep sampling variation in the vertical direction, the VCI and TCI values have been plotted on the ordinate and the relative percentage of pixels on the abscissa. The lines joining the points have been used to assess relative influence of rainfall and temperature respectively, on moisture condition and thermal condition in vegetation, as higher the curve/line more is the VCI or TCI. Correct positions and consistent variation of curves in different ranges of rainfall and temperature indicates greater parameter-influence.

4. DESERT VEGETATION DURING DROUGHT

The time-series analysis of VHI shows that monsoonal drought appeared in major parts of the Thar Desert in the years 1985, 1986, 1987, 1989, 1990, 1991, 2000, and 2002. Intensity of non-monsoonal drought was moderate to severe during 1985-86, 1986-87, and 1988-89, and mild to moderate during 1987-88, 1989-90, 1990-91, 1991-92, 1995-96, and 2001-02.

4.1 Response of Vegetation health to Stresses

Year wise analysis of the VHI shows that during 1985 and 1986 monsoon season, drought appeared in the Thar Desert with different intensities. In both the years, severe to extreme droughts appeared in the western and some northern parts, whereas in rest of the region, drought was restricted to mild to moderate intensities. The VCI and the TCI show that although patterns of drought intensity and spatial distribution were more or less similar in both the years, in 1985, drought was mainly resulted due to thermal-stress, whereas in the very next year moisture-stress was the chief architect of drought (Fig. 2).

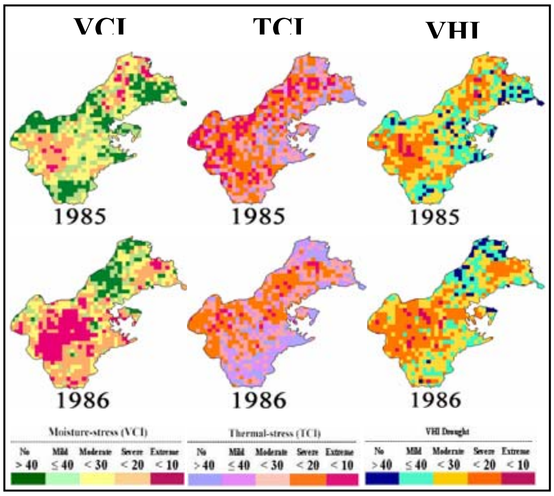

Figure 2: Spatial variation of drought intensity due to unequal development of moisture- and thermal stresses in the region.

In general, a favourable thermal condition accompanies a good moisture condition in vegetation, and vice-versa. However, in certain seasons, favourable moisture and thermal conditions do not go together, owing to the variation in climatic factors. In such cases, they counter each other, and the resultant of their combined influence is manifested in the vegetation health. In certain cases, a good moisture condition nullifies the thermal-stress and initiation of drought is halted or at least the intensity of drought impact is reduced as were the cases during the monsoon of 1989 and 1991 (Fig. 3).

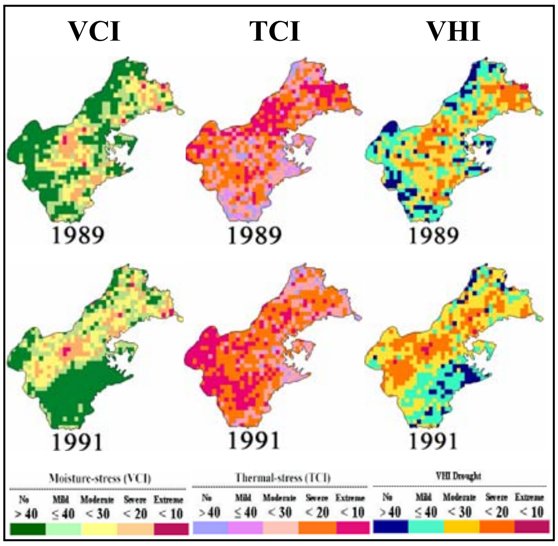

Figure 3: A good moisture condition in vegetation counters thermal-stress and checks drought severity.

Reverse were the cases during the monsoon season of 1990 and 2000, when moisture-stress accumulated in many parts of the region but favourable thermal condition helped vegetation to maintain the health and vigour, and checked the drought intensity and spatial extent (Fig. 4).

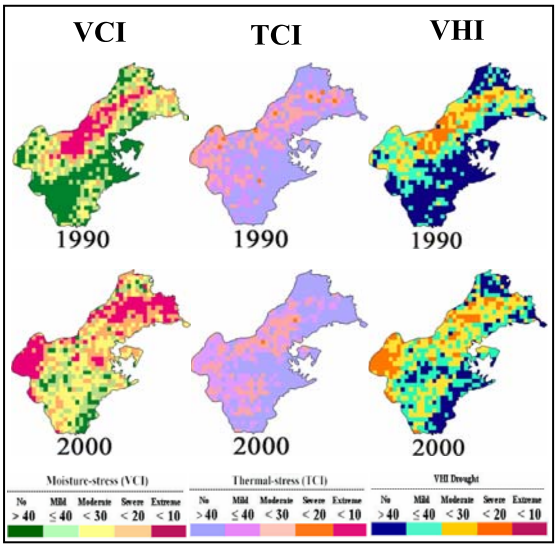

Figure 4: A good thermal condition in vegetation counters moisture-stress and reduces drought severity.

After 1987, during the monsoon of 2002, severe to extreme drought appeared all over India. In the Thar Desert, during 1987 monsoon, both moisture-stress and thermal-stress were extreme. As a result, severe to extreme drought was widespread all over the region. In 2002, while the northern and central parts suffered from extreme moisture-stress, they were almost free from thermal-stress. On the contrary, the southern part of the desert suffered from intense thermal-stress and mild to moderate moisture-stress. As a result, drought was restricted to mild intensity at some northern, southern parts, whereas severe to extreme drought prevailed in rest of the region (Fig. 5).

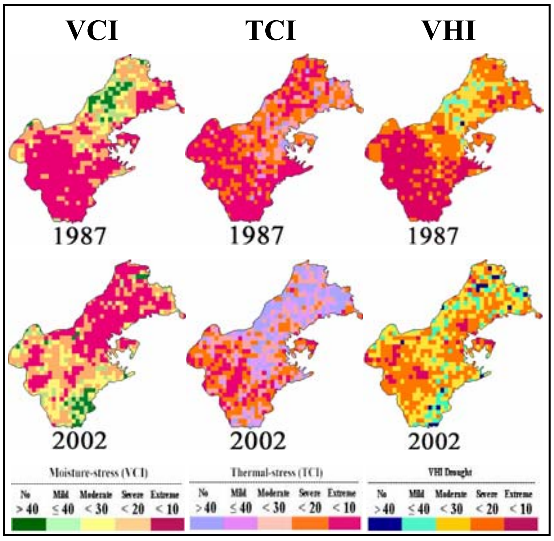

Figure 5: Drought development in cases of spatial match and mismatch of moisture- and thermal stress.

4.2 Sensitivity of Vegetation to Climatic Factors

The NDVI-rainfall relationship is a sensitive indicator for the inter-annual variability of rainfall. Previous studies (Nicholson *et al.* 1990, Lotsch *et al.*2003, Zhang *et al.* 2005) showed a good relationship between rainfall variations and the NDVI on seasonal and inter-annual time scales. In the present study, the SPI, a more refined vegetation index also shows a close resemblance to the spatial rainfall distribution patterns, both for the drought and non-drought years (Fig. 6).

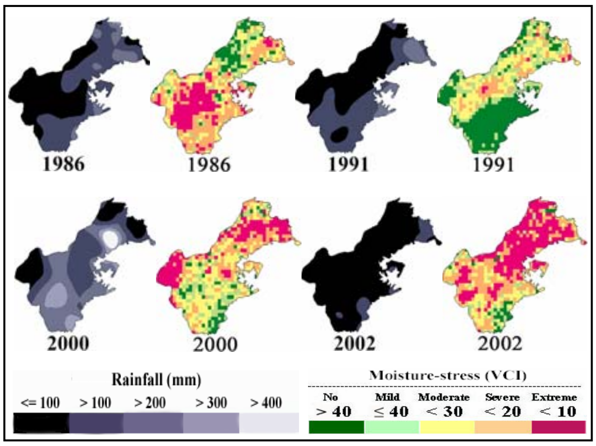

Figure 6: Response of vegetation-moisture to rainfall as indicated by the VCI.

The dependence and response is strong particularly for desert-vegetation, which is heavily dependent on rainfall-driven moisture. However, it is to be noted that vegetative drought is more sensitive to regular availability of moisture. Therefore, frequency and interval of consecutive rainfall events are more important than total seasonal rainfall, particularly for agricultural crops. Thus, in certain years although total seasonal rainfall was low, vegetation-moisture was out-of-stress during the monsoon of 1993 and 1999.

Like rainfall, temperature also affects the growth and health of vegetation in both positive and negative sense. Figure 7 and 8 show that unlike rainfall which shows erratic patterns, temperature follows definite patterns in different seasons. In the Thar Desert, in the monsoon season, temperature increases gradually from south-east to north-west, whereas during the non-monsoon period, temperature gradually varies from north-east to south-west. However, in the drought-years of 1986, 1991, 2000 and 2002, in response to excessively high air-temperature, patterns and intensities of thermal-stress in vegetation of the Thar Desert varied from year to year.

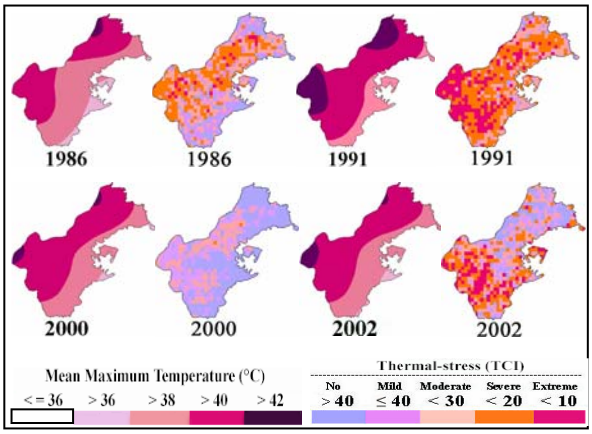

Figure 7: Vegetation thermal condition as indicated by the TCI in response to variation of air-temperature

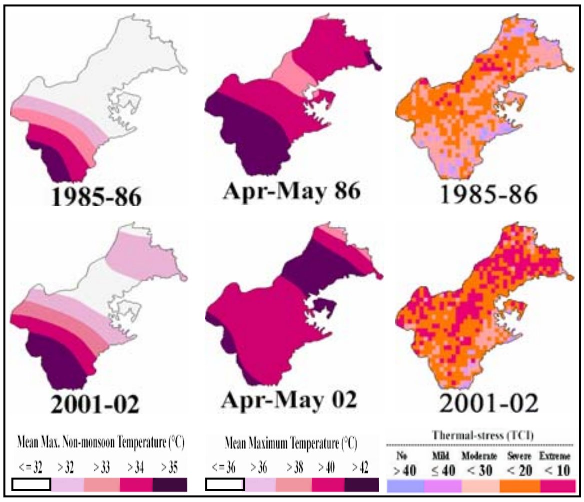

Figure 8: Comparison of spatial patterns of maximum non-monsoonal temperature, maximum summer (April-May) temperature and non-monsoonal TCI.

During the monsoon season, thermal condition in vegetation is governed by both air-temperature and rainfall, whereas during the non-monsoon period, it is supposed to be controlled by air-temperature. Again, the patterns of spatial variation of air-temperature also differ during different months or seasons of the non-monsoon period. The pattern of average above-ground temperature during the pre-monsoon (April and May) varies widely from the spatial pattern of temperature comprising all non-monsoonal months. High temperature of April and May imparts higher stress on vegetation health. Average non-monsoonal TCI has been found to exhibit greater resemblance with the above-ground temperature of immediate pre-monsoon or summer months than average maximum above-ground temperature of the total non-monsoon period (Fig. 8).

The time-series analysis of various vegetation indices infers that vegetation health is sensitive to moisture and thermal conditions, which are governed by rainfall and temperature. Rainfall and temperature follows an inverse pattern, as rainfall causes lowering of both air- and land-surface temperatures.

5. DISCUSSION

The time-series analysis has pointed out the influence and relationship of climatic factors to the vegetation parameters (moisture and thermal conditions), and the probability-plots between rainfall and the VCI and between temperature and TCI reveal the intensity of these relationships.

5.1 Correlation and Factor-influence

The probability-plot between rainfall and the VCI shows that with gradual increase in rainfall probability of higher moisture-condition in vegetation increases in the years (1985, 1986, 1987, 1990, 1991, 2000, and 2002) of severe moisture-stress (Fig. 9). Figure 9 also indicates that there is a great difference in the moisture condition in vegetation receiving less than or equals to 100 mm, from vegetation receiving more than 250 mm rainfall. However, the difference in vegetation moisture is not big at regions with rainfall variation between 101 mm and 250 mm.

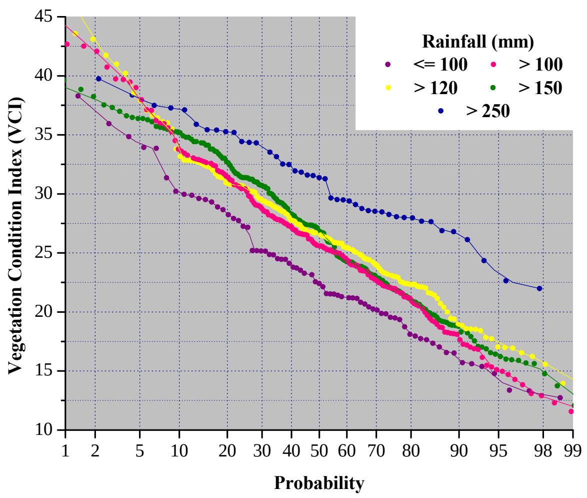

Figure 9: Probability-plot showing a strong positive relation between rainfall and the VCI.

Similarly, when the mean monsoonal TCI of the years of severe thermal-stress (1985, 1986, 1987, 1989, 1991, 2000, and 2002) under different temperature ranges are plotted, it shows that probability of thermal-stress gradually increases with continuous increase of above-ground temperature (Fig. 10).

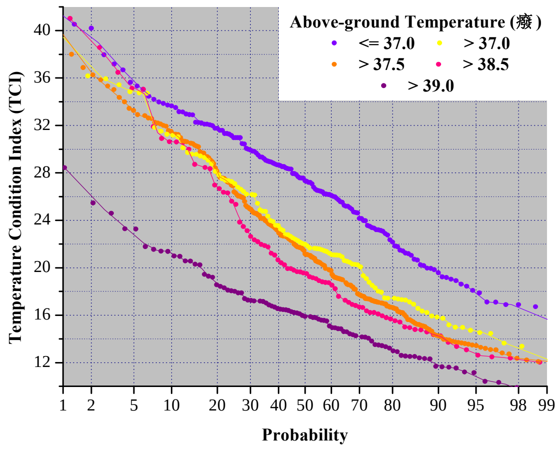

Figure 10: A strong negative relation between above-ground mean maximum temperature and vegetation thermal condition is revealed in the probability-plot.

Figure 9 and 10 show that a big difference in moisture condition in vegetation occurs only with a great variation in rainfall. On the contrary, with a small variation in above-ground temperature (0.5 °C), a big difference in thermal condition in vegetation occurs.

In arid lands, rainfall is seasonal, which affects vegetation directly in the same season and indirectly in the immediate next season through the 'memory effect' (Martiny *et al.* 2005, Philippon *et al.* 2005) and 'recovery effect' (Malo and Nicholson 1990, Martiny *et al.* 2005). Abnormal air-temperature on the contrary may impart stress on vegetation throughout the year. However, rainfall in the immediate previous season also influences the thermal condition of vegetation as was the case during 1990-91 non-monsoon period. Therefore, rainfall controls both the moisture-stress and thermal-stress in vegetation of arid ecosystem.

5.2 Correspondence and Causation

Vegetation is sensitive to both moisture and thermal conditions, and the intensity of moisture-stress and thermal-stress determine the overall vegetation health as well as the drought-impact on vegetation. The VHI represents the combined influence of moisture-stress and thermal-stress on vegetation health, and is found to be an effective drought-monitoring index (Bhuiyan *et al.* 2006)). From the time-series analysis, it has been found that drought resulted and affected the desert vegetation mostly when both moisture- and thermal-stress were generated (years 1985, 1986, 1987, 1989, 1990, 1991, 2000, and 2002) and sometimes due to thermal-stress alone (years 1995). In certain years (1993, 1995, 1996, 1997, 1998, 1999), inspite of high thermal-stress the desert vegetation could avoid drought or reduced drought severity due to adequate moisture supply. Opposite were the cases in the years 1988 and 1994, when excellent thermal condition countered moisture-stress and drought was bypassed. Therefore, it is apparent that presence and supply of moisture is the key to vegetation health. Drought develops in vegetation due to insufficiency of moisture either due to lack of rainfall or due to high heat flow or both. Sufficient and frequent rainfall not only ensures moisture supply in vegetation but also reduces the temperature. Therefore, rainfall is the key to vegetation health and hence to the drought impacts on vegetation.

6. CONCLUSION

Vegetation health as reflected in the seasonal values of vegetation indicates that desert-vegetation responds to the change in rainfall and temperature. Vegetation-response to the climatic factors alters spatially and temporally, depending upon the type of vegetation (natural or agricultural) and intensity of the climatic factors. From the time-series it is clear that air-temperature maintains regular seasonal patterns unlike seasonal rainfall, which is inconsistent and erratic in patterns. Moisture condition in vegetation responds spontaneously to the seasonal rainfall, and indicates a direct correspondence between them. On the contrary, thermal condition in vegetation does not exactly follow the patterns of air-temperature.

The moisture condition and thermal condition in vegetation support and counter one another. Again, when there is a mismatch of moisture-stress and thermal-stress in terms of distribution and intensity, drought appears apparently in a slapdash manner. The time-series analysis of various vegetation indices and the climatic parameters (rainfall and above-ground temperature) has demonstrated and confirmed that the climatic factors govern the vegetation health and the impact of drought on vegetation health. A good correspondence could be found between rainfall and the VCI and between temperature and the TCI. Moreover, the probability-plots revealed that thermal condition in vegetation is more sensitive to above-ground temperature in comparison to the sensitivity of vegetation moisture condition to rainfall, particularly during droughts. However, considering the 'memory effect' and 'recovery effect' in vegetation, which are governed chiefly by rainfall, it could be inferred that supply of moisture to vegetation is the key to defend and counter drought. In this regard, rainfall is the key factor as it ensures moisture supply and also reduces the thermal-stress in vegetation.

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