DROUGHT MONITORING IN INDIA AND THE PHILIPPINES WITH SATELLITE REMOTE SENSING MEASUREMENTS

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ABSTRACT

Droughts are normal recurring climatic phenomena that vary in space, time, and intensity. The spatial and temporal variability and multiple impacts of droughts provide challenges for mapping and monitoring on regional scales. With the launch of new generation sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS), the monitoring of aberrant climatic events may be explored in an efficient way. An empirical method called Temperature Vegetation Dryness Index (*TVDI*) was used for drought monitoring in two different countries. In this paper we demonstrate the usefulness of the *TVDI* approach and of MODIS products for the identification of drought conditions in affected states of India and the Philippines. The satellite derived results reveal that they can detect and monitor the drought accurately. The results were compared with the crop yield for validation of remotely sensed measurements for drought detection. In Gujarat state, the drought years showed a negative yield anomaly as compared to a normal year. The average yield anomaly in 2002 was -11.2 and -35.49 for food grains and oil seeds respectively. This indicates the influence of drought on yields to a greater extent. But in 2003, it gives a positive yield anomaly and indicates no drought effect on crop yields. In Iloilo province, the results revealed that the rice area and the production reduced due to the drought in 2000 as compared to other normal years. Overall, the results imply that the satellite derived drought index (*TVDI*) is a useful tool for the identification of drought affected areas in real time using satellite measurements.

INTRODUCTION

Drought is a natural hazard that impacts economic, social, and environmental aspects of society. In the agricultural sector, it is one of the dominant causes of crop loss. Although a drought first appears as below-average rainfall within a normal part of climate, it can develop as an extreme climatic event and turn into a hazardous phenomenon which can have a severe impact on communities and water-dependent sectors. Droughts are a recurrent feature of the climate, varying in intensity, duration, and frequency across the climatic spectrum. Knowledge about the timing, severity, and pattern of droughts on the landscape can be incorporated into effective planning and decision making. To monitor droughts, decision-makers at the administrative and grass-roots levels need timely and accurate information about the spatial and temporal dimensions of droughts. This information helps officials and farmers to be more proactive in managing drought risks (1). Furthermore, drought impacts can be reduced through better understanding of drought and identifying the appropriate drought indicators for an early warning system. This includes providing decision-makers with timely drought products (e.g., maps and data) that identify the frequency, severity, and spatial extent of droughts.

In the past, climate and meteorological data were the primary sources for drought information used to support decision-making. However, satellite observations have recently proved to be a valuable source of timely, spatially continuous data with improved details for monitoring vegetation dynamics over large areas. Many prior studies of vegetation conditions base analyses on numerical transforms known as vegetation indices (*VI*). These indices have been used for studying vegetation characteristics over large areas since the 1970s (2). Additional studies have presented analyses of droughts in the USA, Africa, South America, and Asia and illustrate how derivatives of the normalised difference vegetation index (*NDVI*) can improve the ability to observe droughts in time-series satellite data (3,4). Remote sensing technology is an economical and promising tool for obtaining land surface parameters. Remote sensing technology used to assess or monitor regional drought is mainly based on an index that is a function of spectral vegetation index or land surface temperature. Wang (5) concluded that drought information is not closely related to *NDVI* data and that a drought index based on *NDVI* should be insensitive to the soil moisture status. A drought index based on land surface temperature (T_s) should be more efficient than those based on *NDVI*. A drought index based on normalised difference vegetation index (*NDVI*) falls short in monitoring a drought because *NDVI* is a rather conservative indicator of water stress, which means that vegetation remains green after initial water stress (6). In contrast, T_s is more sensitive to water stress (7). The combination of *NDVI* and T_s provides information on the vegetation and moisture status. The scatter plot of remotely sensed temperature and spectral vegetation index often exhibits a triangular (8) or trapezoidal (9) shape and is called the *NDVI*-T_s space if a full range of fractional vegetation cover and soil moisture content is represented. In this paper, based on *NDVI*-T_s space, the temperature vegetation dryness index (*TVDI*) has been developed for a drought monitoring approach in drought affected states of India and the Philippines using Terra/MODIS measurements.

MODIS provides a unique opportunity for global assessment and monitoring of vegetation in every eight days at 1 km spatial resolution. The advantage of MODIS data is to develop a prototype for a near real time drought monitoring system at the scale of a country, state, district or pixel with an 8- or 16-day time interval. The results described feed directly into the development of the regional drought monitoring system (10). The objective of MODIS mission is to improve predictions and characterisations of natural disasters like droughts. MODIS is expected to determine the land surface temperature accurately and by integrating MODIS thermal infrared data into land surface monitoring two main problems in current drought monitoring schemes can be addressed. Firstly, accurate temperature observations from remotely sensed data can overcome very coarse spatial resolutions of weather stations at relative low costs. Secondly it can be an appropriate tool for real time drought monitoring, which has not been accomplished successfully by current remotely acquired measures, such as vegetation indices, due to a lagged vegetation response to drought (11).

In this study, an empirical method called Temperature Vegetation Dryness Index (*TVDI*) has been developed for a drought monitoring approach in affected states of India and the Philippines. The sub-objectives of this study are: (a) Mapping drought indices over the western states of India and Western Visayas of the Philippines; (b) to deliver timely geo-referenced information (in the form of maps and data) about areas where the vegetation is impacted by drought.

METHODS

Study area location and drought propensity

The drought affected areas in India and the Philippines have been chosen for the drought analysis using MODIS satellite data. In India, the Gujarat state has been selected for this study which was one of the most drought affected states in recent times. In addition, Assam state in India has also been selected for the drought analysis. In the Philippines, Western Visayas has been selected for timely drought measurements.

Gujarat state is located in the north west of India between 20°01'N to 24°07'N latitude and 68°04'E to 74°04'E longitude (Figure 1). The tropic of Cancer passes through the northern border of the state. The two deserts, one north of Kutch and the other between Kutch and the mainland Gujarat are saline wastes. It covers a total geographical area of 196024 km^2 and accounts for 6.19% of the total area of the country. The climate of Gujarat is moist in the southern districts and dry in the northern region. The year can be divided into: the winter season from November to February, the hot season from March to May, the south-west monsoon season from June to September and the intervening month of October. The average rainfall in Gujarat varies from 33 to 152 cm. The region of Kutch can be described as a desert-like area. In the summer the average temperature is between 25° to 43°C and reaches as high as 48°C. Gujarat is a water scarce region under constant threat of drought, and the availability of water is an ongoing issue of struggle for the people.

Drought being a common occurrence, agriculture fails to support livelihood solely. The incidence of drought has become a regular feature, and any 5-year cycle has 2-3 years of drought.

Assam state is located in the north-eastern part of India between 24°50'N to 28°00'N latitude and 89°42'E to 96°00'E longitude (Figure 1). It is surrounded on all other sides by predominantly hilly or mountainous tracts. During the monsoon the climate is warm and humid. The Brahmaputra river flows through the entire length of the State from east to west. Assam is mainly an agrarian state, 89% of the people live in rural areas. Drought in the northeast of India is an exemption in terms of drought because this area is hit by a flood in nearly every year due to heavy rainfall. The scenario was just opposite in 2006 due to scanty rainfall in most of the districts in Assam.

Figure 1: Location of study area Gujarat and Assam state, India.

The Philippine Republic's Region VI, Western Visayas, comprises six provinces: Negros Occidental, Guimaras, Iloilo, Capiz, Antique, and Aklan. It is located in Central Philippines between two inter-island bodies of water: the Sibuyan Sea and Visayas Sea. Geographically, the region is defined by grid coordinates 121°5'E 123°2'E longitude and 9°25'N 12°12'N latitude (Figure 2). This area is under Region VI, which is an agricultural region. In the Philippines, El Niño events are associated with conditions drier than normal which cause dry spells or even drought. The effects of El Niño can be felt in various sectors of the country: agriculture, environment, water resources, energy and health. The agricultural sector is most vulnerable to drought. Climatological studies showed that major drought events in the Philippines are associated with El Niño occurrences or warm episodes in the central and eastern equatorial Pacific. Provinces in the western portions of the country climate are characterised by two pronounced seasons, dry and wet, with maximum rain period from June to September due to the extension of Southwest monsoon. Seasonal aridity is exacerbated by the increasing incidence of El Niño, which is now occurring at a two to three-year cycle from previous five-year intervals.

Figure 2: Location of study area western Visayas, Philippines.

Satellite data used for remotely sensed measurements

The satellite data we used were Terra/MODIS land surface temperature and surface reflectance. The 8-day composites cloud-free data were downloaded from EOS data gateway during 2000, 2002, and 2006. The MODIS products used for this study are as follows:

a) MOD11A2-LST 8- day composite images (1km resolution)

b) MOD09Q1- Surface Reflectance 8- day composite images (250m resolution)

Land surface temperature (*LST* or T_s)

Land surface temperature (*LST*) is generally defined as the skin temperature of the ground. For the bare soil surface, *LST* is the soil surface temperature; for dense vegetated ground, *LST* can be viewed as the canopy surface temperature of the vegetation; and in sparse vegetated ground, *LST* is determined by the temperature of the vegetation canopy, vegetation body and the soil surface (12). *LST* is a very useful input for modelling energy balance components and mapping evapotranspiration (*ET*). Retrieval of *LST* using thermal IR bands of satellite images is the most effective way to derive energy balance and *ET* on a regional basis. The land surface temperature is an important factor controlling most physical, chemical and biological processes in the Earth.

Vegetation Index

It is a measure of the amount and vigor of the vegetation at the surface. The magnitude of *NDVI* is related to the level of photosynthetic activity in the observed vegetation. In general, higher values of *NDVI* indicate greater vigor and amounts of vegetation. It is defined as:

$$NDVI = \frac{band2 - band1}{band2 + band1} ,$$

where $band2 = 858$ nm and $band1 = 645$ nm.

NDVI is a good indicator of green biomass, leaf area index, and patterns of production (10). *NDVI* was computed using two bands of a surface reflectance image, which varies from -1 to +1.

The MODIS-LST and surface reflectance products were geocorrected using HEGTools and the scale factors were multiplied to all the satellite images. The corrected surface reflectance and LST images were then used for NDVI and TVDI computation.

Temperature Vegetation Dryness Index (*TVDI*)

TVDI is a simple and effective method for regional drought monitoring. In this study, the statistic characteristics of MODIS-*NDVI*, *LST* at different times and locations have been analysed and compared. In the current study, we used MODIS-*NDVI* as vegetation index for *TVDI*.

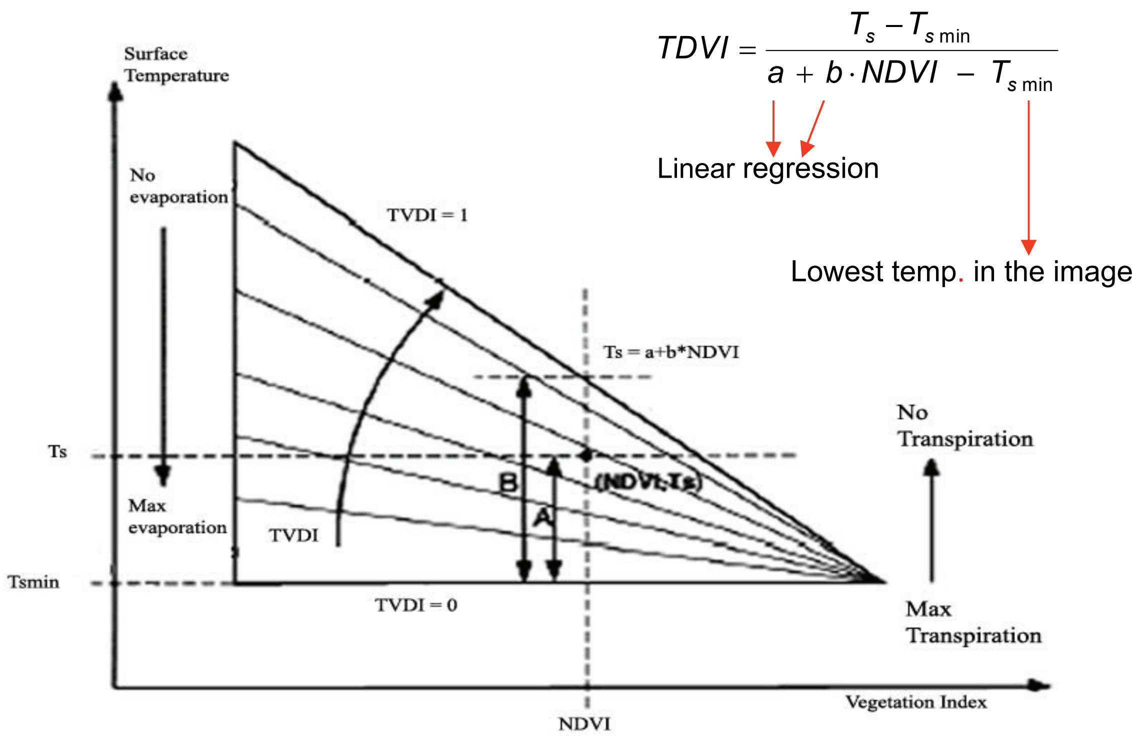

Figure 3: Schematic plot of Temperature vegetation dryness index proposed by Sandholt (6).

Following the concept in Figure 3, isolines can be drawn in the triangle defining the T_s/*NDVI* space. As a first iteration to obtain information on the surface soil moisture content, a dryness index (*TVDI*) having the values of 1 at the "dry edge" (limited water availability) and 0 at the "wet edge" (maximum evapotranspiration and thereby unlimited water access) can be defined:

$$TDVI = \frac{T_s - T_{s\,min}}{a + b \cdot NDVI - T_{s\,min}}$$

where T_{smin} is the minimum surface temperature in the triangle, defining the wet edge, T_s is the observed surface temperature at the given pixel, *NDVI* is the observed normalised difference vegetation index, *a* and *b* are parameters defining the dry edge modelled as a linear fit to data ($T_{smax} = a + b \cdot NDVI$), where T_{smax} is the maximum surface temperature observation for a given *NDVI*. The parameters *a* and *b* are estimated on the basis of pixels from an area large enough to represent the entire range of surface moisture contents, from wet to dry, and from bare soil to fully vegetated surfaces. The uncertainty of *TVDI* is larger for high *NDVI* values, where the *TVDI* isolines are closely set. The simplification of representing the $T_s / NDVI$ space with a triangle in contrast to a trapezoid (e.g., (9)) adds uncertainty to *TVDI* at high *NDVI* values. Likewise, the "wet edge" is modelled as a horizontal line as opposed to a sloping wet edge in the trapezoid approach, which may lead to an overestimation of *TVDI* at low *NDVI* values.

Further this can be written as:

$$TDVI = \frac{T_s - (a_1 + b_1 \cdot NDVI)}{(a_2 + b_2 \cdot NDVI) - (a_1 + b_1 \cdot NDVI)}$$

RESULTS

This study attempts to measure the drought status in Gujarat, Assam state of India and Iloilo province of the Philippines using *TVDI* approach. To evaluate the role of the *NDVI*-T_s relation in drought monitoring, it is necessary to study their sensitivity to *TVDI*. It is computed based on the *NDVI*-T_s space, 2D scatter plot relation for each pixel. The warm edge and cold edge (Table 1) pixels are subjected to linear regression equation and the derived equations are used for computation of *TVDI* using band math in ENVI software, where the land surface temperature (*LST*) and *NDVI* images are used as an input parameter for *TVDI* equations. In Table 1, the day of the year (DOY) is considered for *TVDI* computation for a particular time frame (*e.g.,* 2000 in Iloilo, 2002 in Gujarat, 2006 in Assam) in drought-affected areas in two countries. The critical reproductive period (e.g., 257, 265 DOY) is selected because of its sensitivity to thermal stress. Hence, this index could better represent the drought during the reproductive phase of crops. *TVDI* is more sensitive towards the reproductive stage of the crops than to the early stage of the crops. This is due to the fact that the land surface temperature is more sensitive towards the dryness than to a higher moisture content in the soil, as there is an inverse relationship existing between *LST* and *NDVI*. Goetz (7) reported that the negative correlation between *LST* and *NDVI*, observed at several scales, was largely due to changes in vegetation cover and soil moisture, and indicated that the surface temperature can rise rapidly with water stress.

Table 1: The warm and cold edges in NDVI-T_s space estimated by linear regression for TVDI computation.

Year	DOY	Location	Warm edge($T_{s\,max}$)	R^2	Cold edge ($T_{s\,min}$)	R^2
2002	265	Gujarat, India	-19.581 *NDVI* + 328.03	0.99	2.232 *NDVI* + 298.21	0.90
2006	257	Assam, India	-7.0504 *NDVI* + 308.63	0.95	11.93 *NDVI* + 291.15	0.94
2000	265	Iloilo, Philippine	-6.5064 *NDVI* + 309.78	0.96	4.652 *NDVI* + 290.58	0.91

Spatial pattern of Temperature Vegetation Dryness Index

Gujarat state, India

From Figure 4, it can be noticed that the drought occurred during 265 DOY, 2002 in the northern part of Gujarat state. This is due to the Rann of Kutch desert which is a drought prone area. In the southern part of Gujarat, it can be noticed that drought was absolutely absent; this is due to the agriculture (irrigated conditions) and forest cover in that region. Hence, the *TVDI* value is less than 0.6 in this part of the region, which indicates favourable conditions or no drought. Traditionally, the western part of Gujarat state is called Saurashtra. For the most part, it is a hilly tract sprinkled with low mountains. Particularly this part is very important with respect to agriculture crops. Groundnuts and cotton are the most prominent crops in this region. It was noticed that there was a severe drought (2002) where the *TVDI* values were considered >0.6; as a result it affected the crop yields. In general, it was observed that there was a persistent drought occurrence in the northern part and Saurashtra part of the state. Places where the *TVDI* values >0.8 are considered as severely affected areas whereas areas with values from 0.6-0.8 are considered as moderately affected areas due to drought.

Detrended yield anomaly

The detrended yield anomaly has been computed using historical crop yields data of kharif food grains and oilseeds crop in Gujarat state. The cereals (rice, jowar, bajra, maize, ragi and small millets) and pulses (tur, mung, math, udid and other pulses) belong to food grains and groundnut, sesamum, rape and mustard and castor refer to oilseeds. Crop yield anomaly has been computed using long term crop yield data i.e. from 1981 to 2003. Mathematically, the crop yield anomaly can be represented as:

$$Y_a = \frac{Y_i - Y_t}{Y_t} \cdot 100$$

where Y_a = detrended yield anomaly, Y_i = yield in particular year, Y_t = yield trend for the last 22 years. The yield anomaly has been computed for district level using linear regression where the year 1981 was used as a base year (0) and 2003 was indicated as 22 along the *x*-axis for yield trend analysis in Figure 5. The figure indicates that the yield was increasing due to the technological development in the agriculture sector. The observed correlation was moderate (R^2 = 0.4), which implies the rate of the increased yield trend is slower over the time scale.

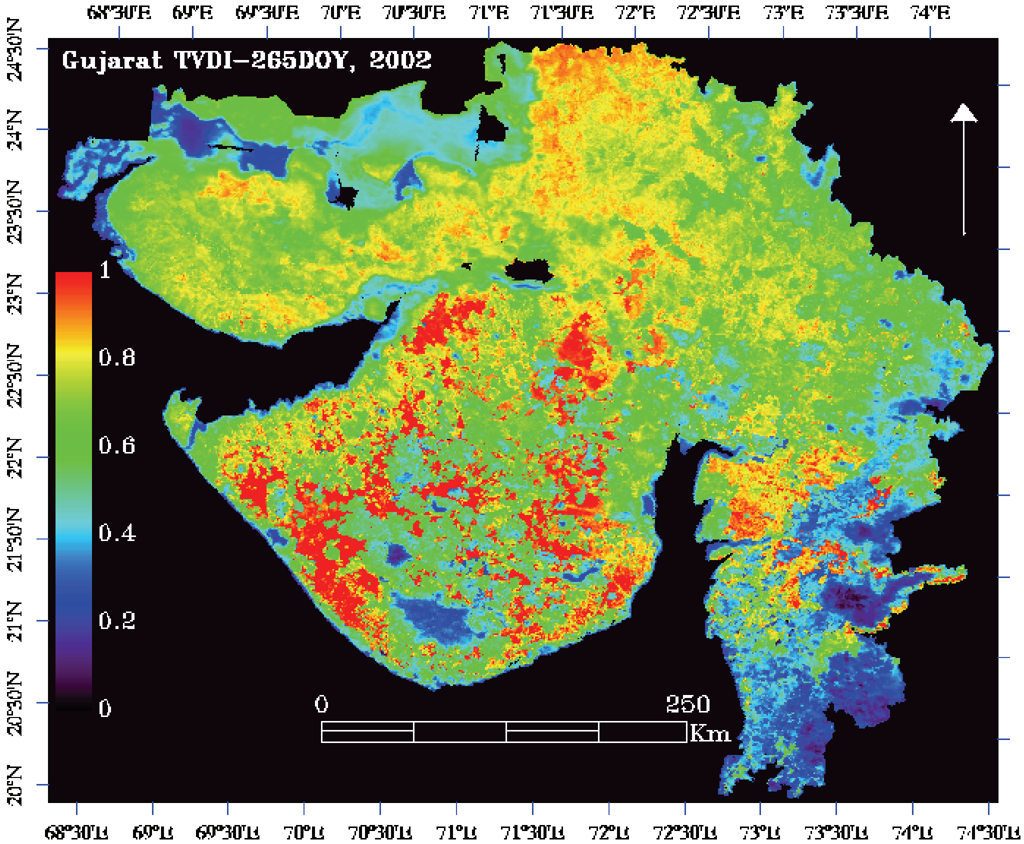

Figure 4: Spatial distribution of temperature vegetation dryness index for Gujarat state.

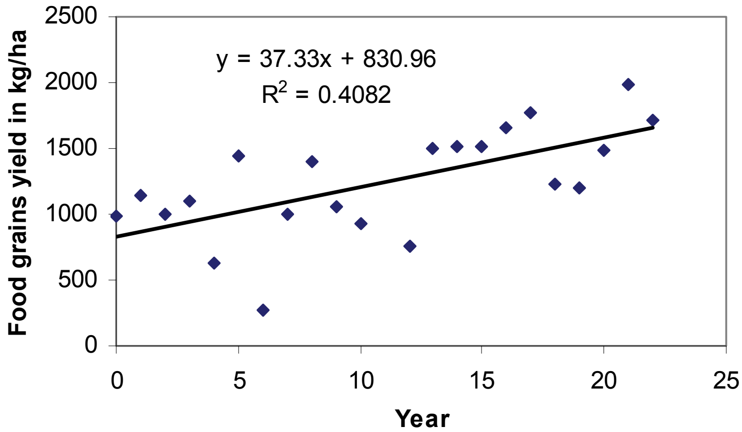

Figure 5: The linear food grains yield trend for Junagarh district from 1981 to 2003.

In Table 2, the yield anomalies for food grains as well as oil seeds are shown for the year 2002 (drought year) and 2003 (non-drought year). The results show that the drought year (2002) gives a negative anomaly for both the food grains and oil seeds whereas the non-drought year 2003 gives a positive anomaly. The average anomaly of -11.2 and -35.49 in 2002 indicates the influence of drought on yields in a greater extent. But in 2003, both food grains and oil seeds yields give the positive yield anomaly and indicate no drought effect on the crop yield. Thus, the above discussed yield anomaly helps to validate the remote sensing based result in the Gujarat state.

Table 2: Detrended food grains and oilseeds yield anomaly for different districts during 2002 and 2003.

Yield Anomaly	Food grains		Oil seeds	
District Name	**2002**	**2003**	**2002**	**2003**
Ahmedabad	-81.79	82.29	-58.96	-48.46
Amreli	15.10	-1.33	-5.52	181.88
Banaskantha	-28.09	364.22	-55.65	-21.88
Bharuch	29.97	43.12	-35.62	9.48
Bhavnagar	32.08	68.58	29.99	66.77
Gandhinagar	-11.06	-22.32	-14.89	-29.17
Jamnagar	-35.35	45.62	-90.58	277.46
Kutchh	-44.81	-91.94	-38.25	84.50
Kheda	-6.02	6.47	-15.61	2.23
Mehsana	5.50	37.16	-10.59	0.86
Panchmahal	53.85	40.24	-40.72	-23.73
Rajkot	-27.60	116.89	-30.59	1082.85
Sabarkantha	-23.14	16.43	-83.65	137.12
Surat	-10.49	-8.27	-63.05	-24.39
Surendranagar	-98.99	44.72	5.58	7.41
Dangs	-23.07	29.59	-23.39	34.95
Vadodara	26.28	40.69	-34.00	193.31
Valsad	-15.67	10.95	-35.57	45.13
Junagadh	23.1	3.6	-56.94	143.70
Average	-11.20	43.85	-35.49	85.15

Assam state, India

A drought in the northeast of India is a contradiction in terms. The flood-prone northeast region of India is reeling under a severe heat wave with scanty monsoon rains affecting agriculture. Compared to the mean average monsoon rains, Assam has received about 30% less rainfall in 2006. The cumulative rainfall during the monsoon in northeastern India has decreased significantly. District-wise distribution in the region also shows that a number of districts were seriously affected but some districts were hit badly, such as Jorhat, Morigaon, Nowgong, and Sonitpur in Assam. A severe drought-like situation affected 14 districts of Assam with the rainfed paddy fields going dry due to a deficit in monsoon rains and most of the irrigation systems lying defunct in the affected districts.

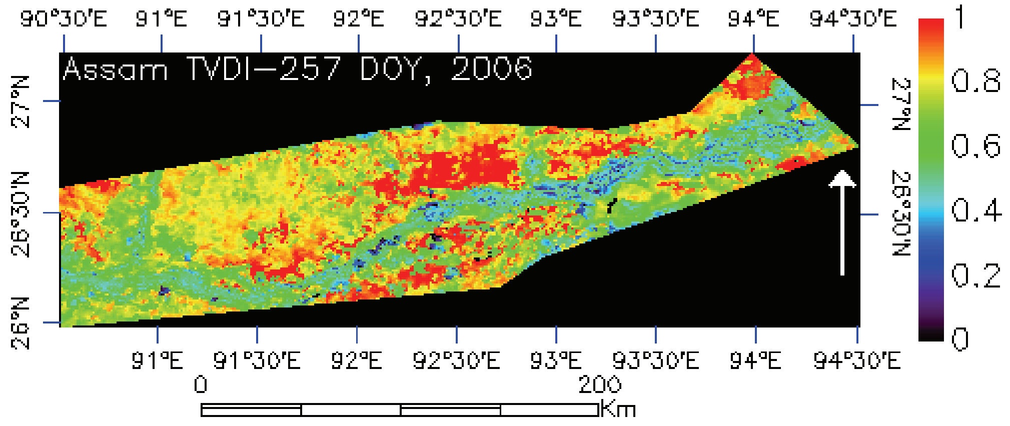

Figure 6: Spatial distribution of temperature vegetation dryness index for Assam state.

From Figure 6, it can be noticed that the upper Assam and central Assam districts were badly affected by the drought during 257 DOY, 2006. As a consequence it has a direct impact on agriculture crop yields in the state. The results based on the *TVDI* approach suggest that there are accurate geographical positions of drought areas where vegetation was mainly affected, although there are no available crop yield data for validation in Assam state.

Iloilo province, Philippines

From Figure 7, it can be noticed that some municipality areas were badly affected by drought due to scanty rainfall and poor vegetation especially by agriculture. The rice crop is the sole agriculture crop in this province. The farmers' economics and livelihood depend on this crop but due to the drought in 2000, the crop yields were affected in this province. It can be noticed that the *TVDI* values are higher than 0.6 in some municipality areas which is an indication of drought.

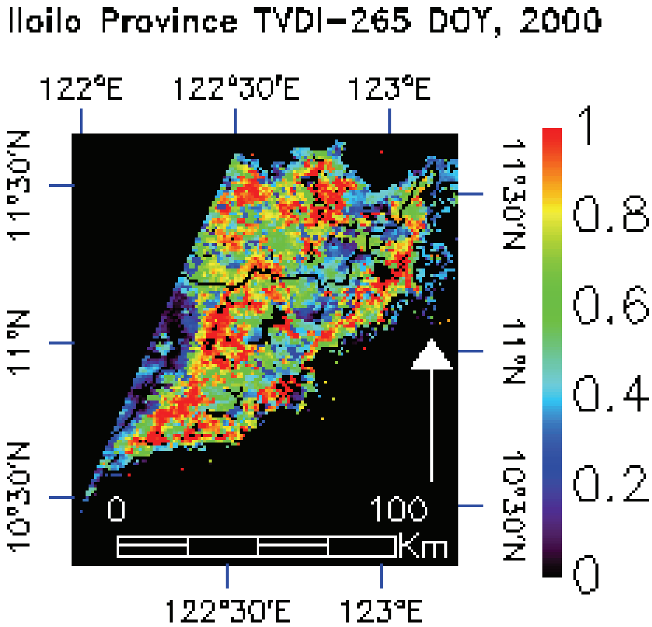

Figure 7: Spatial distribution of temperature vegetation dryness index for Iloilo province.

Impacts of drought on rice yield

In Table 3, the results reveal that the total production and the area decreased in 2000 as compared to 1999 and 2002-03. The maximum production was in 2003 i.e. 444139 metric tons whereas the minimum production was in 2000 i.e. 300909 metric tons. The crop yield dropped in 2000 by drought to some extent as compared to 2002-03. It was observed that the production in 2000 was lower than the average rice production from 1990-2005 (320750 metric tons) in the province. The year 2003 brought the highest yield followed by 2002. The years 2002-03 show that the production was not affected by drought due to normal and favourable conditions in the province. Thus, the above results can validate the remote sensing approach for accurate drought measurements in the Philippines.

Table 3: The agriculture statistics for rainfed agriculture for Iloilo province from 1999-2003 (Area in ha, production in metric tons).

Year	Area (ha)	Production (tons)
1999	117284	318145
2000	97451	300909
2001	112678	370095
2002	127245	426423
2003	119432	444139

Using the satellite derived drought index *TVDI*, it is possible to demarcate the drought occurrence on a regional level for a specific time. The spatial pattern of drought can be represented for every 8-day basis using this approach. The result shows that *TVDI* could be the better approach for monitoring the relative drought occurrences and for studying the spatial pattern of drought occurrences in a specific region. It helps to capture the variation of drought at a specific site and better during the later part of the crop growth.

CONCLUSIONS

MODIS provides a unique tool for global assessment, monitoring of vegetation and for a near real time drought monitoring system at regional level. A drought index based on T_s should be more efficient than those based on *NDVI* only. Based on *NDVI*-T_s space, a *TVDI* approach has been developed for drought monitoring in drought affected states of India and the Philippines using Terra/MODIS measurements. In this study, the drought affected areas in India and the Philippines have been chosen for real time drought analyses using MODIS products. In India, the Gujarat and Assam state have been selected for measurements whereas in the Philippines, Western Visayas has been selected for drought measurements. The results show that *TVDI* could be the better approach for monitoring the drought occurrences, preparing drought maps on a regional level and for studying the spatial pattern of drought occurrences in a specific region. The study has found that TVDI is more sensitive towards the reproductive phase of the crops. This is due to the fact that the land surface temperature is more sensitive towards the dryness than to a higher moisture content in the soil. The crop yields in both countries have been used to validate the results obtained from remotely sensed measurements. We have found that the crop yields decreased due to drought by comparing them with the yield of a normal year and by using the yield anomaly index. Thus, the study has found that *TVDI* is more useful for accurate timely drought mapping and monitoring in the state. It is also possible to deliver timely geo-referenced information (in the form of maps and data) about areas where the vegetation is impacted by drought in the state or provinces. The study recommends that the physical model like SEBAL should be used together with a remote sensing approach for timely drought detection and high spatial and temporal information.

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REFERENCES

1 Wilhite D A, 2000. Drought as a natural hazard: Concepts and definitions (Chapter 1, pp. 3-18). In: Drought: A Global Assessment, Volume 1, edited by D A Wilhite. Natural Hazards and Disasters Series (Routledge Publishers, London, UK)

2 Rouse J W, R H Haas, J A Schell & D W Deering, 1974. Monitoring Vegetation Systems in the Great Plains with ERTS. Proceedings, Third Earth Resources Technology Satellite-1 Symposium, Greenbelt: NASA SP-351, pp. 3010-3017

3 Kogan F N, 1995. Application of vegetation index and brightness temperature for drought detection. Advances in Space Research, 15(11): 91-100

4 Unganai L S & F N Kogan, 1998. Drought monitoring and corn yield estimation in Southern Africa from AVHRR data. Remote Sensing of Environment, 63: 219-232

5 Wang C, S Qi, Z Niu, & J Wang, 2004. Evaluating soil moisture status in China using the temperature-vegetation dryness index (TVDI). Canadian Journal of Remote Sensing, 30(5): 671-679

6 Sandholt I, K Rasmussen & J Anderson, 2002. A simple interpretation of the surface temperature/vegetation index space for assessment of the surface moisture status. Remote Sensing of Environment, 79: 213-224

7 Goetz S J, 1997. Multi-sensor analysis of NDVI, surface temperature and biophysical variables at a mixed grassland site. International Journal of Remote Sensing, 18: 71-94

8 Carlson T N, R R Gillies & E M Perry, 1994. A method to make use of thermal infrared temperature and NDVI measurements to infer soil water content and fractional vegetation cover. Remote Sensing Reviews, 9: 16–173

9 Moran M S, T R Clarke, U Inoue & A Vidal, 1994. Estimating crop water deficit using the relation between surface air temperature and spectral vegetation index. Remote Sensing of Environment, 49: 246-263

10 Thenkabail P S, M S D N Gamage & V U Smakhtin, 2004. The use of remote sensing data for drought assessment and monitoring in Southwest Asia. Research Report Series Vol. 85, International Water Management Institute (Colombo, Sri Lanka) http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub085/RR85.pdf (last date accessed: 18.06.2008)

11 Park S, J J Feddema & S L Egberts, 2004. MODIS land surface temperature composite data and their relationships with climatic water budget factors in the central Great Plains. International Journal of Remote Sensing, 26(6): 1127-1144

12 Qin Z & A Karnieli, 1999. Progress in the remote sensing of land surface temperature and ground emissivity using NOAA-AVHRR data. International Journal of Remote Sensing, 20: 2367-2393