Analysing the effect of severity and duration of Agricultural drought on crop performance using Terra/MODIS Satellite data and Meteorological data

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January, 2006

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by

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Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation with Specialisation in Hazard & Risk Analysis.

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Abstract

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. The livelihood of the rural population is predominantly dependent on agriculture, which is highly dependent on South West monsoon. Drought being a common occurrence, agriculture fails to support livelihood solely. The combination of both remotely sensed land surface reflectance and thermal properties from Terra MODIS gives importance on changes in both land surface temperature and NDVI over a region in real world. This study used remote sensing satellite data to examine the relationship between NDVI-Ts space and NDVI- ΔT space for deriving satellite based the real time agricultural drought monitoring indices. The study found VTCI and WDI is an index, which has capable to identify the drought stress in a regional scale. It has been observed that the slope is negative for warm edge where as slope is positive for cold edge based on NDVI-Ts space relation. The R^2 values for all dry and wet edges are in general varying between 0.90 and 0.99. The slope obtained from NDVI-ΔTs space relation for dry line is negative where as the slope obtained for wet line is positive. In this study the role of satellite derived index for drought detection has been exemplified by integrating meteorological derived index called crop moisture index. Crop moisture index has been computed from last 25 years meteorological data. A critical analysis of satellite derived indices has been done by relating with crop moisture index for establishing the threshold VTCI and WDI values. The Linear regressions between VTCI and WDI with CMI were done for all the year from 2000 to 2004. The temporal observations of VTCI and WDI were linearly regressed against corresponding CMI for each year. Despite R square value of coefficient of determination is less the relationships are significant. The Significant F change result shows for all linear regression equation are less than 0.02 (P at 0.05 level) and hence all the equations for defining the threshold values are significant. The present research found that by integrating Terra MODIS satellite data with meteorological data the VTCI threshold value for drought stress is varying from year to year, which is depending upon the in situ data. The results remark that the integration of both meteorological data and satellite data for identifying the drought stress has an importance to set the threshold VTCI values or WDI values. VTCI is time dependent and usually region specific. This has been used for drought monitoring at a regional level for specific time period during 2000 to 2004 for crop growing period especially for later period of the crop (241-297JD). The temporal variation of drought gives the drought pattern changes over the time. The study realised the presence of clouds in satellite images is a significant obstacle to VTCI and WDI approach for early stage of the crop. Due to this crop moisture index and NDVI has been used in early stage of the crop for identifying the drought stress and VTCI and WDI has been used for late stage of the crop. The ability of VTCI to detect drought stress has been verified by relating the VTCI based drought duration with crop yield. The result observed that as duration of stress in 8 days basis increasing the crop yield decreasing. The drought monitoring at regional scale can be logically conclude that present research gives high spatial information content of the satellite data, which allows for accurate mapping of the spatial extent of drought conditions and temporal variation of drought stress over time and space.

This study also attempted the PS-n model based physical drought (cfH2O) and crop yield simulation for Saurashtra region of the Gujarat state. This approach used to know the physical drought persistent and simulation of crop yield in that region. Further this simulated crop yield has been compared with the actual crop yield to know the yield gap and to determine the effects of drought on crop productivity. The result shows that the simulated yield and the actual yield are highly correlated (R^2 = 0.93 and RMSE = 46.9 kg/ha) and the RMSE observed between actual and simulated yield of groundnut was 46.9 kg/ha, which is about 4.58% of average actual yield (1023.6 kg/ha). To evaluate the relation between PS-n simulated yield and the drought stress, the simulated yield has been relate with the groundnut yield departure from normal. It was observed that in the year 2000 the yield departure was less than 1, which indicates the drought effect on crop performance. Similarly during 2002 there is drought stress and has impacts on groundnut crop yield. The yield departure is more than 1 for all five districts in Saurashtra part during 2003 which implied that there were no drought impacts on crop performance. The simulated yield and yield departure has been correlated and it has been observed that the strong relation (R^2 =0.87) exist between simulated yield and yield departure from normal. It has been concluded that there is a significant change in crop performance especially groundnut yield due to drought during 2000 and 2002 as compared to drought during 2003.

Keywords: Terra MODIS, Land surface temperature, NDVI, VTCI, WDI, NDVI-Ts space relation, NDVI-ΔT space relation, crop moisture index, temporal variation, spatial extent, cfH2O ,PS-n, yield

Acknowledgements

I am greatly indebted to Indian institute of remote sensing, Dehradun for giving the opportunity to follow the M.Sc. course with collaboration with International Institute for Geo-information Science and Earth Observation(ITC),The Netherlands.

My foremost thank goes to my thesis supervisor Dr. N.R. Patel, whose encouragement and stimulating support helped me to shape my research skills, providing assistance during data collection in the field. His valuable feedback contributed greatly for successful complete of dissertation. I thank him for his endurance, creative thoughts and energetic working mode that influenced me greatly insights. I also thank Dr. S.K. Saha, who advised me in various aspects of my research, time to time suggestion, guidance and critical comment for improving the research.

I am deeply indebted to my supervisor M.Sc.Ir.V.Venus, for scientific advice and encouragement for this research. His valuable feedback, illuminating guidance and support especially for the conceptualization of the research helped me to improve the dissertation in many ways.

I profess my thanks and regards to Dr. V. Hari Prasad and Dr. Cees van Westen (Programme Coordinator, in Master of Science in Geoinformation Science and Earth Observation with specialization in Hazard & Risk Analysis) for extending all feasible facilitate throughout my entire study period. I am delighted to express my gratitude to Dr. V.K. Dadhwal, Dean, IIRS, for benevolent motivation towards scientific research and for providing the provision necessary facilities during the project work.

I can never forget to mention my friends for the support, help, appreciation and immensely valuable suggestions during my study. Especially, I would like to give my special thanks to my friends Oinam Bakim Chandra, Brijesh Gulati, Aditi Sharma, Parul Chopra, Rasmi Kandwal, Sushil Dubey and all GID and HRA friends for their cooperation. I would like to express my gratitude to all those who gave me the prospect to complete this thesis fruitfully. I thank my parents for always being there when I needed them most, and for supporting me through all these years.

Bikash Ranjan Parida
Dehradun, India
January, 2006

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List of Abbreviations

MODIS: Moderate Resolution Imaging Spectrometer
EOS: Earth observing system
VTCI: Vegetation temperature condition index
WDI: Water deficit index
CMI: Crop moisture index
PDSI: Palmer Drought Severity Index
CWSI: Crop Water Stress Index
SPI: Standardized precipitation index
NDVI: Normalised difference condition index
SVI: Spectral vegetation index
TVDI: Temperature vegetation dryness index
VCI: Vegetation condition index
TCI: Temperature condition index
LST: Land surface temperature (Ts)
Ta: Air temperature
ETR: Actual evapotranspiration
ΔT: Ts-Ta
cfH2O: coefficient of water sufficiency index
GDP: Gross domestic product
K: Kelvin
JD: Julian days
HDF: Hierarchical Data Format
PS-n: Production situation
RMSE: Root mean square error
RD=Relative deviation

1. Introduction

1.1. General Background

Drought is an elusive climatic event and it is one of the surface processes hazard called exogenic hazard. It is a 'creeping' disaster because droughts develop slowly and have a prolonged existence, sometimes over many years. However the outcome of a drought related disaster could be wide spread and devasting. It is one of the most adverse natural calamities which is called 'life killer'. When there is drought, there is no drinking water for animals and for plant growth in the area. Drought is considered as a slow poison, no one knows when it creeps in, it can last any number of days and its severity cannot be predicted. It is a part of the earth's climate. It occurs every year with no warning, without recognizing borders or economic and political differences. Among all natural disasters, drought affects the largest number of people. During 1967-91; drought affected 51% of the 2.8 billion people who were affected by natural disasters (Obassi, 1994). During the same period, 3.5 million people perished and 45% of them from drought. Drought also related to the timing that is principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stage and the effectiveness of the rains (i.e.; rainfall intensity, number of rainfall events). Other climatic factors such as high temperature, high wind and low relative humidity are often associated with drought and can significantly influence the severity of drought as well as duration of drought. Droughts are recurring climatic events, which often hit South Asia, bringing significant water shortages, economic losses and adverse social consequences. In the last 20 years, increasing population has added to the growing demand for water and other natural resources in the region. The latest drought in South Asia (2000–2003) affected more than 100 million people, with severe impacts felt in Gujarat and Rajasthan States in western India, in Pakistan's Sind and Baluchistan provinces, as well as in parts of Iran and Afghanistan. Existing drought monitoring and declaration procedures (e.g., in India) lag behind the development of drought events. Traditional methods of drought assessment and monitoring rely on rainfall data, which are limited in the region, often inaccurate and, most importantly, difficult to obtain in near-real time. In contrast, the satellite-sensor data are consistently available and can be used to detect the onset of drought, its duration and magnitude (Thiruvengadachari and Gopalkrishne, 1993). The formation and intensity of drought are gradual and cumulative processes, which occur so slowly that they are not easily discerned. The damage to the environment was extensive and the death toll of livestock and wildlife was unprecedented (Wilhite, 1993). Because of the increasing cost of mitigation, recent droughts have attracted government's attention to drought monitoring, occurrences, frequency, duration, advance warning, prediction, impact assessment and management to help mitigate its adverse impacts (WMO, 1994).

Drought produces a complex web of impacts, which spans many sectors of the economy, especially agriculture sector. This complexity leads to lowering down the food grain production due to poor crop performance and this depends upon the intensity and duration of drought stress. Severe drought is currently affecting vast areas of western India, which includes Rajasthan and Gujarat state. This state commonly considered to be the most affected by the drought. The frequent occurrence of drought in these regions is due to poor and untimely monsoon, abnormally high temperature especially in the summer and various other unfavourable meteorological conditions. Over the years farmers experience the worst ill effect of drought in this region in terms of their loss of crop yield and sometimes crop failure due to scarcity of water during peak growth stages of the crop. India is an agrarian country where agriculture is the backbone of Indian economy and in contrast 68% of the total net sown area (144mha) is prone to drought out of which 50% is severely drought prone. The magnitude of this is well understood from the fact that India is an agricultural country with 65% of its population directly depending on agriculture for their livelihood. In spite of significant advances since independence to bring more area under sustainable irrigation and the development of new high yielding crop varieties, Indian agriculture is highly dependent on monsoon rainfall. Owing to the abnormalities in monsoon precipitation in terms of both spatial and temporal distribution, drought is a frequent phenomenon over many parts of the country. Currently although India is self-sufficient in terms of food grain production to feed 1.2 billion populations, still there is hue and cry in terms of stability of food grain production as a result of crop failure. Drought is one of the utmost important disasters which cause instability in food production and on the other hand monitoring of drought is indispensable to understand the complex phenomena in the nature. Now it is the concern of any planner to understand and plan accordingly to face the complex phenomena of drought. Hence drought monitoring is one of the important concerns to Indian agriculture for understanding the complexity in food security and trade as a whole.

1.2. Regional drought monitoring-drawbacks of meterological drought indices

There is no universal definition of drought. Definitions have been classified as conceptual and operational. Conceptual definition is a general term, it makes easier for people to understand the concept of drought and it is important in establishing drought policies. Operational definitions are important because they attempt to determine the onset, severity, spatial extent, and end of drought conditions. Operational definitions help in specifying the degree of departure from average of precipitation over a time period and this can be done by comparing the current conditions with historical climatic data, usually over a 30-year period of data. This definition used when dealing with agriculture, to tell things such as the impact the drought is having on crops and the rate of soil depletion. Drought severity, frequency, and duration for a historical period can be established operationally, but requires weather data from various time scales (such as hourly, daily, monthly, etc). This information is extremely useful in the formulation of mitigation strategies (National Drought Mitigation Center). Many indicators and indices of drought exist and these may disagree as to the severity of drought conditions. Commonly used drought indices in the U.S. include the Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), and Standardized Precipitation Index (SPI). Each of these indices has recognized strengths and weaknesses. Indices are often used to trigger both response and mitigation programs by local, state, and federal government. The PDSI, a meteorological drought index, was the first comprehensive drought index developed in the United States (Palmer, 1965). The PDSI provides a measure of the departure from normal of the moisture supply. The CMI is an indicator of soil moisture in the topsoil. The SPI is a simple calculation solely based on rainfall with a temporal flexibility that is theoretically much better suited to the quicker responses in vegetation detected by satellite imagery. It is a statistical measure on the surplus or lack of precipitation during a given period as a function of the long-term average precipitation (McKee, 1994). Whereas drought indicators may assimilate information on rainfall, stored soil moisture, or water supply, typically they do not express much local spatial detail (that is, one value may be used to indicate climate conditions over an entire county). Alternatively, drought indices may also be calculated at one location where the input data are collected (that is, a climate station). This information is spatially discrete but only valid for a single location. Thus, a significant drawback of climate-based drought indicators is their lack of spatial detail. In addition, meteorologically based indices are dependent on data collected at weather stations. Some areas have very sparsely distributed stations and this affects the reliability of the drought indices. Recently, it has become clear that no one indicator or index is adequate for monitoring drought on a regional scale; instead, a combination of monitoring tools integrated together is preferable for producing regional or national drought maps (Brown, 2002).

There are five perspectives is classified on the basis of the nature and severity of the impacts and they are meteorological, hydrological, agricultural, socio-economic and ecological drought. Agricultural drought is given a prime focus in this study in lieu of other types of drought. Agricultural drought refers to a situation in which the moisture in the soil is no longer sufficient to meet the needs of the crops growing in the area. Focus is placed on precipitation shortages, reduced ground water/reservoir levels, differences between actual and potential evapotranspiration, and so on. Drought is a protracted period of deficient precipitation resulting in extensive damage to crops and loss of yield. A good definition of agricultural drought should be able to account for the variable susceptibility of crops during different stages of crop development, from emergence to maturity. Deficient topsoil moisture at planting may hinder germination, leading to low plant populations per hectare and a reduction of final yield. The water demand of a crop depends on weather conditions (such as temperature, relative humidity), its biological make-up, what stage of growth the crop is in, and the physical/chemical make-up of the soil. However, if topsoil moisture is sufficient for early growth requirements, deficiencies in subsoil moisture at this early stage may not affect final yield if subsoil moisture is replenished as the growing season progresses or if rainfall meets plant water needs. Based on time of occurrence of drought and general climatic conditions, the agricultural drought is characterised into five distinct categories in India. This is classified as early season drought, mid season drought, late season drought, apparent drought and permanent drought.

1.3. Remote sensing and drought stress

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 [Feng, 2001, Idso et al.1981, Jackson et al.1981]in (Wang, 2004) and Wang et al.2004 concluded that drought information is not closely related to NDVI data and that a drought index based on NDVI should be insensitive to soil water status. A drought index based on Ts should be more efficient than those based on NDVI. A drought index based on normalized difference vegetation index (NDVI) falls short in monitoring drought because NDVI is a rather conservative indicator of water stress, which means that vegetation remains green after initial water stress (Sandholt, 2002). In contrast, land surface temperature (Ts) is more sensitive to water stress (Goetz, 1997). In fact canopy and surface radiation temperature have been suggested as water stress indicators since the early 1960s [Tanner, 1963] and have been popularised since the early 1980s (Jackson, 1981). Temperature as a water stress indicator is based on a relationship between leaf temperature and transpiration. Generally, as transpiration rate is reduced owing to plant water deficit, leaf temperature rises relative to air temperature (Wang, 2004). The combination of NDVI and Ts provides information on the vegetation and moisture status. The scatter plot of remotely sensed temperature and spectral vegetation index often exhibits a triangular (Carlson, 1994) or trapezoidal (Moran, 1994) shape and is called the NDVI-Ts space if a full range of fractional vegetation cover and soil moisture content is represented. The NDVI-Ts slope was related to land surface evapotranspiration rate (Boegh, 1998) and can be used to estimate air temperature [Prihodko and Goward, 1997] in (Wang, 2004). (Boegh, 1998) decomposed the remotely sensed temperature into canopy temperature and soil surface temperature based on the NDVI-Ts relation for certain vegetation types when the canopy is sparse. Stomata resistance and evapotranspiration rate have been related to NDVI-Ts slope [Nemani and Running, 1989] and the slope has also been used to evaluate soil moisture status [Goetz, 1997, Goward et al. 2002,Fried and davis, 1994, Smith and Choudhury, 1991] in (Wang, 2004).

1.4. Advantages of MODIS for drought monitoring

MODIS provides a unique opportunity for global assessment and monitoring of vegetation phenology and productivity 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 (Thenkabail, 2004). The objectives of MODIS mission is to improve predictions and characterizations of natural disasters like droughts and as a next generation scientific satellite sensors, MODIS has particular advantages over NOAA AVHRR for land surface temperature detection and biomass estimation. On the other hand MODIS has more finely defined visible and near infrared bands then NOAA AVHRR and it has one of the most accurate calibration subsystems ever flown on a remote sensing instrument. The calibration allows the raw brightness values to be converted into true percentage reflectance or radiance measurements (Wan, 1999). MODIS has a higher radiometric resolution than other sensors. It uses 12 bits for quantization in all bands as compare to AVHRR’s 10 bits. Taking advantage of these characteristics, MODIS is expected to determine land surface temperature accurately and by integrating MODIS thermal infrared data into land surface monitoring can address two main problems in current drought monitoring schemes. First, accurate temperature observations from remotely sensed data can overcome very coarse spatial resolutions of weather stations at relative low costs and secondly it can be an appropriate tool for real time drought monitoring, which has not been successfully accomplished by current remotely acquired measures, such as vegetation indices, due to a lagged vegetation response to drought (Park, 2004). In addition to this the data (version 4) has been validated by NASA for scientific usages meaning that product quality is improved compared to earlier versions. MODIS provides in total 44 standard products to scientists. These products cover the fields of oceanography, biology and atmospheric science. For this research land surface temperature and surface reflectance products are used.

1.5. Drought severity and duration

Droughts are a recurrent feature of the climate, varying in intensity, duration, and frequency across the climatic spectrum. A drought can have substantial economic, environmental, and social impacts and it produces a large number of impacts that affects the social, environmental, and economical standard of living. The characteristics of droughts are expressed in terms of drought index, intensity-duration-frequency. The relations between drought intensity, duration and frequency can be studied with conceptual models, which deal with meteorological droughts lasting at least one year, with specific applicability to subtropical and midlatitudinal regions. The severity of a drought depends upon its nature (whether agricultural, hydrological, or ecological). The overall impact of a drought event depends on several factors, including severity, frequency, area, and duration (Dracup, 1980). Several drought indices have been defined for the characterization of drought severity over time. The timing of drought is important. Short but intense droughts that occur in the growing season typically have a significant impact on agriculture. Fundamental descriptors of droughts include their intensity and duration (Dracup, 1980). Duration can be defined as the number of consecutive time steps that the time series (of soil moisture or runoff) is below a specified threshold level [Byun and Wilhite, 1999] in (Andreadis et al.), intensity as the averaged cumulative departure from the threshold level for that duration, while severity is defined as the product of intensity and duration (cumulative departure from the drought threshold). Because droughts are regional phenomena that can cover large areas for long periods of time, the spatial extent of a drought is an equally important feature. On the other hand, droughts that start in the fall and end in the spring may have minimal impact since they occur in the time of year when the demand for water by both man and the environment are low.

1.6. Motivation and Scientific problem

As compared to other natural disasters like tsunami, cyclone, flood, the nature and impact of drought are more difficult to assess, as it effects are pervasive encompassing all the resources in the region. It has extensive spatial dimension. The problem associated with drought is a recurrent feature in India. It starts at any time of the year but it has a greater impact on agricultural plant growing season and it affect the crops according to the degrees of severity. Drought is perennial feature in some states of India. 16% of the country's total area is drought prone and approximately 50 million people are annually affected by droughts. In fact drought is a significant environmental problem too as it is caused by less than average rainfall over a long period of time. In India about 68 percent of total sown area of the country is drought prone. Most of the drought prone areas identified by Govt. of India lies in the arid, semi arid and sub-humid areas of the country. Thus it has serious impacts on regional food production, destruction of ecological resources, huge economic losses, food shortages and starvation of millions of people. The Indian peasantry, the largest surviving body of small farmers in the world, is currently facing an epidemic of suicide. Therefore it is serious issue to any state authority to know the complexity nature of drought.

Low rainfall during the last two years has caused severe drought conditions in 11 Indian States. An estimated 130 million people - 15 percent of the population - in more than 70,000 villages and 230 urban centres are at risk. Apart from economic loss due to low agricultural production, loss of animal wealth, inadequate nutrition and primary health care, the impact of the drought is likely to retard the development process. The most severely affected States are Gujarat, Rajasthan and Andhra Pradesh. UNICEF is seeking US $3.575 million in funding in support of relief efforts to help an estimated population of 60 million people in the five worst affected states (Drought disasters). Occurrences of drought translate into a fall in growth of Indian economy, since agriculture constitutes about 25 per cent of GDP, a four percentage point decline in agricultural production should directly translate into a one percentage point decline in GDP growth. These linkages were very strong in the past. In the period before the 1990s droughts were accompanied by a drop in GDP growth. The economy did not grow slowly only in that year, it continued to grow slowly even beyond that year into the next year. The hit to the economy was enormous. Annual GDP growth became negative in four years: 1957-58, 1965-66, 1972-73 and 1979-80.

Many drought indices have been used for drought monitoring in India. Among the different indices few indices are used for drought monitoring on weekly basis like crop moisture index (CMI), sometimes PDSI. On the other hand the RS data has benefits of the synoptic view and large-area coverage which helps in obtaining the proverbial "bird's eye-view" of the features and there is a good scope to study the drought using new generation scientific satellite data like MODIS. A lot of studies carried out using NOAA AVHRR data for monitoring drought. Most previous applications of NOAA-AVHRR data for drought monitoring were based on Vegetation Condition Index, Temperature Condition Index, and/or Anomaly Vegetation Index, which extracted from AVHRR derived Normalized Difference Vegetation Index (NDVI) and brightness temperature data. These indices were often applied to monitor drought occurrence at a large scale or a regional level by comparing the indices in inter annual changes for a specific period of the covering years. However, drought occurrences over a region have spatial and temporal variations. Thus, it becomes critical to monitor the relative drought occurrence distributions over a region at a time. EOS Terra and Aqua has the highest number of spectral bands (36 bands) of any global coverage moderate resolution imager. Its advantages can be concluded as follows: Suitable temporal resolution, higher spectral resolution and better spatial resolution. Therefore, a challenge we are facing now is how to produce some suitable spectral indices so as to take the prime advantages of continuous spectra provided by hyper spectral remote sensed data, instead of confining to the vegetation feature within red and NIR spectral range as the broad-band vegetation indices do. Unlike the conventional satellite based drought monitoring using NDVI, the vegetation temperature condition index (VTCI) which integrates both sensitivity of vegetative growth to soil moisture availability and reproductive growth to thermal condition. VTCI involves the normalised difference vegetation index and land surface temperature and thus becoming more acceptable for drought monitoring. This can be used for monitoring daily basis, eight days composite basis or sixteen days composite basis but due to inherent cloud cover in satellite data, it makes difficult to study. Similarly water deficit index (WDI) also a very important satellite based metrics for drought monitoring, which depends upon NDVI and temperature difference that is Ts-Ta. A very large and obvious research gap is the absence of holistic studies pertaining to the phenomenon of drought and in spite of many studies, quantifying drought intensity and duration continues to be a problem. The present study focuses on monitoring of drought considering the meteorological aspects, remote sensing satellite based indices and crop growth simulation model for quantification of its intensity and duration.

1.7. Research objectives

1. To demonstrate the use of Vegetation Temperature Condition Index (VTCI) and Water Deficit Index (WDI) derived from MODIS satellite data for analysing severity and duration of regional drought.
2. To establish the relation among vegetation temperature condition index, water deficit index, crop moisture index and crop performance for an appropriate analysis of the drought condition.
3. To compare coefficient of water sufficiency model and vegetation temperature condition index to detect the drought stress in groundnut crop.

1.8. Research questions

According to the above research objectives, the following research questions can be answered in the development of this research:
1. Is it possible to monitor the effects of drought on crop performance by integrating satellite and meteorological data?
2. How can estimated severity and duration of agricultural drought stress on crop performance be validated?
3. How coefficient of water sufficiency indices and simulated crop yield is helpful to analyze the drought stress on crop performance?

1.9. Research hypothesis

1) Null hypothesis (Ho): There is close relationship between meteorological based indices and satellite derived indices used for identifying severity and duration of drought stress.
Alternative hypothesis (Ha): There is no close relationship between meteorological based indices and satellite derived indices used for identifying severity and duration of drought stress.

2) Null hypothesis (Ho): There is systematic difference between coefficient of water sufficiency indices and satellite derived indices to detect severity and duration of drought stress.
Alternative hypothesis (Ha): There is no systematic difference between coefficient of water sufficiency indices and satellite derived indices to detect severity and duration of drought stress.
3) Null hypothesis (Ho): There is systematic difference between observed and simulated crop production at district level.
Alternative hypothesis (Ha): There is no systematic difference between observed and simulated crop production at district level.

1.10. Assumptions

The following assumptions are indispensable to this research and this address the entire gamut of research questions and research hypothesis:

1. Although severity and duration of drought stress on crop performance is on daily basis in real time (and smaller), it is assumed that weekly drought stress has same effect on crop performance.
2. Simulated or "synthetic observation" of Coefficient of water sufficiency (cfH2O) are representative for actual conditions provided that crop production at district level for the period of 2000 to 2003 can be simulated within an error margin of 10%.

1.11. Outline of the thesis

This thesis comprises different chapters. A detailed literature review has been done on drought monitoring using space technology in chapter 2.

Chapter 3: It describes the geographic setting of study area, agro climatic zones, climatic conditions, agriculture and land use.

Chapter 4: It gives an overview about the data used for present study, which includes satellite data preparation from EOS- data gateway and meteorological data collection from various organisations during field work. In addition to this it explained about the different approaches for drought monitoring and its methodology.

Chapter 5: This chapter is the result part of the thesis, which gives a critical observation for different drought indices and their relationships. It gives a brief discussion based on the results achieved and the analysis carried out.

Chapter 6: Conclusions and recommendations it draws some conclusions from the study results obtained and proposing some recommendations and opportunities for further research.

2. Literature Review

This section address the review of previous works related to the research topic on assessment of the severity and duration of agricultural drought on crop performance using satellite data and other ancillary data. The prime subjects would be reviewed are concerned to different drought indices, satellite metrics and potential of MODIS satellite data for drought monitoring.

2.1. Drought Indicators classification

Drought indicators are classified as meteorological, satellite based and process based indicators. Crop moisture index is classified under meteorological based indicator where as vegetation temperature condition index and water deficit index is classified under satellite based indicator. Vegetation temperature condition index is a dimensionless indicator and vary from zero to one. A process based indicator is the result of the modelling of the energy and matter transfer between the atmosphere and the surface. Other indicators are physical and biophysical. Physical indicators of drought includes rainfall, ENSO effect, water levels in streams/rivers and flow rates of springs, ground water levels, soil moisture condition, and surface water availability index, where as biophysical indicators includes plant yellowing, animal migration and emergence of plant pathogens (Murray, 2005).

2.1.1. Satellite based indicators

(Kogan, 1990) suggested the Vegetation Condition Index (VCI) for drought detection and tracking.
$VCI = 100 \times (NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min})$
Where $NDVI_{max}$ and $NDVI_{min}$ are the multi year maximum and minimum NDVI in a given area for a growing season. (Price, 1990) and (Carlson et al. 1994) found a scatter plot of Land Surface Temperature and vegetation index often results in a triangular shape. (Nemani, 1993) found the slope of LST/NDVI to be negatively correlated to crop moisture index. (Kogan, 1995) proposed the Temperature Condition Index (TCI). The TCI is derived from brightness temperature, and its algorithm is similar to VCI except that the formula was modified to reflect the opposite to the NDVI vegetation's response to temperature. The resultant expression for TCI is
$TCIi = 100 \times (BT_{max} – BT_i)/ (BT_{max} –BT_{min})$
Where BT, BT_{max}, and BT_{min} are smoothed brightness temperature, its maximum and minimum, respectively calculated for each pixel and week from multiyear data i is year. (Yang, 1997) showed the concept of Vegetation Index/Temperature Trapezoid (VITT) by using Landsat-5 TM data.
$(Ts-Ta)\ max = a0+a1\ NDVI$ and $(Ts-Ta)\ min = b0+b1\ NDVI$.
Boegh, 1998 and Goward, 1997 found the slope of Ts/NDVI is related to the evapotranspiration rate of the surface and has been used to estimate air temperature.

(Moran, 1994) defined the VIT trapezoid by substitute Y-axis with Soil Adjusted Vegetation Index (SAVI) [Huete, 1988]. SAVI = (Ts-Ta) x = c0+c1 (SAVI) (Ts-Ta) m = d0+d1 (SAVI). (Wang, 2001) proposed the VTCI based on the triangular space of LST and NDVI for monitoring drought. Sandholt, 2002 developed VTCI for assessing soil surface moisture status. Wan et al. (2003) used LST and NDVI of MODIS products to generate the Vegetation Temperature Condition Index (VTCI) for monitoring drought in the southern Great Plain, USA. [Monteith and Szeicz, 1962 and Tanner, 1963] were among the first to use infrared thermometry to determine plant temperatures. [Ehrler, 1973] used thermocouples embedded in cotton leaves to determine leaf temperatures. His data indicated that a linear relationship exists between the leaf-air temperature difference and the vapour pressure deficit of the air. [Idso and Jackson, 1977] used the canopy temperature Tc (as measured by infrared thermometry) minus the air temperature Ta as an index of crop water status. They called the difference Tc-Ta the "stress-degree-day" and related this parameter to yield and water requirements in (Sirikul). (Jackson, 1981) and (Idso, 1981) derived the theoretical foundation for the crop Water Stress Index (CWSI). (Moran et al. 1994) defined the water deficit index (WDI) for computing evapotranspiration rates of both full-cover and partially vegetated sites.

$$\mathrm{WDI} = 1 - \frac{\mathrm{LE}}{\mathrm{LE_p}} = 1 - \left[\frac{(T_{su} - T_a) - (T_s - T_a)}{(T_{su} - T_a) - (T_{sl} - T_a)} \right]$$

Where T_{su} and T_{sl} are the upper and lower temperatures and LE and LEp are instantaneous actual and potential evapotranspiration (Wm-2) respectively, encountered for a given vegetation cover or vegetation index on the left- and right-hand edges of the trapezoid. It is equal to 1 for crop extreme stress conditions and 0 for a well-watered crop evaporating at the potential rate (Luquet, 2004).

2.1.2. Process based indicators

A process based indicator is the result of the modelling of the energy and matter transfer between the atmosphere and the surface. Evapotranspiration is the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration (ET). The energy known as latent heat of vaporization (λ), is a function of water temperature. The evapotranspiration rate is represented by λET or "latent heat flux".

Energy Balance

The evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. When the land surface experiences a persistent moisture deficit, transpiration processes are restricted and the cooling mechanism of plants stops. This process affects plant vigour and has a direct impact on the energy balance of the land surface. Reduced moisture conditions not only affect plant life but also form an important component of the surface energy balance through the processes of evaporation and transpiration or latent heat flux. The evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of this limitation; it is possible to predict the evapotranspiration rate by applying the principle of energy conservation [Bastiaanssen, 1995] in (Mendez Jocik, 2004). The energy arriving at the surface must be equal to the energy leaving the surface for the same time period. All fluxes of energy should be considered when deriving an energy balance equations. The equation for an evaporating surface can be written as:

$Q= k+L=\lambda E+H+G$

Where Q is the net radiation, K is net short-wave radiation; L is net long -wave radiation, λE is latent heat flux (Wm-2), H is sensible heat flux (Wm-2), and G is soil heat conduction (Wm-2) in (Park, 2004).The partitioning of sensible heat flux, latent heat flux and soil heat conduction from net radiation during the daytime is governed by the nature of the surface. When water is restricted, it is expected that more energy will be disposed of through sensible heat flux, soil heat conduction (G) and outgoing long-wave radiation, which is accompanied by surface temperature increases [Seguin et al. 1994, Nichol, 1995]. The relative importance of sensible versus latent heat fluxes is mainly governed by the availability of water for evaporation. Since the sensible heat flux (H) is governed by the difference between the radiometric surface temperature and the air temperature, thermal infrared sensors provide an ideal tool for detecting water limited areas in the environment [Jackson et al. 1981, Lhomme and Monteny 1993, Moran et al. 1994] in (Park, 2004).

$H = \rho aCp\ (Tc\text{-}Ta)/ra$

Where ρa = the volumetric heat capacity (kgm-3), Cp = the heat capacity of air (Jkg-1 °C-1), Tc & Ta = surface & air temperature (°C), ra = aerodynamic resistance (sm-1),

$\lambda E= \rho aCp\ (ec^*\text{-}ea)/\ [(ra+rc)]$

Where ec* = the saturated vapour (Pa), ea = vapour water of air (Pa), rc = the canopy resistance (sm-1) = the psychometric constant (Pa °C-1) given by (Monteith, 1973).

According to (Green, 2002) there is a consistent correlation between remotely sensed surface temperature from AVHRR estimates and monthly mean Ta observations from meteorological ground measurements for both the African and European continents, and [Ferreira, 2001 in Portugal] evaluated the suitability of relationship between canopy temperature and air temperature differential (Tc-Ta) and the saturation deficit to be used as crop water stress indicator and also the linear regression between these parameters with R^2 around 0.52-0.73 in (Mendez Jocik, 2004). Finally the concept of potential evapotranspiration is an important measure from which surface moisture conditions may be estimated. The term potential evapotranspiration is defined as the maximum water loss from a homogeneous, vegetated surface that never suffers from a lack of water. By comparing precipitation and potential evapotranspiration, the method keeps track of changes in soil moisture and estimates actual evapotranspiration, water surplus and deficits. These techniques have been widely accepted because they are simple to evaluate and require only limited climatic data [Thornthwaite and Mather, 1957, Mather, 1978] in (Park, 2004).

The combination of meteorological data, satellite data and various environmental layers in a GIS gives promising results for the mapping and monitoring of drought conditions in the Mediterranean basin. Both approaches, using either a combination of meteorological and satellite based indices or a process based model, have proven their capability to detect and monitor water stress conditions of the vegetation canopy (Jurgen, 1998).

2.2. Drought monitoring from space

Utility of remote sensing data especially satellite data in drought assessment has long been proven and needs no reiteration. It is far superior to conventional methods at an optimal spatial extent. Remote Sensing technology in its current state of art can help in predicting, mitigating and monitoring all the five different types of drought. Data from various satellites can be utilized for the purpose depending on the perspective that a researcher has towards drought, whether it is agricultural, meteorological, hydrological, socio-economic or ecological. It enables to understand the manifestations of drought in a larger area more directly than the conventional methods, which used to utilize indirect methods for assessing the various impacts of drought. Drought monitoring mechanisms exist in most of the countries that use ground based information on drought related parameters such as rainfall, weather, crop conditions and water availability. Earth observations from satellites are highly complementary to those collected by in-situ systems. Satellites are often necessary for the provision of synoptic, wide-area coverage and provision of the frequent information required putting in-situ information into broader spatial monitoring of drought conditions.

2.2.1. Thermal Satellite data for Agricultural drought monitoring

Though many factors affect the canopy temperature, it is evident that it indicates water stress. As water stress increases the canopy resistance for vapour transport, incident energy will be partitioned increasingly towards sensible heat. Canopy temperature must then rise in order to dissipate the additional sensible heat. Sensible heat transport between the canopy and the air above it is proportional to the temperature difference, $\Delta T= Ts- Ta$ and thus the radiative temperature of a plant canopy is very complex. Indices such as Stressed Degree Day (SDD) and Crop Water Stress Index (CWSI) are two indices of wide use in estimating drought from thermal data. Measuring brightness temperatures are affected by water vapour in the atmosphere but the method of the “split window”, uses two thermal bands of NOAA-AVHRR, offers accuracy of 10 to 20 K. The radiation flux that is detected by a radiometer integrates a series of elementary fluxes that arise from various layers of leaves and soil, all of which may be at different temperatures. Many factors interact to determine the composite radiative temperature of a plant canopy; these factors are external, internal, physiological and environmental. These factors determine the radiative temperature which includes the components of surface energy balance, such as the net radiation, evapotranspiration, wind speed, sun elevation and azimuth. In addition to this the geometry of a canopy and stomata control of water loss from the leaves also influence the radiative temperature. Therefore the thermal data is found to be of extensive use in understanding drought dynamics. Agricultural drought monitoring using Remote Sensing focuses on crop stress during growth and yield prediction with respect to crop types. Agricultural drought can be observed primarily using optical remote sensing. Thermal remote sensing techniques and microwave remote sensing has proven its capability in observing and enabling one to comprehend agricultural drought.

2.2.2. Satellite Metrics

Vegetative conditions over the world are reported occasionally by NOAA National Environmental Satellite Data and Information System (NESDIS) using the Advanced Very High Resolution Radiometer (AVHRR) data (Kogan, 2000). Impacts, monitoring and reporting of drought development is of critical importance in politically, economically and environmentally sensitive countries of South Asia**.** The ability of governments in the region and international relief agencies to deal with droughts is constrained by the absence of reliable data, weak information networks as well as the lack of technical and institutional capacities. Some countries, like Afghanistan, are just beginning to establish relevant drought monitoring and management procedures and institutions. Traditional methods of drought assessment and monitoring rely on rainfall data, which are limited in the region, often inaccurate and, most Drought indicators can be derived for any world region using these data, but the characteristic spatial resolution of 10 km (at which well-calibrated long-term historical data are freely available), is likely to be coarse for effective drought monitoring at small scales (a district or a village). A recent successor to AVHRR is the Moderate-Resolution Imaging Spectrometer (MODIS), an advanced narrowband- width sensor, from which composited reflectance data are made available at no cost every 8 days by NASA and USGS, through the Earth Resources Observation Systems (EROS) data centre [Justice and Townshend, 2002] in (Thenkabail, 2004). Raw images are available on a daily basis, but their use involves considerable extra processing. Time series of MODIS imagery provide near real- time, continuous and relatively high-resolution data, on which the assessment of drought development and severity in regions with scarce and inaccurate on the ground meteorological observations (like southwest Asia) could be based.

Today the application of remote sensed data in vegetation studies is widely operational. Applications as sophisticated as highly accurate yield estimates and crop disease and water stress detection at sub-pixel level have been operational in northern America and Europe [Cracknell, 1997, EWSE, 1999], while its application for drought monitoring is operational world wide (Kogan, 1997). The increasing use of satellite remote sensing for civilian use has proved to be the most cost effective means of mapping and monitoring environmental changes in terms of vegetation, rainfall and non-renewable resources [Richards, 1994]. Data can be obtained as frequently as required. Mapping and modelling environmental changes as they progress can be achieved by integrating digital datasets obtained by remote sensors with relevant ground information. This is facilitated by Geographic Information Systems (GIS). GIS also have the added value of enabling the presentation of findings from such analysis in a comprehensive format. The GIS products form the basis for environmental monitoring and decision support.

However, systems for monitoring environmental change based on remote sensing are not yet perfected. (FAO, 1993) argue that improvements are still needed in three major areas: acquisition of data and data types, storage and analysis, and dissemination and communication of results. There is a particular need to improve and harmonize data from meteorological satellites such as NOAA and METEOSAT, in order to produce standard, compatible outputs which can be used to aid decision-making in agricultural warning and forecasting, in particular by estimating rainfall and plant activity. Another problem is the need to improve assessments of soil degradation at all levels, from the global to the local. This could be accomplished by combining remote-sensing information from satellites, such as LANDSAT or SPOT, with data from ground observation sites. This has the potential to provide information for continuous monitoring of climatic change and land degradation. FAO stresses the importance of integrating "high-resolution spatial and spectral satellite pictures such as LANDSAT or SPOT, combined with those from satellites with higher temporal frequency and low spatial resolution, such as METEOSAT or NOAA into GIS and spatial models and complemented by new methods of gathering ground data through navigation satellites" (FAO, 1993)

Satellite data analysis, however, provides a means to measure broad scale changes at the ecosystem level by making numerous, repeatable observations. Multi-temporal satellite observations have allowed researchers to quantify seasonal events and to characterize vegetation according to its seasonal patterns [Lloyd, 1990, Loveland et al. 1991, Reed et al. 1993, DeFries et al. 1999, Reed et al. 1996]. Many of the aforementioned studies based their analysis on vegetation indices computed from combinations of visible red and near-infrared spectral measurements collected from satellite-borne sensors. The advantages of using these numerical transforms rather than strictly spectral observations include minimizing soil and other background effects, reducing data dimensionality, providing a degree of standardization for comparison, and enhancing the vegetation signal [Curran, 1981, Malingreau, 1989 and Goward, 1989]. One of the more commonly used vegetation indices, the normalized difference vegetation index (NDVI), takes advantage of the reflective and absorptive characteristics of plants in the red and near-infrared portions of the electromagnetic spectrum and has been used in research on vegetation yield and productivity. The ability to derive NDVI measurements combined with the frequent temporal coverage and moderate spatial resolution of the AVHRR make this sensor well suited for regional to global scale studies on ecosystem dynamics in (Brown, 2002).

Environmental factors that appear to cause changes in the phenologic patterns exhibited in satellite data include drought, flood, disease, fire, and human-induced land cover change (such as clearing land for forest harvest or conversion to cropland). Several previous studies have shown the utility of satellite measurements for observing and monitoring drought. For example, Kogan (1991, 1995) has analysed droughts in the United States using AVHRR data. In this research, he developed several derivations of the NDVI in order to improve the ability to extract drought information from a time-series of satellite composite data. One index, the Vegetation Condition Index (VCI), is a ratio of the NDVI collected in a given period compared to its historical range (maximum minus minimum) derived over several years of record. Possible VCI values range from 1 to 100. (Kogan, 1995) stated that VCI values of 35 and under indicate drought. Building on this research, Kogan et al.1997 has demonstrated the utility of the VCI in Africa, South America, and Asia. They also have developed an index that utilized the thermal data from AVHRR channel 4 known as the Temperature Condition Index (TCI). The satellite index data are compared to other measures, such as precipitation, atmospheric anomaly fields, and agricultural crop yield for validation purposes. The authors were able to predict corn yields from 6 to 13 weeks prior to harvest with reasonable accuracy by applying the VCI and TCI data. These studies were conducted at a spatial resolution of 16 square km based on NOAA Global Vegetation Index product. [Viau, 2000] have compared the previously mentioned VCI and the NDVI (extracted from AVHRR data) to measurements of the SPI over less than 20 weather stations in Spain. The authors were very encouraged by their results, but since so few sites were used; the results were not statistically significant. In addition, [Peters et al. 2002] developed a Standardized Vegetation Index (SVI) for the central United States based on 1-km^2 resolution AVHRR data and cover the period 1989 through the present in (Brown, 2002).

Several studies have investigated relationships between satellite-derived metrics and climate variables. In a recent study based in the Great Plains, Budde and Reed (written communication) demonstrated the relationships between NDVI-based seasonal metrics and climate variables for 68 stations in the central United States. Using a stepwise linear regression approach, the authors demonstrated that variables associated with moisture availability and thermal conditions were found to exert control on the performance of both grassland and cropland areas. Another study [Yang et al. 1998] shows moderate to strong relationships (R^2 = 0.39-0.94) between annual integrated NDVI and several precipitation measures for specific grassland classes in the U.S. The authors suggest an integrated approach involving numerical models, remote sensing, and field observations to monitor grassland dynamics. This drought monitoring work builds on the aforementioned research, and is complementary to those studies not based on seasonal metrics. We plan to model the relationships between meteorological drought indicators and satellite-derived metrics. The satellite-derived metrics will add improved spatial detail that is currently not a feature of many drought indicators and will also indicate where the drought is impacting the surface vegetation in (Brown, 2002).

2.3. Potential of MODIS satellite and LST for drought monitoring

Land surface temperature (LST)

It is called surface temperature and denoted as Ts. It is generally means skin temperature of the ground. For bare soil, LST represents soil surface temperature, where as densely vegetated ground LST represents canopy surface temperature. However, for sparsely vegetated ground, LST is determined by the temperature of the vegetation canopy, vegetation body and soil surface (Qin and Karnieli, 1999). The surface temperature Ts is the temperature of the layer of air immediately in contact with the leaf, and Ta is the conventional air temperature measured in a screen. 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.

Land surface temperature (LST) is one of the key parameters in the physics of land-surface processes on regional and global scales, combining the results of all surface-atmosphere interactions and energy fluxes between the atmosphere and the ground (Mannstein, 1987). Besides its necessity in the LST retrieval, the surface emissivity can be used to discriminate senescent vegetation (French, 2000). LST can be also used to monitor drought and estimate surface soil moisture (Feldhake, 1996) to evaluate water requirements of wheat (Jackson, 1977). The strengths of MODIS include its global coverage, high radiometric resolution and dynamic ranges suitable for atmosphere, land, or ocean studies, and accurate calibration in multiple TIR bands designed for retrievals of SST, LST and atmospheric properties. Specifically, band 26 will be used to detect cirrus clouds (Gao, 1995), band 21 for fire detection (Kaufman, 1998), all other TIR channels will be used to retrieve atmospheric temperature and water vapour profiles [Smith et al. 1985], and TIR bands 20, 22, 23, 29, 31–33 will correct for atmospheric effects and retrieve surface emissivity and temperature [Wan et al. 1997] in (Wan, 2002).

Drought impacts are usually first apparent in agriculture. Agriculture production is closely linked to actual crop evapotranspiration, which is usually monitored by the water balance of the whole crop growing cycle. Therefore, a drought index, which closely describes temporal and spatial variations of crop water use status, is suitable for drought monitoring. Satellite remotely sensed data offer considerable advantages and should be an integral part of monitoring drought, especially for the temporal and spatial evolution of drought. Since 1981, Advanced Very High Resolution Radiometer (AVHRR) data collected from the National Oceanic and Atmospheric Administration (NOAA) series of satellites have been used to generate vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and to retrieve Land Surface Temperature (LST). AVHRR NDVI was applied successfully to classify land vegetation types (Menenti, 1993), and monitor vegetation growth conditions from excellent to stressed (Kogan, 1990). A successor of AVHRR, the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument on the Terra satellite was launched in December 1999. The MODIS remotely sensed data can be used to produce NDVI imagery at 250m resolution, and to retrieve LST at the global scale (Wan, 1996). AVHRR NDVI and/or LST time series plots have been used to identify and monitor drought evolution (Kogan 1990, 1995, Chen et al. 1994, Liu et al. 1994, Lozano et al. 1995, Liu and Kogan, 1996).

Associated with the drought, LST increase slightly earlier than plant cover decreases (Mcvucar, 1998). During dry conditions (there is less soil moisture availability), rising leaf temperatures are good indicators of plant moisture stress and precede the onset of drought. This thermal response can occur even when plants are green, as stomata closure to minimize water loss by transpiration results in a decreased latent heat flux. At the same time, due to the requirement that the energy flux must balance, there will be an increase in the sensible heat flux, which may result in increased leaf temperatures. This increase in leaf temperature can be used for stress detection in crops. This land surface energy flux balance finally results in high LST. Goetz (1997) reported that the negative correlation between LST and NDVI, observed at several scales (25m2 to 1.2 km2), was largely due to changes in vegetation cover and soil moisture, and indicted that the surface temperature can rise rapidly with water stress. (Nemani, 1993) found the slope of LST versus NDVI to be negatively correlated to a crop-moisture index. Therefore, the ratio of LST/NDVI increases during times of drought. Advances are currently being made to use LST versus NDVI plot combined with meteorological data and process based models to provide a more mechanistic interpretation of the remotely sensed data (Mcvicar, 2001). There are two methods currently being put forward. The first is a progression from the slope of LST versus NDVI approach, which describes the data as falling into a triangle (Price 1990 et al.) and (Gillies, 1995). The Vegetation Index/ Temperature Trapezoid (VITT) (Moran et al. 1994, Yang et al. 1997) is an evolution of the Crop Water Stress Index (CWSI) (Jackson et al. 1981) that promotes the ideas of data falling into a trapezoid. Based on AVHRR NDVI and brightness temperature, Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) have been developed and used for monitoring drought (Kogan 1990, 1995). On the basis of the triangular space of LST and NDVI, the Vegetation Temperature Condition Index (VTCI) approach was proposed for monitoring drought occurrence at a regional level (Wang et al. 2001), and the Temperature Vegetation Dryness Index (TVDI) was developed for assessing soil surface moisture status (Sandholt et al. 2002). Since meteorological data, such as precipitation and land air surface temperature, collected by surface observation stations often possess poor spatial resolution, especially in remote regions with difficult access and in some developing countries, remotely retrieved NDVI and LST data may provide a valuable source of information for monitoring drought. The drought monitoring approaches with satellite remotely sensed data are based on NDVI, LST (or brightness temperature), and the single ratio of LST and NDVI; therefore, it becomes critical to develop more complicated and physically based drought monitoring approaches by integrating remotely sensed LST and NDVI products (Wan, 2004).

2.4. Relationships of NDVI, Land surface temperature and Rainfall

The relationship between LST and vegetation indices, such as NDVI, has been extensively documented in the literature. The basis for using NDVI in LST estimation is that the amount of vegetation present is an important factor, and NDVI can be used to infer general vegetation conditions. The combination of LST and NDVI by scatter plot results in a triangular shape (Carson et al. 1994, Gillies and Carlson, 1995, Gillies et al. 1997). The slope of the LST–NDVI curve has been related to soil moisture conditions (Carson et al. 1994, Gillies and Carlson, 1995, Gillies et al. 1997, Goetz, 1997, Goward et al. 2002), and the evapotranspiration of the surface (Boegh et al., 1998). Several methods have been developed to interpret the LST–NDVI space, including: (1) the 'triangle' method using soil vegetation atmosphere transfer (SWAT) model (Gillies, 1997).(2) In situ measurement method [Fried and Davis, 1994], and (3) remote sensing based method [Betts et al. 1996]. However, difficulties still exist in interpretation of LST for sparse canopies because the measurements have combined the temperature of the soil and that of the vegetation, and the combinations are often nonlinear (Sandholt et al. 2002). The relationship between NDVI and fractional vegetation cover is not singular. Recent studies have shown that NDVI does not provide a real estimate of the amount of vegetation [Small, 2001]. NDVI measurements are a function of the visible and near-infrared reflectance from plant canopy, the reflectance of the same spectra from the soil, and the atmospheric reflectance, and are subject to the influence of an error related to observational and other errors [Yang et al. 1997]. This nonlinearity and the platform dependency suggest that NDVI may not be a good indicator for quantitative analyses of vegetation [Small, 2001], and the relationship between NDVI and LST needs further calibration. More quantitative, physically based measures of vegetation abundance are called for, especially for applications that require biophysical measures [Small, 2001]. The importance of spatial resolution for detecting landscape patterns and changes should also be emphasized [Frohn, 1998], and the relationship between NDVI variability and pixel size should be further investigated [Jasinski, 1990] in (Wenga, 2004).

A method was developed by the TAMSAT group in Reading (Bonifacio, 1992) for application in Sahelian and Southern Africa. It is based on the relationship of NDVI to rainfall during the plant-growing season. A similar method is also used by the FAO of the United Nations (FAO, 1997). Based on previous work that concluded that rainfall estimates could be used to forecast biomass production as indicated by the NDVI (Justice, 1991), the method characterises the dynamics of the vegetation development via its growing season's parameters on a consistent spatial scale. These parameters are related to a rainfall derived moisture satisfaction index. Furthermore, although rainfall amounts averaged over long time periods or large areas may be adequately estimated, localised intensity variations are not well represented. In particular, heavy rainfalls are underestimated. (Bonifacio, 1998) tried to reduce the errors associated with these problems by modulating the satellite estimates with available real-time rain gauge data.

However this approach poses a problem. While the rain gauge data are point measurements, the satellite values are averages over pixel-sized areas. This was dealt with by deriving pixel average values from the gauge data, and merging these with the satellite estimates in a way that reflects the likely accuracy of the two data sets. This is done using the geostatistical technique of kriging that was developed for the DFID funded Drought and Flood Warning project in Southern Africa (Bonifacio and Grimes, 1998). The method reportedly provides optimal areal estimates in any given situation and is applicable both for drought monitoring and flood forecasting.

Kogan (1995, 1997) developed the relation ship between rainfall, NDVI and surface temperature, which is based on the relationship of the Global Vegetation Index (GVI), and the Temperature Condition Index (TCI) with rainfall. The GVI, unlike the GAC data, is in the form of a ready mapped processed geophysical product, namely the NDVI. The GVI is of coarser resolution than the GAC from which the NDVI for the FAO datasets is derived. This is because the GVI is sampled, both spatially and temporally from GAC, with the final product made from a composite of the daily NDVI arrays over a seven-day period such that the maximum NDVI value is retained for each location (Belward et al., 1986). The TCI is derived from 10.3 – 11.3 _m thermal band AVHRR measured radiances, converted to brightness temperature, (BT). The VT (the Vegetation and Temperature Condition Index) is a combination of the VCI and TCI indices. It is used to monitor the water and temperature related vegetation stress occurring during drought. The methodology is based on the assumption that:

> "first impression of drought climatology can be obtained from the global distribution of the surface moisture balance, that is, the difference between annual precipitation and annual potential evaporation as an approximate measure of estimating vulnerability of territories toward drought" (Kogan, 1997).

The VCI-TCI values for a given region for each week are calculated and compared with yields of agricultural crops. The results reportedly showed a very strong correlation between these indices and yield, particularly during the critical periods of crop development. The method follows the consideration that the absolute maximum and minimum of NDVI and BT calculated from several years of data that contain the extreme weather events (drought and non-drought years) can be used as criteria for quantifying the extreme conditions (Kogan, 1995). Accordingly the largest and smallest NDVI and BT values during 1985-1993 were calculated for each of the 52 weeks of the year and for each pixel. These form the criteria for estimating the upper (favourable weather) and the lower (unfavourable weather) limits of the ecosystem resources.
These limits

> "characterise the 'carrying capacity' of the ecosystems and the range in which NDVI and BT fluctuates due to weather changes. These fluctuations were estimated relative to the maximum and minimum intervals of both NDVI and BT variations and named the vegetation (VCI) and temperature (TCI) condition indices" (Kogan, 1997).

The methodology has already been tested globally, in very diverse environments, including Kazakhstan, China, Ukraine, Zimbabwe, Ethiopia, USA and Argentina, with encouraging results (Kogan, 1995). Global or regional assessment methodologies based on GVI have limitations for applications at the sub-regional level, particularly those areas with high spatial variation such as the Sudan. Data such as the TCI above, derived from TIR, need to be treated with caution, since the information content of composited TIR measurements is uncertain, as TIR emissions from the earth change rapidly with time of day and atmospheric conditions,(Goward, 1991). Furthermore, existing algorithms have limitations in accounting and correcting for factors such as emissivity variations in space, in time, different wavebands and view angle (Kassa, 1999).

Relationships between surface temperature and spectral vegetation index (SVI)

A spectral vegetation index (SVI) is generated by combining data from multiple spectral bands into a single value. Usually simple algebraic formulations, SVIs are designed to enhance the vegetation signal in remotely sensed data and provide an approximate measure of live, green vegetation amount. Most SVIs compare the differences between the red and near-infrared reflectance. Red (or visible) reflectance is sensitive to chlorophyll content and the near-infrared reflectance is sensitive to the mesophyll structure of leaves. Spectral vegetation indices have been found to be related to a number of biophysical parameters (variables) of interest to many researchers, including Leaf Area Index (LAI), percent vegetation cover, green leaf biomass, fraction of absorbed photo synthetically active radiation (fAPAR), photosynthetic capacity, and carbon dioxide fluxes. Two widely used SVIs are the Simple Ratio or SR (sometimes referred to as the RVI or ratio vegetation index) and the Normalized Difference Vegetation Index, or NDVI. Existing spectral vegetation indices have been enhanced and others developed to improve upon parameter estimations in various applications. These include greenness, PVI (perpendicular VI), SAVI (soil adjusted VI), ARVI (atmospherically resistant VI), SARVI (soil adjusted, atmospherically resistant VI), and in addition to ratio indices, the DVI (difference vegetation index).

Remotely sensed radiation temperatures are influenced by the interaction of several factors, such as fractional vegetation cover, evapotranspiration, thermal properties of the surface, net radiation, atmospheric forcing and surface roughness (Sandholt, 2002). A bilinear relationship between the fractional vegetation cover and the spectral vegetation index was obtained [Ormsby et al. 1987], and the fractional vegetation cover was found to influence the remotely sensed thermal infrared information that determined the remotely sensed radiation temperature. The correlation between surface temperature and transpiration is based on the fact that, as a crop transpires, the evaporated water cools the leaves. As the crop becomes water stressed, transpiration will decrease and thus the leaf temperature will increase. (Jackson, 1981) first presented the theory behind the energy balance that separates net radiation from the sun into sensible heat ,which heats the air, and latent heat ,which used for evapotranspiration. As the crop undergoes water stress the stomata closes and transpiration decreases while leaf temperature increases (Wang, 2004).

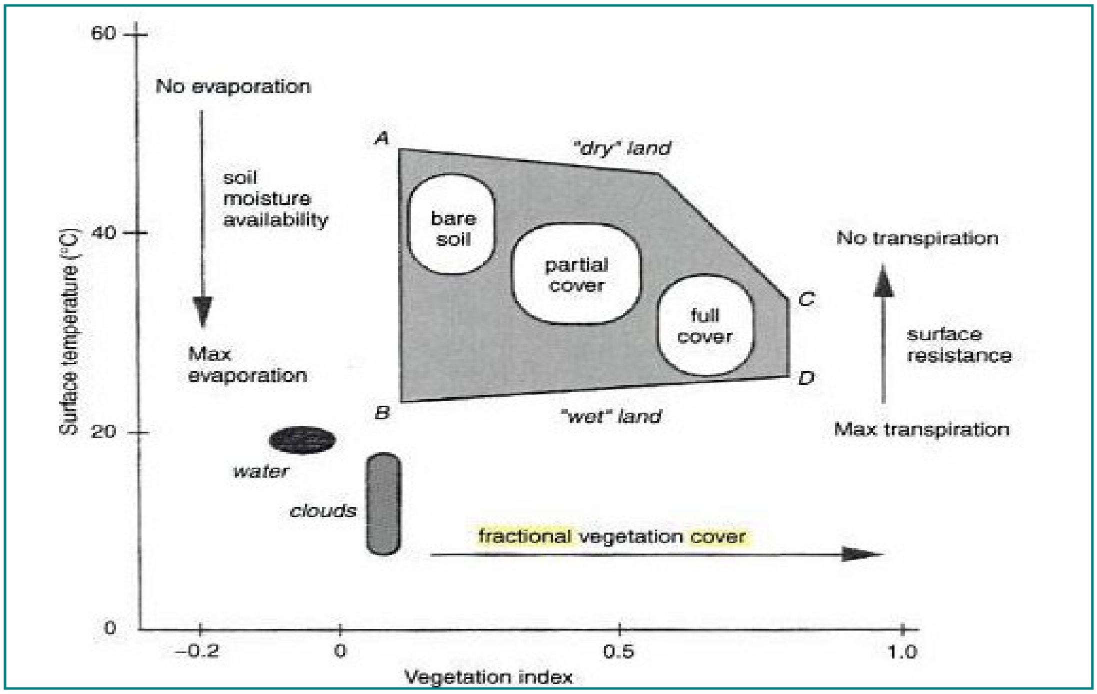


Figure 2.1:Schematic plot of surface temperature and vegetation index space, and the conceptual relationships with evaporation, transpiration and fractional vegetation coverage (Liang, 2003)

A and B represent as dry bare soil (low VI, High LST) and moist bare soil respectively. As the fractional vegetation increases, surface temperature decreases as a result of several biophysical mechanisms. Point C corresponds to continuous canopies with a high resistance to evapotranspiration (high VI, relatively high LST), which may result from a low soil water availability. Point D corresponds to continuous vegetation canopies with low resistance to evapotranspiration, high VI, low LST), which may occur on well water surfaces (Liang, 2003).

2.5. Crop Growth Modelling for Reference and Actual production situations

Remote sensing and crop growth simulation models have become increasingly recognized as potential tools for growth monitoring and yield estimation. RS data provide timely, accurate, synoptic and objective estimation of crop growing conditions or crop growth for developing yield models and crop productivity. Hyperspectral remote sensing satellite data like MODIS has become an important tool for crop yield modeling. Currently RS data can regularly provide information on regional crop distribution, crop phenology. The main purpose of CGMS models and GIS is to carry out spatial and temporal analysis of crop phenology and crop yield model. The GIS can help in spatially visualizing the results as well as their interpretation by spatial analysis of model results. A crop simulation model is a simple representation of a crop and is explanatory in nature. Crop simulations models are based on physical plant processes and simulate the effects of change in growing environment on plant growth and development on a daily basis. An integration of crop growth simulation models, RS data and GIS can provide an excellent tool for monitoring and modeling the crop yield and biophysical parameters. Remote Sensing (RS) data, acquired repetitively over agricultural land help in identification and mapping of crops and also in assessing crop vigour. As remote sensing data and techniques have improved, the vegetation indices (VI) to crop yield have been replaced by approaches that involve retrieved biophysical quantities from remote sensing data. Thus, crop simulation models (CSMS) that have been successful in field-scale applications are being adapted in a GIS framework to model and monitor the crop growth.

Natural weather conditions are affecting crop production with the main factors known as air temperature, canopy temperature, rainfall and solar radiation. These parameters have been used in various applications for crop yield assessments, in which some take into account a combination of crop physiology factors, climatic components and soil properties known as crop growth models or crop growth simulation, while the others use less complicated approaches mostly based on empirical, semi-empirical or physical relations between crop production and weather conditions. Since the use of crop growth models requires very detailed data, which is usually hard to collect because of the data scarcity in third world countries like India, the other choice is to use physical approach called coefficient of water sufficiency model where we can simulate the yield for each crop types based on different crop parameters. In addition to this it requires the climatic data and some ancillary data to prove more cost efficient way as it requires less data. For the long time remote sensing data can provide unique data for a large study area and it contributes to the task of yield estimation through different approaches. The most common way to assess crop yield is to use the Normalized vegetation index (NDVI) retrieved from Advance very high Resolution Radiometer (AVHRR) onboard the polar orbiting satellite NOAA. However the use of NDVI in estimating the potential yield requires not only satellite observations but also some other environmental factors known as climatic and soil conditions in order to be get reasonable results (Trucker and Sellers, 1986).

Hierarchy of production situations

The simplest production situa-tion (PS-1) quantifies crop performance, within the physiological possibilities of the crop, as a function of the only land qualities that a farmer cannot modify, viz. the availability of solar radiation and the tempera-ture. All other land qualities are assumed to fully satisfy the corresponding land use requirements. Production situation PS-1 constitutes the highest level in the hierarchy of production models. The production calculated is the highest that can be realized on an experimental field; it is the biophysical production potential. At the second highest level (PS-2), the assumption of optimum water supply is waived and the land quality “moisture availability” is quantified and matched against the consumptive water needs. The result of this matching is incorporated in the calculation of the production potential. In other words, crop production in production situation PS-2 is determined by the amount of intercepted radiation, the temperature and the availability of water. All other land qualities or limitations that influence production in normal farming (availability of nutrients, competition by weeds, occurrence of pests and diseases, harvest losses) are assumed not to constrain crop performance. The outcome of a PS-2 analysis is the water limited production potential (Driessen and Konijn, 1992). At the third hierarchical level (PS-3), the availability of nutrients is additionally taken into account and so on.

PS-1: Biophysical production potential

Production situation PS-1 represents a land use system with the least possible analytical complexity; all land qualities which can be influenced by a farmer through irrigation and drainage, use of fertilizers, weeding and control of pests and diseases are assumed to be optimum. The production calculated for production situation PS-1 is the highest production possible on a farmer's field. It is the "biophysical production potential". The biophysical production potential is determined by the solar radiation and temperature during the growing period and by the physiological characteristics of the crop. Analysis of production situation PS-1 is based on the same principles as calculation of net biomass production for agro ecological zoning but the procedure is dynamic and considerably more detailed. It is solely determined by the available light, the temperature and the photosynthetic mechanism of the crop.
PS-1: P, Y=f (light, temperature, C3/C4)

PS-2: Water limited production potential

Production situation PS-2 represents a land use system in which production possibilities are determined by irradiance of photo synthetically active radiation (PAR), temperature, and availability of water. The land use requirements "optimum availability of PAR", "optimum temperature" and "optimum availability of water" are matched against the land qualities "actual PAR", "actual temperature" and "actual availability of water" to determine the water limited production potential. Production situation PS-2 is already a much more complex situation than PS-1 but still less complex than the production environment of many farmers in developing countries. Advanced farmers may examine alternative PS-2 scenarios to evaluate water management options, identify optimum planting or sowing dates, select physically suitable areas for agricultural expansion in critically dry regions, and much more. It is a function of the available light, the temperature and the photosynthetic mechanism and available water of the crop.
PS-2: P, Y=f (light, temperature, C3/C4, water)

Actual yield that is the yield realised by a farmer, is likely to be less than the biophysical potential because it is generally not economical to fully remove all constraints to crop growth. Crop growth is a highly dynamic process. Calculations of reference production levels must therefore make use of dynamic crop growth modelling and actual crop performance must be repeatedly gauged (Rugege, 2002).

3. General Overview of the study area

The geographic setting of the study area includes location and extent, drought propensity in study area, agro climatic zones and climatic conditions, physiography and soils and finally agriculture and land use. The overview of the study area has been briefly described below.

3.1. Location and extent

Gujarat state is located on the north west of India between 20° 01' N to 24° 07' N latitude and 68° 04' E to 74° 04' E longitude. The tropic of cancer passes through the northern border of the state. It is bounded by the Arabian Sea on the west, Pakistan and Rajasthan in the north and north-east respectively, Madhya Pradesh in the south-east and Maharashtra in the south. The State has an international boundary and has a common border with the Pakistan at the north-western fringe. The two deserts, one north of Kutchch and the other between Kutchch and the mainland Gujarat are saline wastes. It comprises of 25 districts, sub-divided into 226 talukas, having 18618 villages and 242 towns. It covers total geographical area of 196,024 sq km (75,685 sq mi) and accounts for 6.19 percent of the total area of the country. According to the provisional results of Population Census 2001, the population of Gujarat as on 1st March 2001, stood at 5.06 crore. It has about 1600 km of coastline, which is about a third of India's total coastline and the longest coastline of all Indian states. This coastline includes the Gulf of Kutchch and Gulf of Cambay. The state comprises three geographical regions.

- The peninsula, traditionally known as Saurashtra. It is essentially a hilly tract sprinkled with low mountains.
- Kutch on the north-east is barren and rocky and contains the famous Rann (desert) of Kutch, the big Rann in the north and the little Rann in the east.
- The mainland extending from the Rann of Kutch and the Aravalli Hills to the river Damanganga is on the whole a level plain of alluvial soil.

3.2. Drought propensity in study area

The Indian hot arid zone, occupying an area of 31.71 Mha, spreads over Western Rajasthan, North Gujarat, South West Haryana and Punjab, some parts of Andhra Pradesh and Karnataka State (Singh, 2003). The state of Gujarat experiences droughts, flash floods, cyclones and earthquakes frequently and among them one phenomenon that recurs with unfailing regularity is drought. The Western part of the country is prone to drought. 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. Salinity and desertification is a common feature in most part of Gujarat. The livelihood of the rural population is predominantly dependent on agriculture and livestock rearing. Agriculture is mainly rained and only the monsoon crop (kharif) is taken by small and marginal farmers. 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. On the vulnerability atlas of India the Kutchch district of Gujarat is one of the most prominent regions of multi-dimensional importance. The disaster clock has brought particular distress to the environmentally fragile district of Kutchch. In the last ten years, it has suffered six droughts, two cyclones, one earthquake and one flood. Seventy-three per cent of Gujarat's arid area falls in Kutchch district and more than half its terrain is covered by saline mudflats (the Great and Little Ranns) (UNDP).

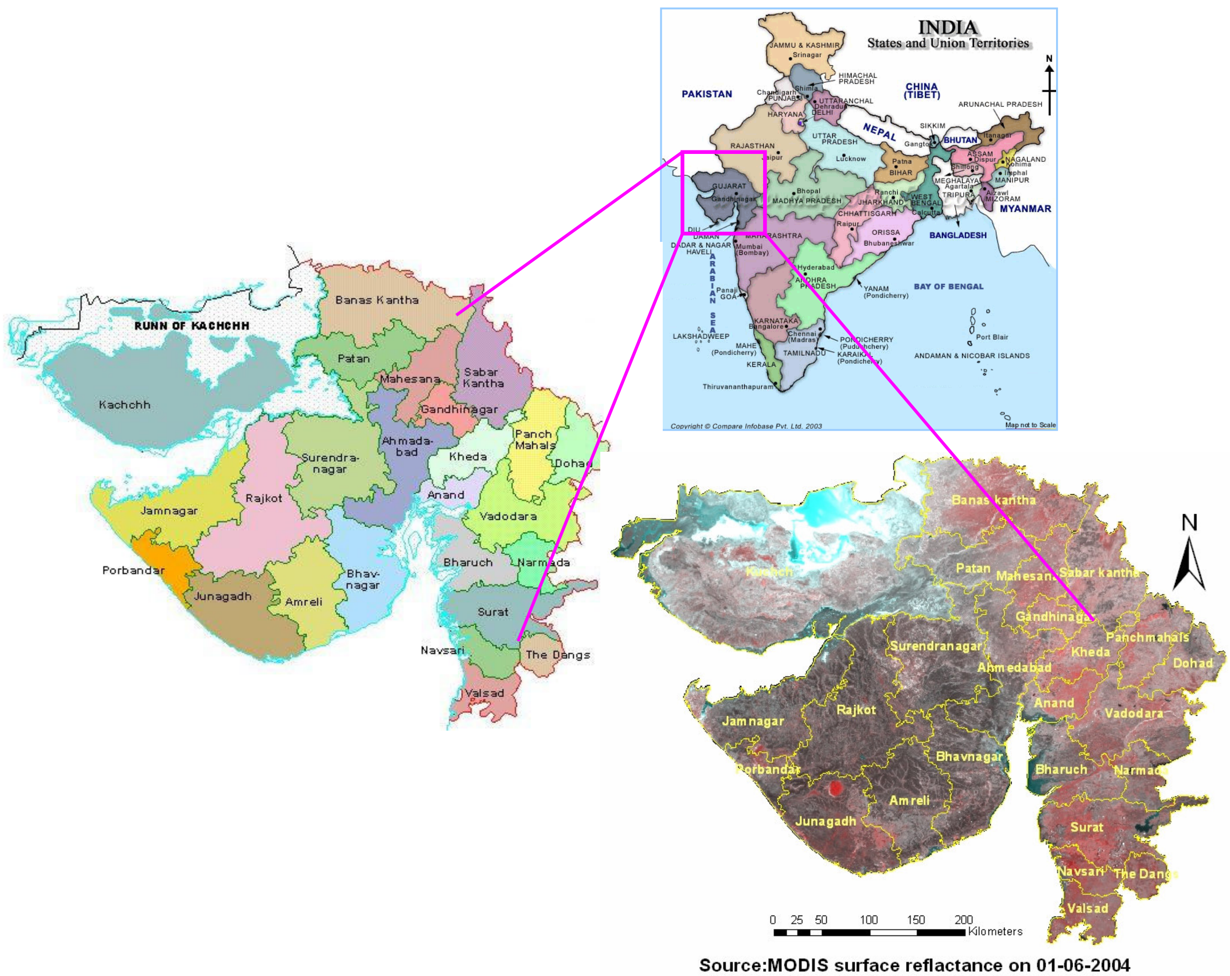


Figure 3.1: The location of study area "Gujarat state" in India

3.3. Agro climatic zones and climatic conditions

Agro climatic zones of Gujarat state is sub grouped into following categorised.

- Southern Hills
- Southern Gujarat
- Middle Gujarat
- North Gujarat
- North West Arid
- North Saurashtra
- South Saurashtra

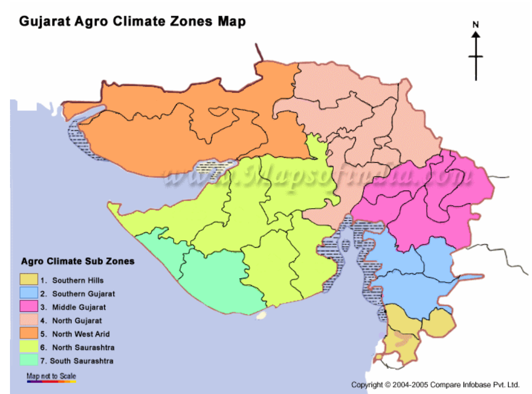


Figure 3.2: The Gujarat Agro climatic zones

Source:(Gujarat Agro Climate Zones Map)

Climate:

The climate of Gujarat is moist in the southern districts and dry in the northern region. The Arabian Sea and the Gulf of Cambay reduce the temperature and render the climate more pleasant and healthy. 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 to152cms. The southern region of the state has an average rainfall ranging from 76 to 152cms, the Dangs district having the highest average of about 190cms. The northern districts have a rainfall varying from 51 to 102cms. The rainfall in the southern highlands of Saurashtra and the Gulf of Cambay is approximately 63cms while the other parts of Saurashtra have a rainfall less than 63cms. The semi-desert area of Kutchch has a very low average rainfall. Certain areas in Ahmedabad, Mehsana, Banaskantha, Panchmahals, Surendranagar, Jamnagar and Kutch districts face chronic water scarcity conditions for want of adequate rains. As the Tropic of Cancer passes through the northern border of Gujarat, the state has an intensely hot or cold climate. But the Arabian Sea and the Gulf of Cambay in the west and the forest covered hills in the east soften the rigors of climatic extremes.

During the winters the temperatures reach up to 27ºC and go down to 12ºC. These vary in different parts of the state and certain areas, particularly the desert ones can get really cold spell at night. The region of Kutch can be described as the desert like area. In the summer average temperature is in between 25º to 43ºC and reach as high as 48ºC. The highest temperatures have been recorded at Ahmedabad and in regions of Banaskantha while temperatures are relatively low at places located in coastal regions.

3.4. Physiography and soils

The Gujarat state has been divided into three major physiographic regions, namely the Central Highlands, the Western Hills and the West Coast. The extreme part of the state is occupied by the Central Highlands, a wide belt of hilly region bordered by the Arravali Range on the west. The Western Hills forms the part of the peninsular plateau while the Western Coast covers major portion of the state, comprising of Gujarat Plain, Kathiawar Peninsula and Kutch Peninsula. It has fertile plain in the south cut by several rivers, low hills in the west and broad mudflats in the north that adjoin the Thar (Great Indian) Desert.

The Soils of Gujarat can be broadly classified into nine groups namely black soils, mixed red and black soils, residual sandy soils, alluvial soils, saline/alkali soils, lateritic soils, hilly soils, desert soils and forest soils [Kanzaria and Patel, 1985] in (Shekh, 1989). The Saurashtra region of Gujarat is characterized by mainly two types of soil, i.e., Entisols and Inceptisols. Entisols are light grey, greyish brown and reddish brown in colour and have formed under tropical semi-arid climate. The depth ranges from a few cm to 1 m. By texture, they are sandy-clay, loam or clay-loam to clay. Structurally weak, mainly sub-angular, blocky and sometimes crumb-like, these soils are calcareous and alkaline in nature. Inceptisols, on the other hand, is the main soil type of Bhavnagar area. They are dark to light grey, reddish brown, yellowish red and dark reddish brown in colour, produced through weathering under tropical semi-arid to humid climates, calcareous in nature and vary in depth from 30-80 cm. Texturally, the soils are silty loam to clay and neutral to alkaline in reaction. The coastal inceptisols are sandy-clay-loam to clay and rich in smectite group of clay minerals (Yogesh, 2004).

3.5. Agriculture and Landuse

Agriculture in Gujarat forms a vital sector of the state's economy. It has to provide the required food grains for the state's population and raw materials for most of the agro-based industries. Unsuitable climatic conditions in some parts and rocky terrain with thin or no soils in others, have limited the area suitable for cultivation. The difficulty of drainage in coastal areas and in the two Ranns has made a large part of the state agriculturally unproductive. The state's agricultural productivity is low. The yields are poor and in most cases do not even approaches the low level of average yield for the country. Low yields result from poor soils, inadequate rainfall, frequent droughts and floods, bad drainage and undeveloped irrigation facilities. A characteristic feature of the state's agriculture is its cropping pattern un-proportionately dominated by cash crops. The high yield of cotton in fact the highest in the country reflects the overall emphasis on cash crops, which have claimed the best agricultural land.

A higher percentage of the land is used for cultivation in central Gujarat. Kaira, Baroda, Broach and Surat districts are the main contributors to the agricultural production of the state. The major food crops in the State are Rice, Wheat, Jowar, Bajra, Maize, Tur, Gram, Groundnut while major non food crops are Cotton, Tobacco. In the year 1999-2000, the gross cropped area and net cropped area were reported to be 107.02 lakh ha and 94.99 lakh ha. respectively. In the year 1999-2000, the total net area irrigated was 29.80 lakh ha in the State. In the year 1995-96 the average size of land holding was reported to be 2.62 ha. As per triennium average ending the year 2001-02, the production of the total food grains was estimated to be 38.28 lakh tonnes. Valsad has become India's first integrated horticulture district. The state produces a large variety of crops and its cropping pattern reflects the spatial variations in climate and topography. Groundnut (highest production in the country), cotton, Tobacco (second highest production in the country), isabgul, cumin, sugarcane, Jawar, Bajra, Rice, Wheat, Pulses, Tur and Gram are the important crops of Gujarat. Gujarat stands the first in the production of cotton, groundnut, salt and milk in India. It stands second in the production of tobacco. The leading crops are rice, maize (corn), peanuts, cotton, and tobacco. Another cash crop, which has recently entered the field, though in a few selected localities is banana. Plenty of mangoes for export as well as home consumption are part of cash crops.

4. Materials and methods

4.1. Materials

4.1.1. Data collected during Field work

The preparatory phase of fieldwork has been done before going to field for study the agricultural drought stress on crop performance. During this period the basic information and data were colleted related to the literature searching for drought stress and its impacts on agricultural crops and the advance satellite based indices for monitoring agricultural drought like vegetation temperature condition index. The following materials and equipments have been listed for field study. This includes

- MODIS satellite imagery: Surface reflectance FCC (2, 1, 1) images for the period of 2000 to 2004. All these images were downloaded before fieldwork from Earth observing system data gateway.
- GPS (Global position system)
- Administration map of Gujarat state

The fieldwork took place in the period from 6th August to 19th August 2005.During field work the data has been collected from different organisation/institute in Gujarat. The institute includes Directorate of Agriculture Gujarat State, Gandhinagar; SAC, Ahmedabad; BISAG, Gandhinagar; Gujarat Agriculture University, Anand; and Junagarh Agriculture University. During field work the library work also done for the collection of crop parameters for crop growth modelling. The crop parameters include dry matter partioning, heat units (GDD), phenological stages for groundnut and cotton. In addition to this GPS location has been taken with respect to crop coverage in different districts of Gujarat state. The important data collected are given below.

Meteorological data: The meteorological data has been collected for 20 stations, which covers entire Gujarat state. The parameter includes rainfall, maximum temperature, minimum temperature, solar radiation, and evapotranspiration for the period of 2000 to 2004, which is distributed all over Gujarat state. The metrological stations used for study has given in the appendix 4.

Crop Yield statistics: Crop yield statistics has been collected for entire state at district level for the period 2000 to 2003. It includes all major crops like groundnut, cotton, wheat, rice, Jawar, Bajra, Tur, sugarcane and pulses etc.

Software used: ENVI 4.1, ERDAS IMAGINE 8.7, ARC GIS 9.0, PS-n, SPSS

4.1.2. Satellite Data

Especially in natural hazard monitoring, remote sensing techniques plays a crucial tool for timely decision making processes .The moderate resolution imaging spectroradiometer (MODIS), launched on NASA's Earth observing system (EOS) Terra satellite on December 18, 1999 provides a comprehensive series of global observations of the Earth's land, ocean, atmosphere and for satellite measurements of global LST in the visible and infrared regions of the spectrum. NASA's EOS Aqua system, a sister satellite to Terra, has already been launched, and it has an early afternoon observation time, crossing the equator at approximately 1:30 PM MODIS is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon (Conboy, 2004). At higher temperatures, radiation fluxes are much greater and more representative of surface conditions, therefore it is expected that the afternoon observations allows a significant improvement in drought monitoring. It is comprehensive in that it has a wide spectral range (36 discrete spectral bands ranging from 0.4μm to 14.4μm) and spatial coverage and it takes measurements in spectral regions that have been used in past and current satellite sensors .It provides daylight reflection and day/night emission imaging for all points on earth at least once every two days. Satellite data used for study are MODIS Land surface temperature and surface reflectance and the product name is MOD11A2 and MOD09Q1 respectively. These two products have been downloaded from EOS data gate way for the period of June to October from 2000 to 2004. This time series represents the kharif season. All this data is 8 days composite basis and the naming of processed intermediate image has been done according to the Julian day (See appendix 1).

4.1.3. MODIS product characterization

1. MODIS/Terra Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid V004
2. MODIS/Terra Surface Reflectance 8-Day L3 Global 250m SIN Grid V004

1. MODIS/Terra Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid V004 (MOD11A2)

MODIS Land Surface Temperature and Emissivity (LST/E) products provide per-pixel temperature and emissivity values. LST is one of the key parameters in the physics of land surface processes, combining surface-atmosphere interactions and the energy fluxes between the atmosphere and the ground. The moderate resolution imaging spectroradiometer (MODIS) land surface temperature/emissivity product is created, using multiple methods. For land surfaces with high and stable emissivities, a view-angle dependent, split-window algorithm provides calculation of temperature to the nearest Kelvin. For land cover types with variable emissivity, surface temperature is calculated from daytime and night time observations in seven MODIS thermal infrared (TIR) bands using a statistical regression approach, a least-squares fit approach, or both. These MOD11A2 data are provided every 8 days as a gridded level-3 product in the Sinusoidal projection. It has twelve layers and out of these only layer1-MODIS _LST_Day_1km and Layer 02- MODIS_QC_Day has been used for analysis. Land surface temperature (MOD11A2) image shown (Figure 4.1) was retrieved from MODIS data during June and October 2004 over Gujarat state in India. It is an example of the MODIS Level 3 LST 8-Day product at 1 km resolution. MOD11A2 is a composited version of the Level 3 daily LST product.

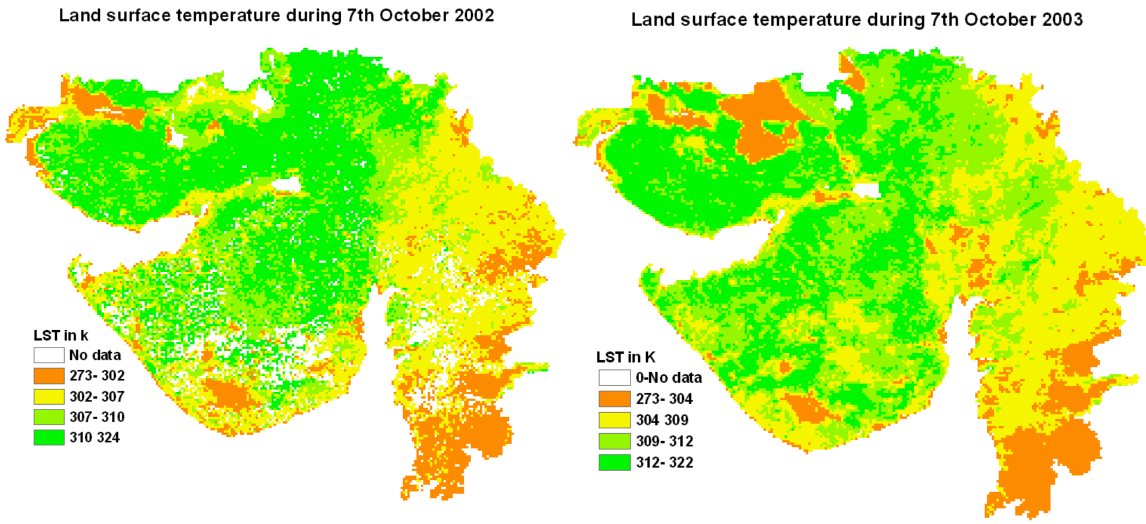


Figure 4.1: The Land surface temperature in different year

2. MODIS/Terra Surface Reflectance 8-Day L3 Global 250m SIN Grid V004 (MOD09Q1)

The surface reflectance product is the input for product generation for several of the land products: Vegetation Indices (VIs), BRDF, Thermal Anomalies, Land cover, Snow/Ice Cover, and LAI/Fpar. It is an estimate of the surface spectral reflectance for each band as it would have been measured at ground level if there were no atmospheric scattering or absorption. This product is a composite using eight consecutive daily 250 m images. The "best" observation during each eight day period, for every cell in the image, is retained. This helps reduce or eliminate clouds from a scene. The file contains the same spectral information as the daily file listed above, centered at 645 nm and 858 nm. There is one additional band of data for quality control. It has three layers and the layer1 and 2 has been used for NDVI computation. The surface reflectance (MOD09Q1) and NDVI derived from surface reflectance image shown (Figure 4.2) was retrieved from MODIS data during October 8-15, 2004 over Gujarat state in India. It is an example of the MODIS Level 3 surface reflectance product at 250m resolution.

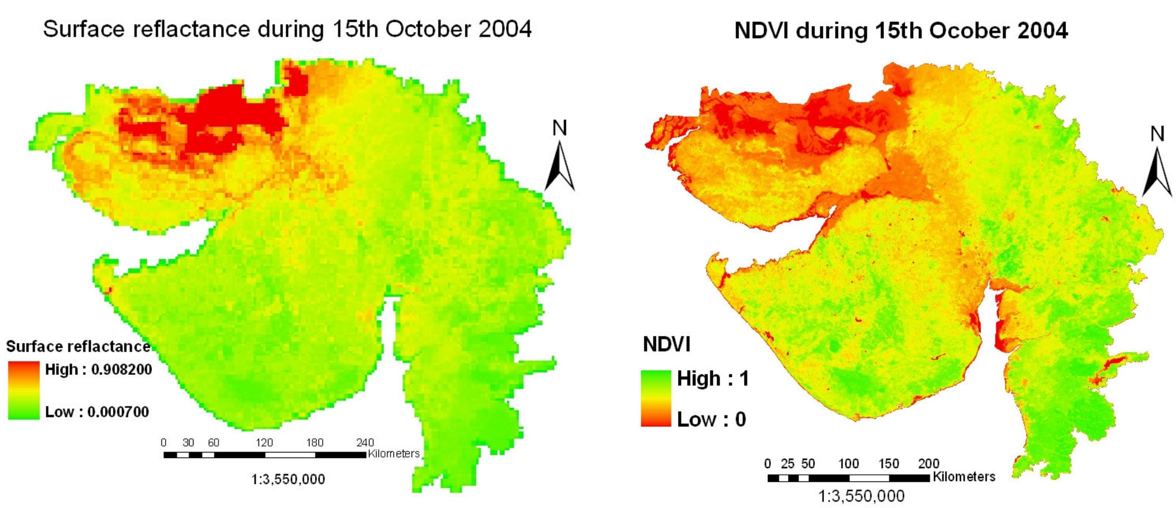


Figure 4.2: The Surface reflectance and NDVI during 15th October 2004

Normalized Difference Vegetation index (NDVI): It is a measure of the amount and vigour of 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 vigour and amounts of vegetation. The reason NDVI is related to vegetation is that healthy vegetation reflects very well in the near infrared part of the spectrum. Previous research suggests the estimation of air temperature extrapolating the best fit line through the NDVI of full vegetation canopy (generally 0.7) and LST correlation. Mathematically it can be written as-

NDVI= (band2-band1)/ (band2+band1)

Where band2=858nm and band1=645nm

4.1.4. Preprocessing of Satellite data

This includes many intermediate steps like

1. Conversion of HDF format to IMG format
2. Reprojection
3. Subset
4. Multification factor
5. NDVI computed from model maker
6. Inherited cloud problem with NDVI and LST products
7. Layer stacking

1. Conversion of HDF format to IMG format: The original MODIS data are provided in the Hierarchical Data Format (HDF-EOS). HDF is a multi-object file format for sharing scientific data in multi-platform distributed environments. This HDF-EOS format image is exported to img format using ERDAS IMAGINE software. After exporting all images it is subjected to reprojection. Version three MODIS data use the Integerized Sinusoidal projection with the WGS84 datum and Version four MODIS data use the more common Sinusoidal projection.

2. Reprojection: MODIS Land surface temperature and surface reflectance image is in sinusoidal projection and WGS84 datum. This sinusoidal projection is reprojected to albers conical equal area and WGS84 datum.

Albers conical equal area

Parameters:

a=6378137.00

b=6356752.31

1/f=298.25

b/a= (1-1/f)

Central Meridian: 78°

Central Parallel or Central Latitude of origin: 20°

Standard Parallel 1:12°

Standard Parallel 2:28°

False Easting: 2000000.00

False Northing: 2000000.00

3. Subset: Using AOI layer of Gujarat state boundary, subset area corresponds to Gujarat state has been done for all the images.

4. Multification factor: Multification factor is different for land surface temperature as well as for surface reflectance. All the LST images has been multiplied by scale factor 0.02 and similarly all surface reflectance images has been multiplied by scale factor 0.0001 in model maker.

5. NDVI computed from model maker: Normalised difference vegetation index has been computed using two bands of surface reflectance image. In Surface reflectance image band 1 represents red and band 2 represents near infrared (wavelength).Mathematically it can be written as-

NDVI= (NIR-R)/ (NIR+R) that is (band2-band1)/ (band2+band1)

6. Inherited cloud problem with NDVI and LST products: The presence of clouds in satellite images is a significant obstacle to land surface studies. Undetected clouds distort the real reflectivity of the land surface and consequently develop into an additional source of error. Clouds in satellite images must thus be precisely identified prior to any further analysis. The total number of NDVI images processed is hundred for the period from 2000 to 2004 and out of these some images were cloudy. Similarly in land surface temperature (LST), the total number of images processed is hundred for same period and most of them images were cloudy. LST products (MOD11A2) from June to end of August month for every year are covered with cloud and to overcome this problem the aqua LST products (MYD11A2) has been downloaded for same period. But it also is having the problem of cloud. Hence in this study the cloud free LST product available during September and October month has been used. It is very important to the reader that satellite observations are often scanty during Kharif season which falls between June to October month in India. Hence there is a lot of scope to use geostationary satellite to overcome this issue.

7. Layer stacking: After processing above intermediate steps, all the images were stacked.

4.1.5. Ambient air Temperature

It is the measurement of the heat content of the air (WMO, 2000). Maximum air temperature occurs near the Earth's surface in troposphere. With increasing height, air temperature drops uniformly with altitude at a rate of approximately 6.5 Celsius per 1000 meters. Air temperature near the Earth’s Surface is a crucial parameter for understanding the boundary layer climate, especially as an index of the thermal energy of the atmosphere. Air temperature is also a key parameter for the energy and water cycles of the earth–atmosphere system. Generally, a meteorological station provides air temperature as a synoptically representative value. The density of the station network is normally not sufficient when air temperature is employed in regional numerical models for climate or for evapotranspiration.

Station air temperature has been interpolated for entire study area using spatial analyst technique called spline for the period of September to October during 2000-2004. The stations used for air temperature interpolation are given in the figure 4.3 and appendix-4. ΔT is the temperature difference between canopy temperature and air temperature and this is computed using LST (To) and interpolated air temperature (Ta). Surface temperatures remain higher than ambient air temperatures until the NDVI reaches a maximum value coinciding with a fully closed canopy. Thereafter fluctuations are (almost) entirely attributed to transpiration (Rugege, 2002).

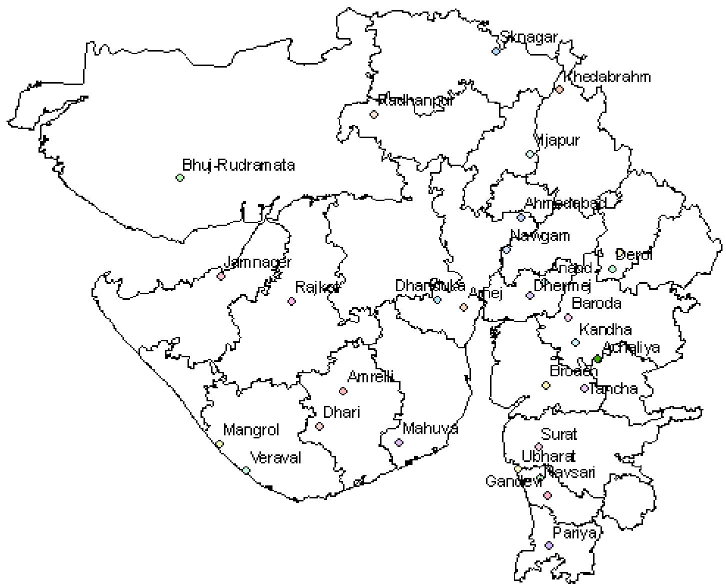


Figure 4.3: The stations used for ambient air temperature interpolation using spline technique

All the processed data sets were used for computing vegetation temperature condition index (VTCI) and water deficit index (WDI).

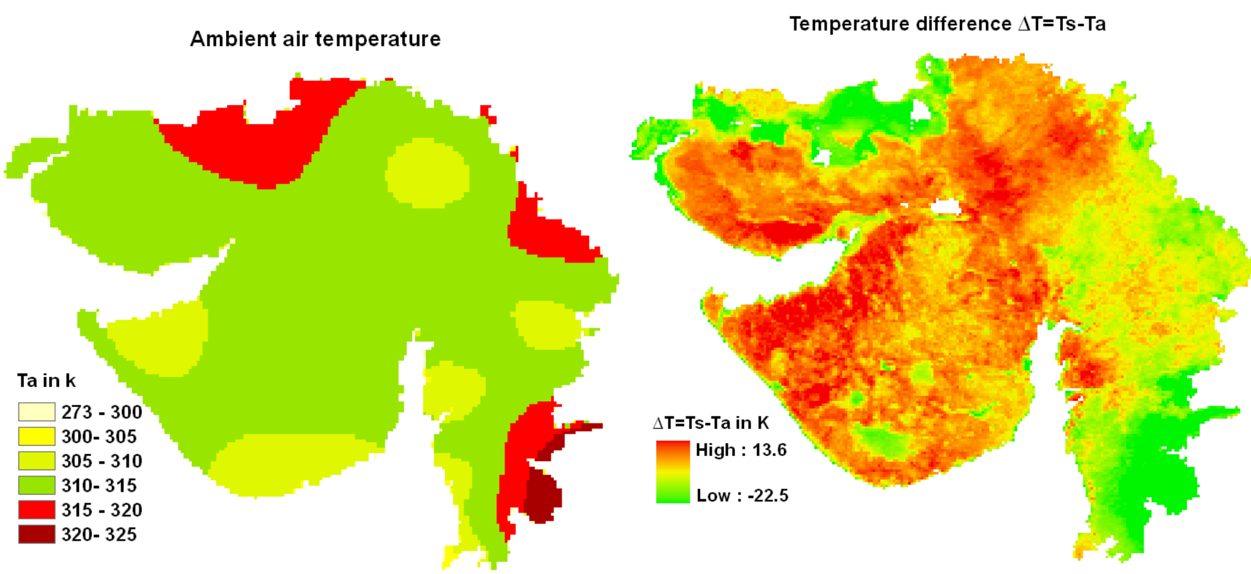


Figure 4.4: The ambient air temperature and temperature difference during 2002(273JD)

4.2. Methods

Various methods used for drought detection has been categorised into three approaches namely
1. Semi-empirical Approach: It includes satellite based vegetation temperature condition index (VTCI) and water deficit index (WDI).
2. Physical Approach: It includes coefficient of water sufficiency (CfH2O) indices and simulated yield using PS-n growth model
3. Meteorological Approach: It includes crop moisture index (CMI)

Methodology Developed For Study

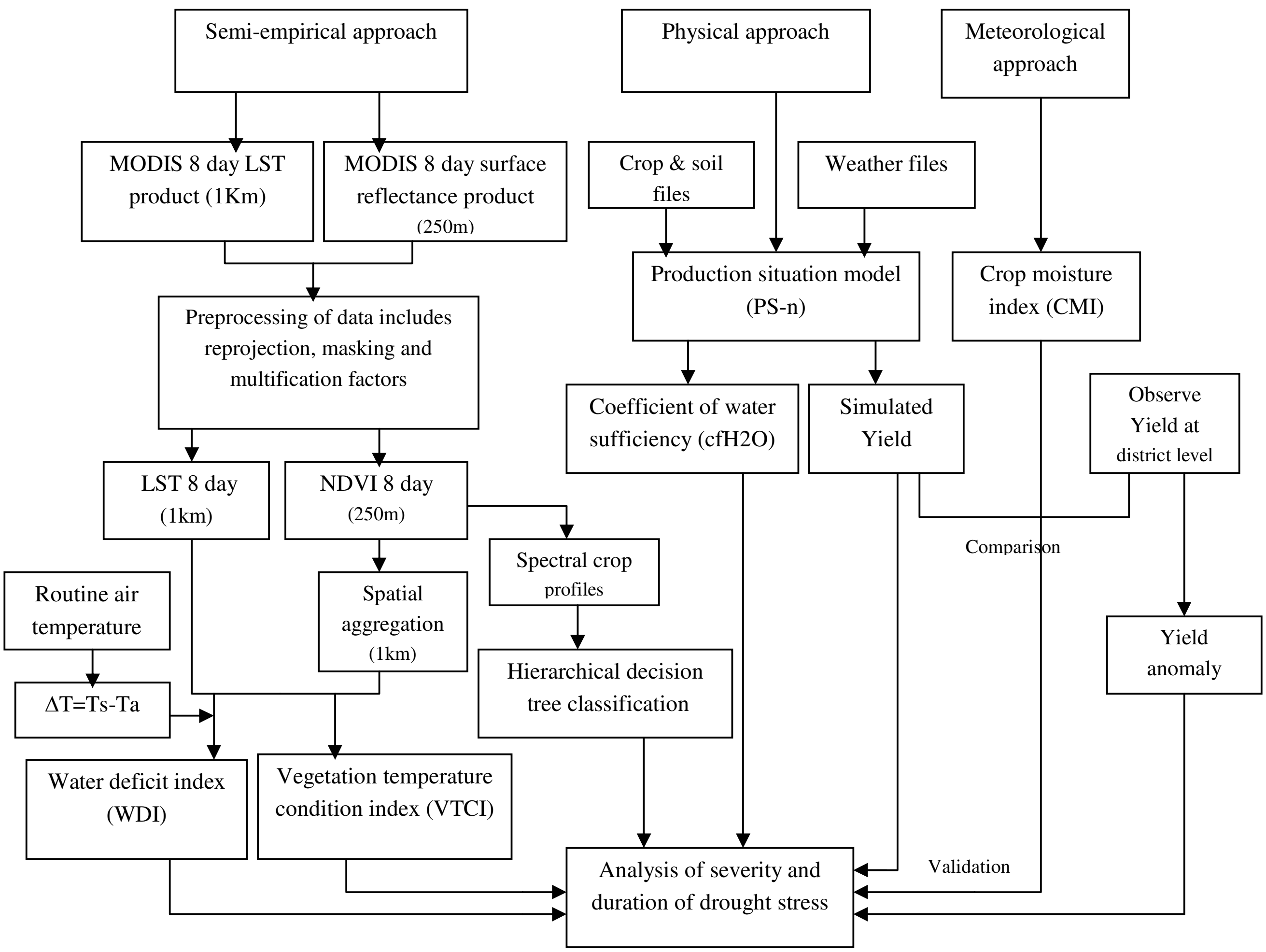


Figure 4.5: Flow chart showing the methodology

4.2.1. Vegetation temperature condition index (VTCI)

A near-real time drought monitoring approach is developed using Terra Moderate Resolution Imaging Spectoradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) products. The approach is called Vegetation Temperature Condition Index (VTCI), which integrates land surface reflectance and thermal properties. VTCI is not only related to NDVI changes in the region, but also related to LST changes of pixels with a specific NDVI value. It is defined as the ratio of LST differences among pixels with a specific NDVI value in a sufficiently large study area; the numerator is the difference between maximum LST of the pixels and LST of one pixel; and the denominator is the difference between maximum and minimum LSTs of the pixels. VTCI is lower for drought and higher for wet conditions. The value of VTCI ranges from 0 to 1; the lower the value of VTCI, the higher is the occurrence of drought.

Mathematically it can be written as

$$VTCI = \frac{LST_{NDVIi\max} - LST_{NDVIi}}{LST_{NDVIi\max} - LST_{NDVIi\min}}$$ **Equation 1**

Where $LST_{NDVIimax}$ = a + bNDVIi
$LST_{NDVIimin}$ = a' + b'NDVIi

$LST_{NDVIimax}$ and $LST_{NDVIimin}$ are maximum and minimum LSTs of pixels, which have same NDVIi value in a study region, respectively, and LST_{NDVIi} denotes LST of one pixel whose NDVI value is NDVIi. Coefficient a, b, a' and b' can be estimated from an area large enough where soil moisture at surface layer should span from wilting point to field capacity at pixel level. In general, the coefficients are estimated from the scatter plot of LST and NDVI in the area. The shape of the scatter plot is normally triangular at a regional scale (Gillies, 1997) and (Wang, 2001), If the study area is large enough to provide a wide range of NDVI and surface moisture conditions. The numerator of equation (1) is the difference between maximum LST of the pixels and LST of one pixel, while the denominator of equation (1) is the difference between maximum and minimum LSTs of the pixels. In figure 4.6, LST_{max} can be regarded as the "warm edge" where there is less soil moisture availability and plants are under dry conditions; LST_{min} can be regarded as the "cold edge" where there is no water restriction for plant growth (Gillies et al. 1997, Wang et al. 2001). Following the above concept the methodology has been developed based on determination of warm edge and cold edge.

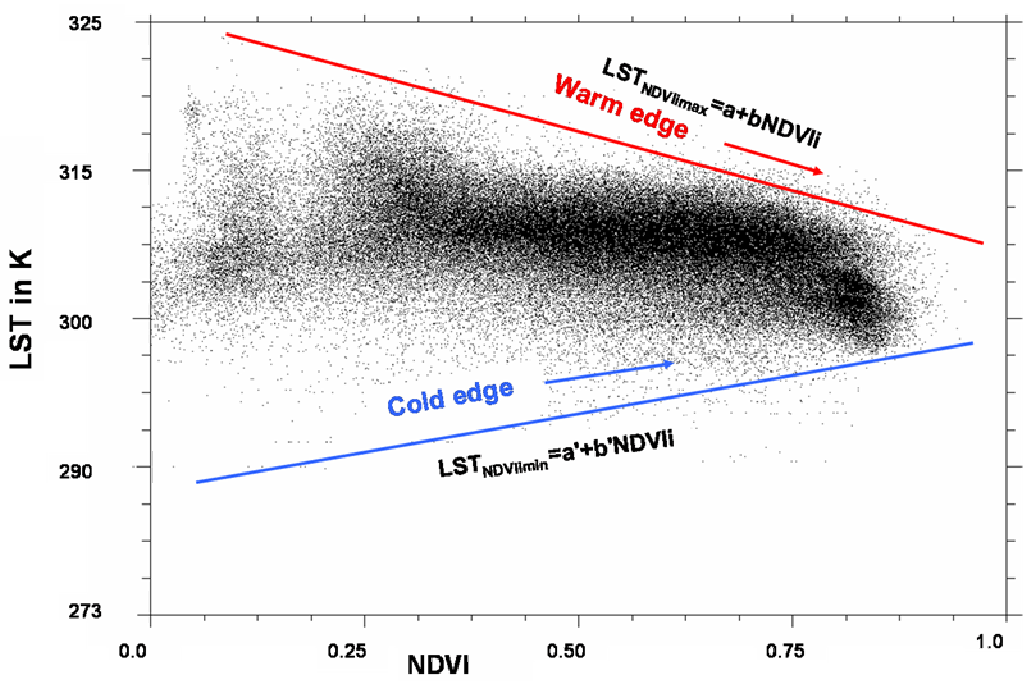
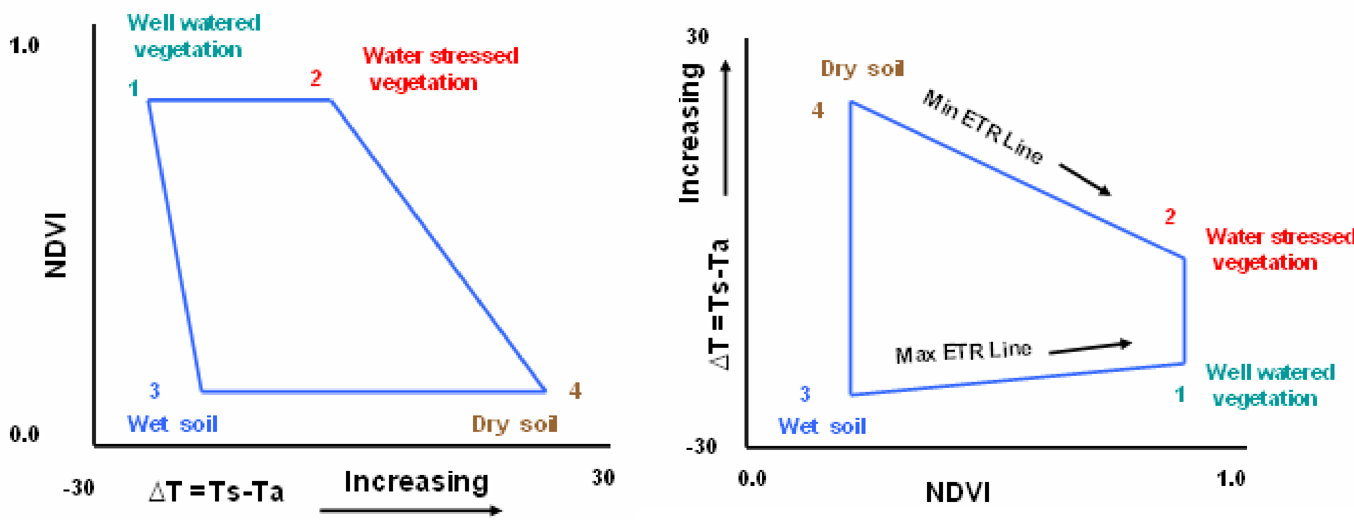


Figure 4.6: Schematic scatter plot of the physical interpretation of VTCI

VTCI is based on the interpretation of a simplified NDVI-Ts space, in which the “cold edge” (no water stress condition) was treated as a line having a lowest temperature to the NDVI axis (X-axis) and the “ warm edge” (no water available condition) was described as having a negative correlation with NDVI. The 2D scatter plot of NDVI and LST data has been made using ENVI and following the concept of VTCI, isolines can be drawn in the triangle, the upper limit of the triangle represents $LST_{NDVIimax}$, where water supply is limited, and the lower limit of the triangle represents $LST_{NDVIimin}$, where there are no water restrictions. The coefficients a, b, a' and $b^{'}$ can be estimated from the scatter plot. In the equation a, a' are the intercept and b, b' are the slope of the warm edge and cold edge respectively. The dry and wet edges were estimated with the linear regression method. Based on the obtained NDVI-Ts space, the VTCI was calculated for each pixel, excluding water body pixels using band math in ENVI. Thus the spatial temporal pattern of drought in Gujarat state can be obtained.

4.2.2. Water Deficit Index (WDI)

It is determined by analysing the spatial distribution relationships of surface temperature-fractional vegetation cover (Shen, 2004). The WDI quantifies the relative rate of latent heat flux leaving a surface by evaporation and transpiration, where the surface is a mixture of vegetation and bare soil. The WDI is defined as 0.0 for well-watered conditions (i.e., a completely wet surface where latent heat flux is limited only by atmospheric demand) and 1.0 for no available water (i.e., a completely dry surface where there is no latent heat lost to the atmosphere). This definition is analogous to the CWSI where the surface is restricted to full vegetation (canopy) cover. Although the WDI is analogous to the CWSI, the WDI as defined is not strictly related to crop water stress because it also accounts for evaporation from bare soil. (Moran, 1994) developed the water deficit index (WDI) that uses both surface minus air temperature and a vegetation index to estimate the relative water status of a field. The distribution of surface minus air temperature at a particular time was found to form a trapezoid when plotted against percent cover. Note that for many crops, there is a linear relationship between percent cover and a vegetation index (such as the normalized difference vegetation index (NDVI = [NIR-Red]/ [NIR+Red]), so the index can be used in place of a direct measure of percent cover. The upper left of the trapezoid corresponds to a well-watered crop at 100 percent cover and the upper right to a non transpiring crop at 100 percent cover (points 1 and 2, respectively). These two points are the upper and lower limits of the trapezoid. The lower portion of the trapezoid (bare soil) is bound by a wet and dry soil surface. These points can also be calculated using the energy balance concepts. The concept of the WDI is illustrated in the figure 4.7(A). In the other way WDI can be modified and represented as figure 4.7(B), by reversing x- axis and y-axis as NDVI and temperature difference respectively. ETR line is the actual evapotranspiration and this can be derive through the use of surface temperature and vegetation index scattergrams (Troofleau, 1998).



(A) (B)

Figure 4.7:The Schematic plot for WDI (Moran, 1994) and modified schematic plot of WDI

(Verstraeten, 2001) formulated the water deficit index (WDI) as

$$WDI = 1 - \frac{ET}{ETm} \approx \frac{\Delta LST_{\min} - \Delta LST_0}{\Delta LST_{\min} - \Delta LST_{\max}} \approx \frac{a\min NDVI + b\min - \Delta LST_0}{(a\min - a\max)NDVI + (b\min - b\max)}$$

Equation 2

Where a_{min} , a_{max}, b_{min}, b_{max} are the coefficient of isoline drawn and ΔLST_0 denotes the difference between the LST and ambient air temperature. Further WDI can be represented as -
Wet line or Max ETR line equal to $\Delta LST_{NDVIimin}=a_{min}NDVIi+b_{min}$ and dry line or Min ETR line equal to $\Delta LST_{NDVIimax}=a_{max}NDVIi+b_{max}$.

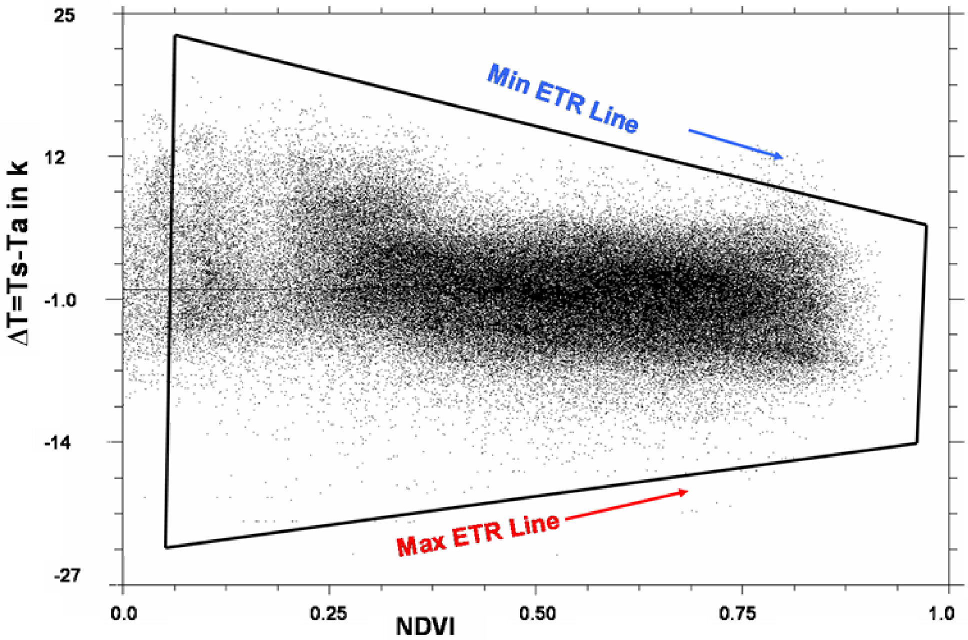


Figure 4.8: Schematic scatter plot of physical interpretation of WDI based on NDVI-ΔT space

WDI is computed using above equation and the isolines are drawn based on the interpretation of a simplified NDVI-ΔT space, in which the "wet line or max ETR line" (no water stress condition) was treated as a line having a lowest temperature difference to the NDVI axis (X-axis) and the "dry line or Min ETR line" (no water available condition) was described as having a negative correlation with NDVI. The dry and wet lines were estimated with the linear regression method. Based on the obtained NDVI-ΔT space, the WDI has calculated for each pixel, excluding water body pixels using band math in ENVI.

4.2.3. Coefficient of water sufficiency (CfH2O) indices

Only few satellite sensors have a sufficient number of channels to derive input parameters meaningful for crop growth simulation. Key to remotely sensed (RS) production estimation is the crop's energy budget. Incident solar radiation incident on the crop canopy is used in part for vaporization of water (crop transpiration). If less water is used (and assimilation and production are depressed) more energy is left for canopy heating, and vice versa. In other words, the difference between the remotely sensed crop canopy temperature and the corresponding ambient temperature is co-determined by the actual rate of crop transpiration. This temperature difference as detected at the moment of the satellite pass is then converted into daily equivalent values. If the transpiration term is isolated from the energy budget and divided by the theoretical transpiration rate of a constraint-free reference crop, a so called 'coefficient of water sufficiency' with daily equivalent values (cfH2O, 0-1) results, indicating the degree stomata closure and therewith the degree to which photosynthetic activity is reduced by the compounded constraints to the actual crop. Recurrent reading at short intervals accounts for the dynamics of crop growth and produces successive, near real-time estimates of actual crop performance (Venus and Rugege, 2004). In short it can be written as-

Coefficient of water sufficiency (cfH2O) = TRact/TRmax

Or

$$cfH2O = \left[\frac{INTER - \left(\dfrac{\Delta T * VHEATCAP}{AERODR} \right)}{LATHEAT * TRO * CFLEAF * TC} \right]$$ **Equation 3**

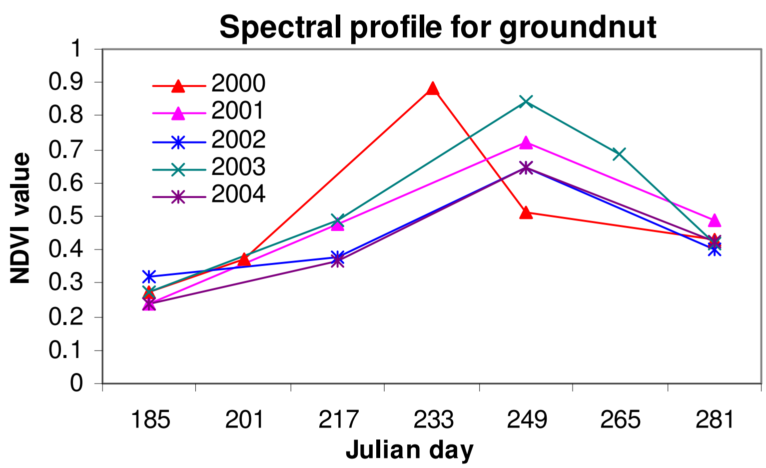
For this study Coefficient of water sufficiency (cfH2O) has been computed using PS-n model and for running this model it requires weather files, crop files and soil files. Weather file includes different climatic parameters such as elevation, Julian day, Tmax, Tmin, precipitation, relative humidity, E0, sunshine hour's duration and ET_0 for the period of 2000 to 2003.The remotely sensed temperature difference has not been taken for PS-n model for yield simulation as well as cfH2O index. In addition to this crop file includes different crop parameters like plant types, threshold temperature(T0),Tsum, Tleaf,Tlow, RDSroot,RDm, RDint,PSIleaf, SLA,TCM,r(leaf), r(root),r(stem), r(so), EC, and relative development stage of the specific crops and soil parameters (See appendix 6).

For this study PS-n model has been used for groundnut because this crop is one of the dominant crops in the Saurashtra region of the Gujarat state which includes seven major districts namely Jamnagar, Surendranagar, Rajkot, Porbander, Junagarh, Amreli and Bhavnagar. Hence PS-n model has been used to know the physical drought persistent and simulation of crop yield in that region. Further the simulated crop yield has been compared with the actual crop yield to know the yield gap and to determine the effects of drought on crop productivity.

Crop stress: It is defined as the factor, which reduces the productivity of the canopy below its potential or optimal value. The response of vegetation productivity to stress can be either an affect on the fraction of light intercepted and absorbed by the canopy or an effect on the efficiency with which that light is used to photosynthesis biomass, which needs adequate soil moisture. So monitoring the biomass and soil moisture can provide sufficient inputs in assessing crop efficiency or stress. Satellite sensed data based vegetation indices are extremely useful in this regard.

Crop Calendar: It indicates the generalized planting and harvesting dates for different crops. Different vegetation types and crops have different phenological cycles, largely depending on the climate of the country. In India there are two main seasons for crop cycles namely Kharif season and Rabi season. Kharif season crops highly depended on south west monsoon which falls in the month of June to October and on the other hand Rabi season crops which are planted after monsoon and generally it includes winter months. Phenology refers to the changes in the life stages of biological organisms and more precisely to the study of the timing of biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelations among them. Development of plants has been defined as a sequence of phenological events controlled by external factors; each event making important changes in morphology and in partitioning of assimilates among different organs during the plant's life-cycle. Crop phenology can be derived from temporal characteristics of vegetation indices (VI) such as NDVI. The phenology indicators extracted from RS data are length of growing season, date of peak vegetation indices (corresponds to ear-emergence/anthesis phase in grain crops), and spectral emergence (indicator of date of sowing). These RS-based phenology indicators have been used in regional crop monitoring applications such as relating length of growing season to crop yields, using spectral emergence date as input in crop simulation models, and using temporal-spectral derived crop stages for accumulating phenology. The interpretation of crop calendar information from growth patterns is aided by the following growth properties and the spectral response pattern of groundnut and cotton.

Time series of NDVI data have extensive applications for crop growth monitoring and yield prediction and from time series vegetation data, spectral crop profiles can be drawn for phenological characteristics. The imaging frequency of satellite data makes a phenological approach possible, defining class in terms of their timing, duration and intensity of photosynthetic activity. Phenological metrics can be calculated and incorporated within an adapted hierarchical decision tree to identify and separate the crop classes. Analyzing NDVI data during the growing season and using the spectral profiles it can described specific phenological metrics for different crops. Spectral profile for groundnut and cotton has been made using time series NDVI data and this has used for land use mapping and crop level classification mapping using hierarchical decision tree method.



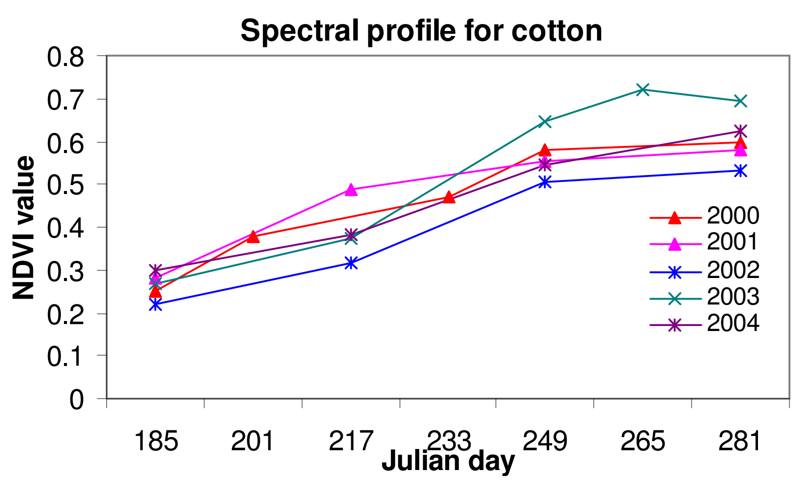


Figure 4.9: The spectral profiles for groundnut and cotton in different years

Hierarchical decision tree:

The generalised land use /land cover classification has been done using hierarchical decision tree method in ENVI. This classification has been done by taking the actual value of various thresholds of NDVI image. Classification criteria/rules used for generalised land use classification are given in the table.

Table 4.1: The rules used for generalised land use classification

Rules	Class
(d6 > 0.74)	Forest
(d6 > 0.46) and (d6 < 0.74)	Irrigated crops
(d6 > 0.20) and (d6 < 0.46)	Rainfed crops
(d6 > 0.15) and (d6 < 0.20)	Fallow land
(d6 > 0.05) and (d6 < 0.15)	Bare soil
(d6 > 0.001068) and (d6 < 0.05)	Salt pans
(d6 < (-0.001)	water

Where d6 is the 8 day composite MODIS derived NDVI image during 15th October 2004(JD 281)

Crop levels classification:

Crop levels classification has been done using above methodology and this is only to Saurashtra region of Gujarat state. This classification has been done using multidate 8 day composite MODIS derived NDVI image.

Table 4.2: The rules used for generalised crop level classification

Rules	Class
(d6 > 0.58) and (d6 < 0.74)	Cotton
(d3 > 0.37) and (d3 < 0.47)	Groundnut
(d6 > 0.20) and (d6 < 0.58)	Other crops
(d6 > 0.15) and (d6 < 0.20)	Fallow land
(d6 > 0.74)	Forest
(d6 < (-0.001)	water

Where d6 is the 8 day composite MODIS derived NDVI image during 15th October 2004(JD 281) and d3 is the NDVI image during 27th August 2004(JD 233).

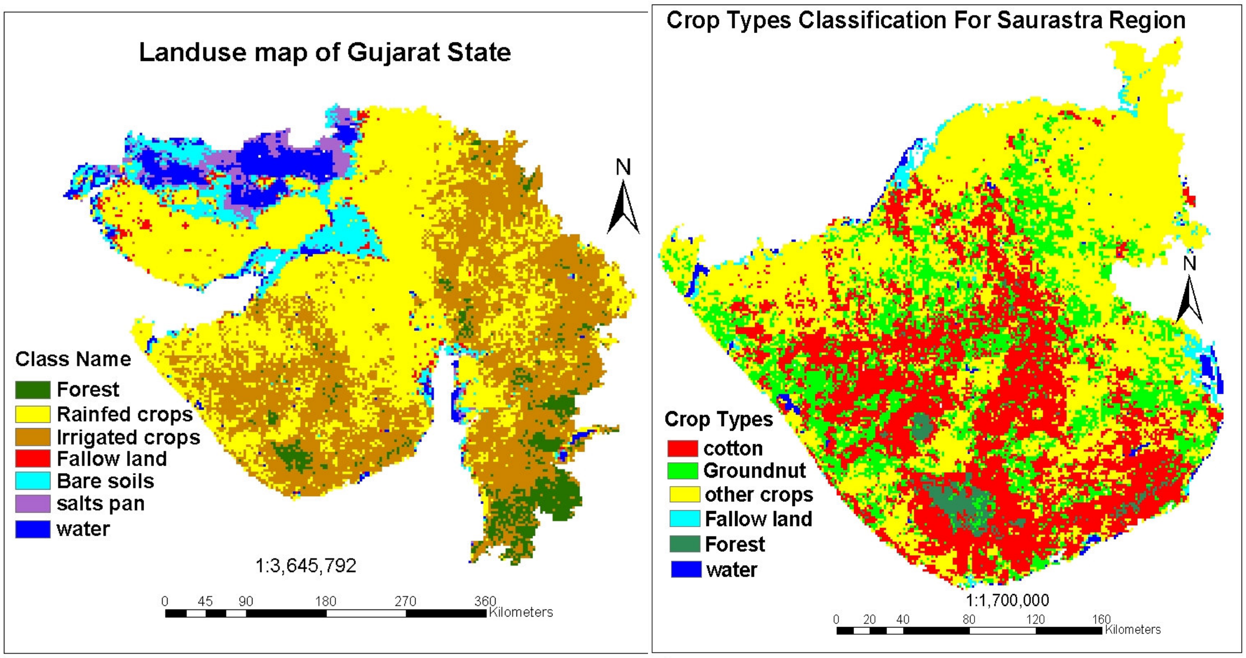


Figure 4.10: The classified land use map and crop types map

4.2.4. Crop moisture index

The Crop Moisture Index (CMI) developed by Palmer (1968), is a complement to the PDSI. It measures the degree to which crop moisture requirements are met, is more responsive to short-term changes in moisture conditions and is not intended to assess long-term droughts. CMI is normally calculated with a weekly time step, is based on the mean temperature, total precipitation for each week and the CMI value from the previous week. Each growing season, CMI typically begins and ends near zero. It is, in principle, possible to use a combination of PDSI and CMI for drought monitoring, where PDSI would serve as a long-term drought monitoring tool, whereas the CMI may indicate the progression of seasonal water shortages during a crop growing stage. The CMI gives the short-term or current status of purely agricultural drought or moisture surplus and can change rapidly from week to week. The Crop moisture index ranges are as follows

Table 4.3: The crop moisture index ranges

-3 or less	Severely dry
-2 to –2.9	Excessively dry
-1to –1.9	Abnormally dry
-1 to +1.0	Slightly dry/favourably moist
+1.0 to +1.9	Abnormally moist
+2.0 to +2.9	Wet
+3.0 and above	Excessive wet

Source: (Climate prediction canter, NOAA)

Crop Moisture Index Calculations

CMI has been computed using PDSI program where precipitation and mean temperature for last 25 years (1980-2004) is given as an input file. In addition to this available water capacity (AWC) also given as an input to the PDSI programme. The calculations of the CMI pick up after all the potential and actual values have been calculated. This allows the moisture levels to be computed. The first step is to calculate the percent of field capacity. This is basically a measure of how full the soil is. The abbreviation has given in the appendix 5. CMI for 25 years overall 20 meteorological stations were calculated.

M = (Ss + Su) / AWC .Next, the relative evapotranspiration anomaly is computed.
CET = Alpha * PE
DE = (ET - CET) / sqrt (Alpha) .Now Y' can be calculated.
Y'i = 0.67 * Y'i-1 + 1.8 * DE
Now Y is calculated based on Y'. if (Y' < 0), Y = Y' else Y = M * Y'
The value of H is determined by the value of Gi-1
If (Gi-1 = 0), H = 0, else if (Gi-1 < 0.5).
H = Gi-1, else if (Gi-1 < 1.0).
H = 0.5, else H = 0.5 * Gi-1.Now Gi can be calculated.
Gi = Gi-1 - H + (M*R) + RO. And finally, the CMI is calculated.
CMI = Y + G

4.3. Historical Crop yield trend and detrended yield anomaly

Historical crop yield represents both kharif food grains and oilseeds crop. All the cereals (Rice, Jowar, Bajra, Maize, Ragi and small millets) and pulses (Tur,Mung,Math,Udid and other pulses) belongs to food grains and in contrast oilseeds refers to groundnut ,sesamum,rape and mustard and castor. Crop yield anomaly trend has been made using long term crop yield data, from 1981 to 2003. Mathematically crop yield anomaly can be represented as-

$$Ya = \frac{(Yi - Yt)}{Yt} \times 100$$

Equation 4

Where Ya=Detrended yield anomaly, Yi =yield in particular year, Yt= yield trend for last 22 years. Yield anomaly has been estimated for district level using linear regression. Year 1981 used as a base year for trend and is indicated by 0 (1981) and finally 22 (2003) in figure 4.11.

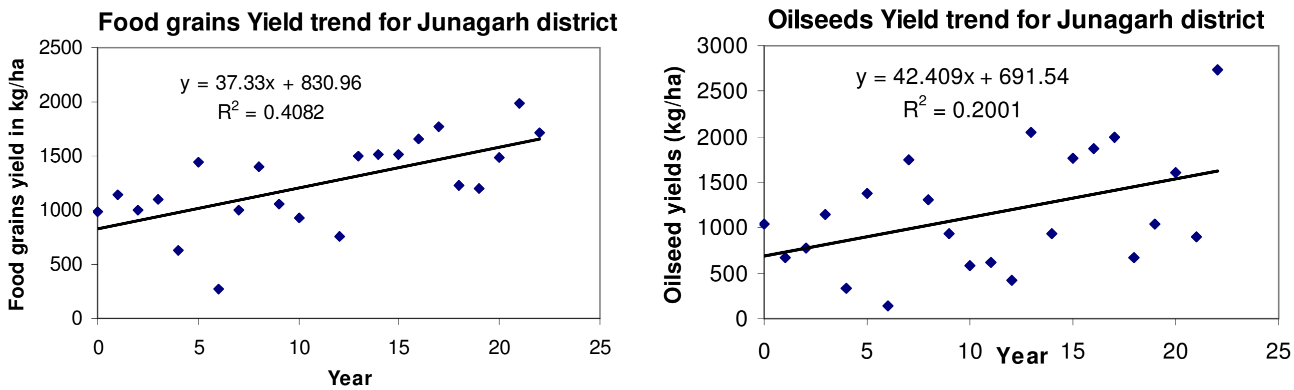


Figure 4.11: The linear yield trend for food grains and oilseeds

4.4. Statistical Analysis

1. Regression between crop moisture index and satellite derived drought indices

Crop moisture index computed value has been correlated with satellite derived index such as VTCI and WDI for each year during 2000 to 2004. The linear regression has been computed with vegetation temperature condition index and crop moisture index. The statistical analyses used are R square, adjusted R square, Std.error of the estimate, F change and Sig.F change. The significance (probability) of the F value or the F value itself has been set as 0.05 level (P value 0.05). In this study the entry probability of F value taken is less than 0.05 for significant result. Similarly the linear regression has been done for water deficit index and crop moisture index. All the above statistical analysis has been done using SPSS software.

2. Correlation of drought indices with detrended yield anomaly of food grains and oilseeds

The detrended food grain and oilseeds anomaly has been correlated with the satellite derived indices. The Pearson's correlation has been used for analysis to observe how strong relationships exist between drought indices and detrended yield anomaly in the study area.

3. Drought duration and crop yield

The food grain yield and oilseeds yield has been correlated with drought duration from 2000 to 2003.The R square value has been used for analysis to observe the relationships between them.

4. Regression between simulated yield and cfH2O with VTCI and actual crop performance

The PS-n simulated yield and actual groundnut yield has been relate on 1:1 line plot and root mean square error has been computed to observe the yield deviation from actual yield. The other statistical analysis used for analysis is R square, adjusted R square and F change.

Root mean square error

Equation 5

$$RMSE = \sqrt{\sum_{i=1}^{n} \left(\frac{P_i - Q_i}{n} \right)^2}$$

The simulated yield has been correlated with the yield departure to study the impacts of drought on crop performance. The historical groundnut yield from 1981 to 2003 has been used for average yield (ym) computation and subsequently yield departure has been calculated to observe the relationships between simulated crop yield and yield departure.

Equation 6

$$Yield\ departure = \frac{Actual\ yield\,(ya)}{Average\ yield\,(ym)}$$

Relative deviation in percent has been calculated to know the deviation of crop yield from the actual yield and this can be written as

Equation 7

$$RD\% = \frac{Simulated\ yield - Actual\ yield}{Actual\ yield} * 100$$

5. Results and discussion

This study attempts to evaluate the drought status in Gujarat state using the vegetation temperature condition index (VTCI) value based on an interpretation of the NDVI-Ts space; and compare VTCI with the estimated crop moisture index (CMI) to verify the efficiency of VTCI in drought monitoring with MODIS satellite data. To evaluate the role of NDVI-Ts relation in drought monitoring, it is necessary to study their sensitivity to VTCI. VTCI has been developed for drought monitoring at a regional level for specific time period that is 2000 to 2004 during crop growing period. This index has been used to monitor the drought occurrences in 8 days composite basis. Similarly WDI has been used to evaluate the drought status using WDI value based on an interpretation of the NDVI-ΔT space; and compare WDI with the estimated crop moisture index (CMI) to verify the efficiency of WDI in drought monitoring with MODIS satellite data.

5.1.1. VTCI from NDVI- Ts space relationships

Vegetation temperature condition index (VTCI) has been computed based on the NDVI-Ts space, 2D scatter plot relation for each pixel. The warm edge and cold edge pixels are subjected to linear regression equation and the derived equations are used for computation of VTCI using band math in ENVI, where land surface temperature (LST) and NDVI images are used as an input parameter for VTCI equations. VTCI has been computed for 5 years (2000-2004), which comprises Julian day of 241 to 297. This index was calculated for September and October month in each year for regional agricultural drought monitoring because these two months corresponds to reproductive period which is more sensitive to thermal stress. Hence this index could better represent the drought during reproductive phase. VTCI is more sensitive towards the reproductive stage of the crops in lieu of early stage of the crops, this is due to land surface temperature is more sensitive towards the dryness rather than more moisture content in the soil as well as there is an inverse relationships existing between LST and NDVI. (Goetz, 1997) 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. In India Kharif season crops highly depended on south west monsoon which falls in the month of June to October and in the study area it has been observed that there is a persistent cloud cover in the LST images during June to August and due to this there is hindrance in the study during early stage of the crops using VTCI index. Generally it has been observed that 20 to 70 percent cloud cover in LST image in the month of June to August in the study area. From this figure it is clear that it is very difficult to study VTCI index during monsoon period using MODIS satellite data. The linear regression equations derived from NDVI-Ts space for VTCI index are as follows.

Table 5.1:The warm and cold edges in NDVI-Ts space estimated by linear regression for every 8 day period in September and October during 2000 to 2004 for VTCI

Year	Julian Day	Warm edge (T_{max})	R^2	Cold edge (T_{min})	R^2
2000	241	$LST_{NDVImax}$ = -14.581NDVI + 319.63	.99	$LST_{NDVImin}$ = 9.9859NDVI + 286.28	.99
	249	$LST_{NDVImax}$ = -15.992NDVI + 328.46	.95	$LST_{NDVImin}$ = 4.3434NDVI + 292.82	.86
	257	$LST_{NDVImax}$= -16.211NDVI + 328.23	.99	$LST_{NDVImin}$= 1.921NDVI + 298.69	.94
	265	$LST_{NDVImax}$ = -14.805NDVI + 329.08	.99	$LST_{NDVImin}$ = 3.3155NDVI+ 300	.97
	273	$LST_{NDVImax}$= -23.37NDVI + 331.86	.99	$LST_{NDVImin}$ = 0.8475NDVI+ 300.94	.60
	281	$LST_{NDVImax}$ = -22.235NDVI + 330.79	.99	$LST_{NDVImin}$= 3.5288NDVI + 297.22	.95
	289	$LST_{NDVImax}$ = -21.877NDVI + 330.88	.99	$LST_{NDVImin}$ = 1.3253NDVI+ 300.86	.90
	297	$LST_{NDVImax}$ = -23.193NDVI + 328.17	.99	$LST_{NDVImin}$ = 2.8904NDVI + 301.84	.99
2001	241	$LST_{NDVImax}$ = -5.3024NDVI + 314.11	.99	$LST_{NDVImin}$ = 5.72NDVI + 292.58	.99
	249	$LST_{NDVImax}$= -13.731NDVI + 319.84	.99	$LST_{NDVImin}$ = 5.4101NDVI + 292.04	.97
	257	$LST_{NDVImax}$= -12.086NDVI + 323.89	.99	$LST_{NDVImin}$ = 2.4165NDVI + 297.3	.96
	265	$LST_{NDVImax}$= -9.8519NDVI + 322.18	.99	$LST_{NDVImin}$ = 3.9041NDVI + 296.25	.99
	273	$LST_{NDVImax}$ = -17.448NDVI + 327.25	.99	$LST_{NDVImin}$ = 5.4196NDVI+ 296.99	.99
	281	$LST_{NDVImax}$ = -13.195NDVI + 324.82	.99	$LST_{NDVImin}$ = 7.0262NDVI + 293.56	.99
	289	$LST_{NDVImax}$= -15.395NDVI + 325.99	.99	$LST_{NDVImin}$ = 4.0422NDVI + 300.25	.99
	297	$LST_{NDVImax}$ = -12.612NDVI + 325.45	.99	$LST_{NDVImin}$ = 0.7407NDVI + 302.31	.80
2002	241	$LST_{NDVImax}$ = -12.499NDVI + 309.79	.99	$LST_{NDVImin}$ = 9.3349NDVI + 286.82	.95
	249	$LST_{NDVImax}$ = -13.209NDVI + 320.62	.99	$LST_{NDVImin}$ = 5.3852NDVI + 292.75	.96
	257	$LST_{NDVImax}$ = -17.618NDVI + 323.87	.99	$LST_{NDVImin}$ = 4.485NDVI+ 294.05	.94
	265	$LST_{NDVImax}$ = -19.581NDVI + 328.03	.99	$LST_{NDVImin}$ = 2.232NDVI+ 298.21	.90
	273	$LST_{NDVImax}$= -15.258NDVI + 327.51	.99	$LST_{NDVImin}$ = 3.8621NDVI + 301.62	.98
	281	$LST_{NDVImax}$ = -16.874NDVI + 326.94	.99	$LST_{NDVImin}$ = 4.8594NDVI+ 300.67	.97
	289	$LST_{NDVImax}$ = -15.613NDVI + 324.84	.99	$LST_{NDVImin}$ = 3.1049NDVI + 300.32	.96
	297	$LST_{NDVImax}$ = -17.761NDVI + 325.38	.99	$LST_{NDVImin}$ = 3.4135NDVI + 301.21	.98
2003	241	$LST_{NDVImax}$ = -5.0938NDVI + 307.65	.96	$LST_{NDVImin}$ = 11.192NDVI + 287.36	.99
	249	$LST_{NDVImax}$ = -9.4377NDVI + 315.28	.99	$LST_{NDVImin}$ = 8.6961NDVI + 290.28	.99
	257	$LST_{NDVImax}$ = -11.339NDVI + 319.1	.99	$LST_{NDVImin}$ = 5.4474NDVI+ 293.24	.98
	265	$LST_{NDVImax}$= -14.833NDVI + 321.9	.98	$LST_{NDVImin}$ = 7.2352NDVI+ 291.61	.98
	273	$LST_{NDVImax}$ = -20.816NDVI + 326.75	.99	$LST_{NDVImin}$ = 2.2807NDVI + 298	.75
	281	$LST_{NDVImax}$= -23.139NDVI + 328.47	.99	$LST_{NDVImin}$ = 1.1777NDVI+ 300.41	.45
	289	$LST_{NDVImax}$ = -16.885NDVI + 324.8	.99	$LST_{NDVImin}$ = 3.4464NDVI + 300.6	.96
	297	$LST_{NDVImax}$ = -22.482NDVI + 325.67	.99	$LST_{NDVImin}$ = 3.4466NDVI + 299.85	.97
2004	241	$LST_{NDVImax}$ = -21.066NDVI + 324.03	.95	$LST_{NDVImin}$ = 8.7953NDVI + 289.29	.99
	249	$LST_{NDVImax}$ = -17.951NDVI + 323.04	.99	$LST_{NDVImin}$ = 7.6205NDVI + 292.4	.94
	257	$LST_{NDVImax}$ = -17.493NDVI + 322.26	.99	$LST_{NDVImin}$ = 8.6475NDVI + 290.76	.97
	265	$LST_{NDVImax}$= -20.737NDVI + 323.93	.99	$LST_{NDVImin}$ = 5.7734NDVI + 292.95	.91
	273	$LST_{NDVImax}$ = -25.74NDVI + 327.9	.97	$LST_{NDVImin}$ = 13.089NDVI + 285	.98
	281	$LST_{NDVImax}$ = -15.333NDVI + 319.14	.97	$LST_{NDVImin}$ = 3.2698NDVI+ 295.59	.89
	289	$LST_{NDVImax}$= -14.615NDVI + 322.03	.99	$LST_{NDVImin}$ = 5.9779NDVI + 299.33	.98
	297	$LST_{NDVImax}$ = -19.104NDVI + 323.18	.99	$LST_{NDVImin}$ = 11.341NDVI + 296.11	.98

From the above table it has been seen that NDVI-Ts Scatter plot for VTCI for entire duration having 40 scatterplot and due to this reason only 5 selected scatterplot from each year has been shown below.

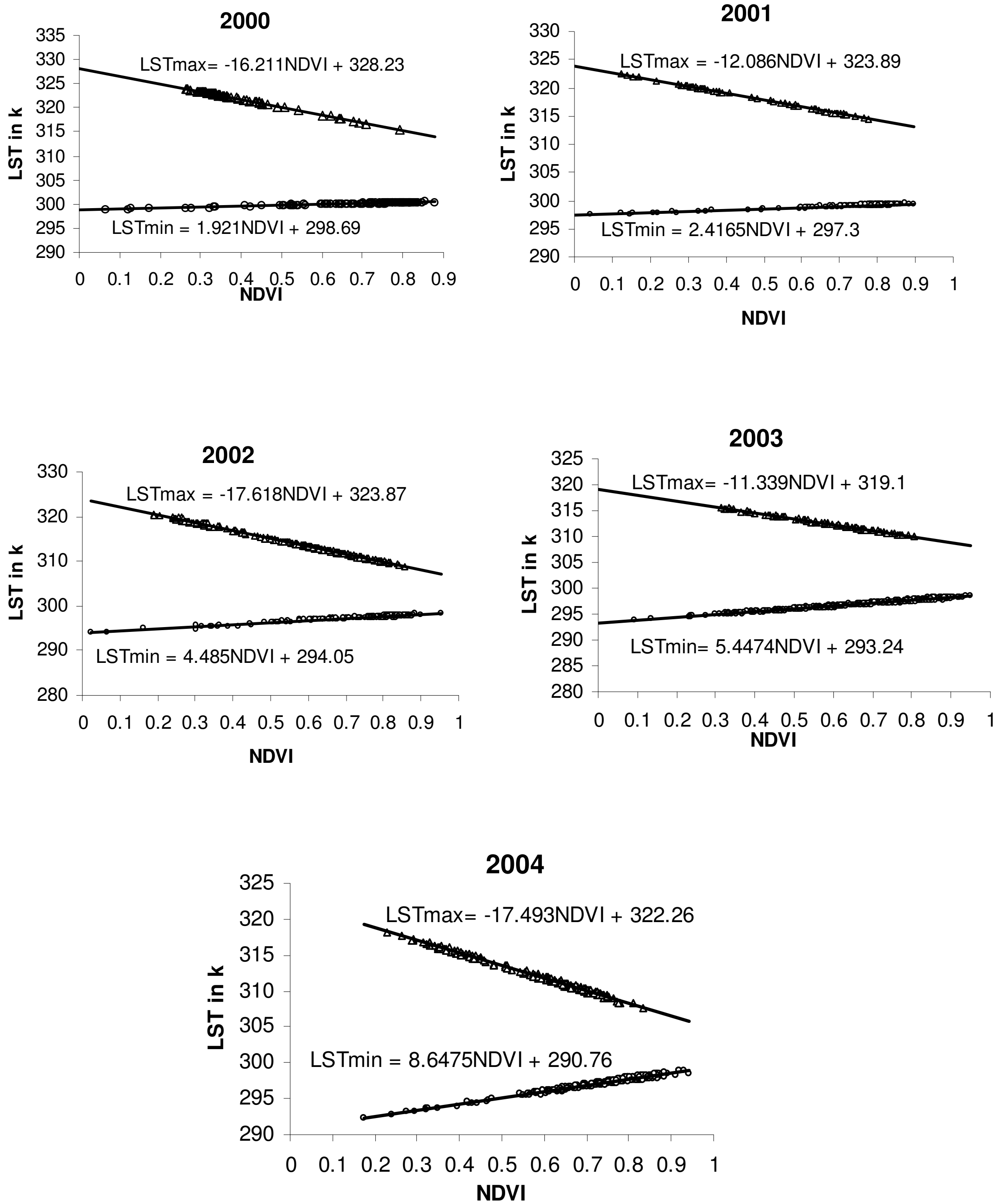


Figure 5.1: The warm edge and cold edge from NDVI-Ts space on 257JD

In all the years it has been observed that the slope is negative for warm edge where as it is positive for cold edge. The slope of warm edge indicates that the Tmax decreasing as NDVI increasing for every NDVI value interval. The slope in cold edge indicates the Tmin increasing as NDVI increasing. In general in warm edge and cold edge, it has been observed that the intercept value is higher during drought year 2000, 2001, 2002 as compared to non drought year 2003, 2004.Particularly on 257JD the intercept of cold edge gives a decreasing trend from 2000 to 2004.But in warm edge the intercept is more than 323 Kelvin for 2000-03 where as less than 323 Kelvin in 2003-04.The overall R square vary from 0.90 to 0.99 in NDVI-Ts space relation.

5.1.2. WDI from NDVI- ∆Ts space relationships

Water deficit index (WDI) has been computed based on the NDVI-∆Ts space, 2D scatter plot relation for each pixel. The wet line and dry line pixels are subjected to linear regression equation and the derived equations are used for computation of WDI, where temperature difference (∆Ts) between land surface temperature and stations air temperature and NDVI images are used as an input parameter for WDI equations. WDI was also computed for 5 years (2000-2004) as similar to VTCI. The linear regression equations derived from NDVI-∆Ts space for WDI index are as follows.

Table 5.2: The wet line and dry line in NDVI-∆T space estimated by linear regression for every 8 day period in September and October during 2000 to 2004 for WDI

Year	Julian Day	Dry line or Min ETR line	R^2	Wet line or Max ETR line	R^2
2000	241	-13.793NDVI + 14.546	.99	11.773NDVI - 20.343	.99
	249	-17.442NDVI + 22.675	.99	7.6011NDVI - 12.76	.99
	257	-20.396NDVI + 24.039	.99	2.678NDVI - 8.8197	.95
	265	-26.784NDVI + 28.373	.99	6.5502NDVI - 10.223	.99
	273	-22.656NDVI + 26.527	.99	6.5019NDVI - 13.457	.98
	281	-25.485NDVI + 29.843	.99	7.1192NDVI - 16.387	.99
	289	-25.839NDVI + 24.436	.99	6.5176NDVI - 12.265	.92
	297	-12.257NDVI + 14.634	.99	5.154NDVI - 7.8986	.99
2001	241	-11.646NDVI+ 12.7	.99	9.4159NDVI - 18.693	.99
	249	-5.3486NDVI+ 14.395	.98	6.7973NDVI - 14.185	.98
	257	-15.441NDVI+ 20.619	.99	4.0816NDVI - 11.547	.95
	265	-10.105NDVI+ 17.454	.99	3.9011NDVI - 11.495	.97
	273	-8.5307NDVI+ 14.085	.97	4.1052NDVI - 12.893	.96
	281	-10.245NDVI+ 17.795	.99	6.3077NDVI - 12.442	.99
	289	-16.551NDVI+ 18.205	.99	5.6347NDVI - 9.0713	.99
	297	-11.82NDVI+ 15.168	.99	5.4986NDVI - 9.5831	.98
2002	241	-16.269NDVI+ 18.56	.99	13.031NDVI- 19.496	.99
	249	-14.044NDVI+ 17.085	.99	4.4925NDVI- 11.588	.99
	257	-11.626NDVI+ 16.537	.99	5.6629NDVI- 12.816	.98
	265	-11.881NDVI+ 19.361	.99	6.3019NDVI- 14.023	.99
	273	-11.345NDVI+ 15.727	.99	8.0466NDVI- 17.196	.99

	281	-14.901NDVI+ 14.442	.99	11.037NDVI- 19.106	.99
	289	-12.508NDVI+ 12.94	.99	9.5868NDVI- 16.18	.99
	297	-15.366NDVI+ 14.23	.99	9.2098NDVI- 16.461	.99
2003	241	-11.948NDVI+ 12.392	.99	10.823NDVI- 19.487	.98
	249	-16.778NDVI+ 15.775	.99	6.1244NDVI- 14.831	.98
	257	-10.445NDVI+ 14.088	.99	5.1952NDVI- 13.715	.99
	265	-16.387NDVI+ 22.373	.99	4.9086NDVI- 12.49	.97
	273	-21.408NDVI+ 22.549	.99	5.7466NDVI- 23.768	.97
	281	-18.472NDVI+ 25.589	.99	10.423NDVI- 23.521	.99
	289	-21.582NDVI+ 20.798	.99	8.9042NDVI- 23.595	.99
	297	-28.545NDVI+ 33.38	.99	16.23NDVI- 20.866	.99
2004	241	-14.923NDVI+ 16.169	.99	5.5061NDVI- 13.315	.98
	249	-15.418NDVI+ 16.185	.99	7.1418NDVI- 14.446	.99
	257	-18.279NDVI+ 18.767	.99	9.1658NDVI- 16.973	.98
	265	-17.916NDVI+ 16.952	.99	5.4639NDVI- 14.973	.91
	273	-16.415NDVI+ 18.99	.99	11.43NDVI- 18.89	.98
	281	-8.9361NDVI+ 12.322	.99	5.3737NDVI- 11.822	.95
	289	-10.881NDVI+ 14.215	.99	5.1892NDVI- 9.1758	.99
	297	-11.567NDVI+ 16.89	.99	8.8365NDVI- 11.951	.99

Similar to VTCI scatterplot, WDI was also having 40 scatterplot based on NDVI-ΔTs space for entire duration and due to this reason only 5 selected scatterplot from each year has been shown below. The slope obtained from NDVI-ΔTs space relation for dry line is negative where as the slope obtained for wet line is positive. The negative slope implies that ΔTmax decreases with increasing in NDVI and positive slope implies that the ΔTmin increases with increasing in NDVI. The intercept vary from 12-33 Kelvin for dry line and -23.7 to -8.8 Kelvin for wet line. It has been observed that in 257JD the intercept of dry line and wet line gives a decreasing trend from 2000 to 2004.

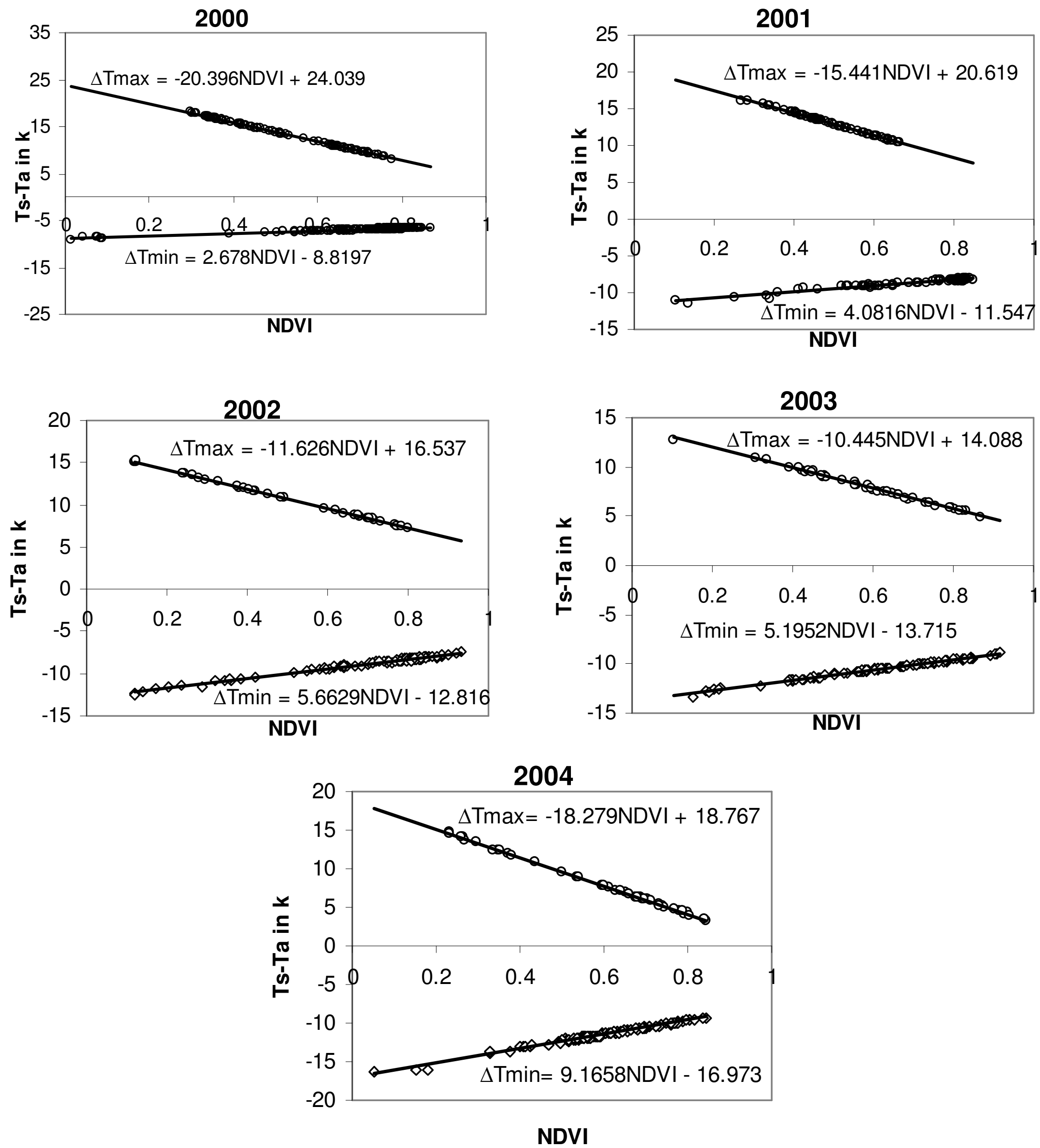


Figure 5.2: The wet line and dry line from NDVI-ΔTs space on 257JD

5.2. Spatial pattern of VTCI and WDI

The spatial pattern of VTCI has been discussed in sub region wise for Gujarat state. For particular Julian day 249 it has been shown in the map. The lower VTCI value denotes the stress condition where as higher VTCI value denotes favourable condition in that region. This period shows year 2000 and 2002 having lower VTCI value in study area as against higher VTCI value during 2004. The lower VTCI tends to stress and higher VTCI value denotes the favourable condition. The VTCI map has been stretched into lower VTCI value to higher VTCI value and it corresponds favourable to stress condition respectively. It has been observed that during 2004, the VTCI value could be more than 0.5 and due to this the favourable condition is dominated in the map.

In general the Northern Gujarat, central Gujarat and Saurashtra regions are showing stress condition during 2000 and 2002. These areas show the lower VTCI as compared to other area. Few districts like Vadodara, Bharuch, Normada belongs to South Gujarat are also showing lower VTCI. It has been observed that the Southern districts having higher VTCI value and it could be more than 0.75 and implies that these districts are favourable. The higher VTCI is due to these districts are having the irrigation facility which tends to no moisture stress to the vegetation. In addition to this the few districts in extreme south is covered by forest. But during 2004 the entire image represents a balanced VTCI value which could be more than 0.45.

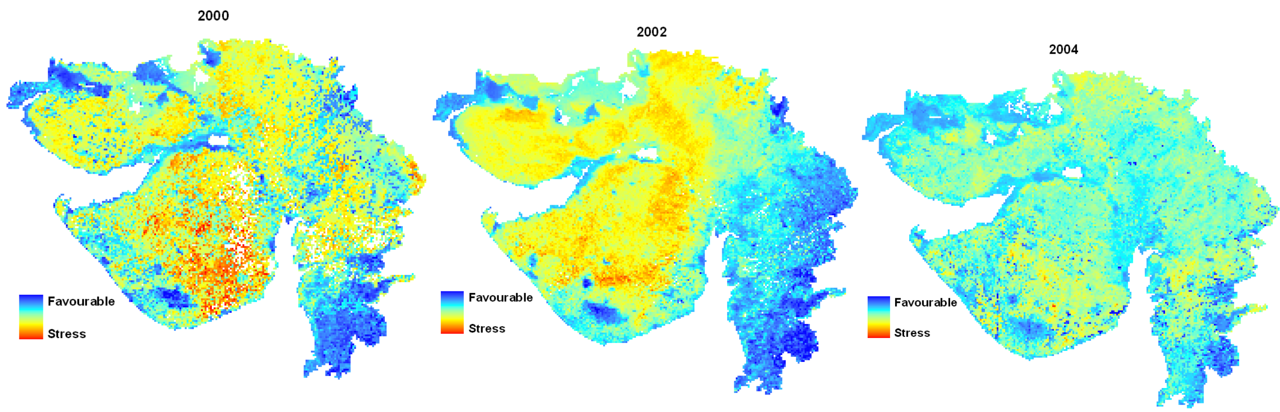


Figure 5.3: Spatial pattern of VTCI on 249 JD during 2000, 2002 and 2004 in Gujarat state

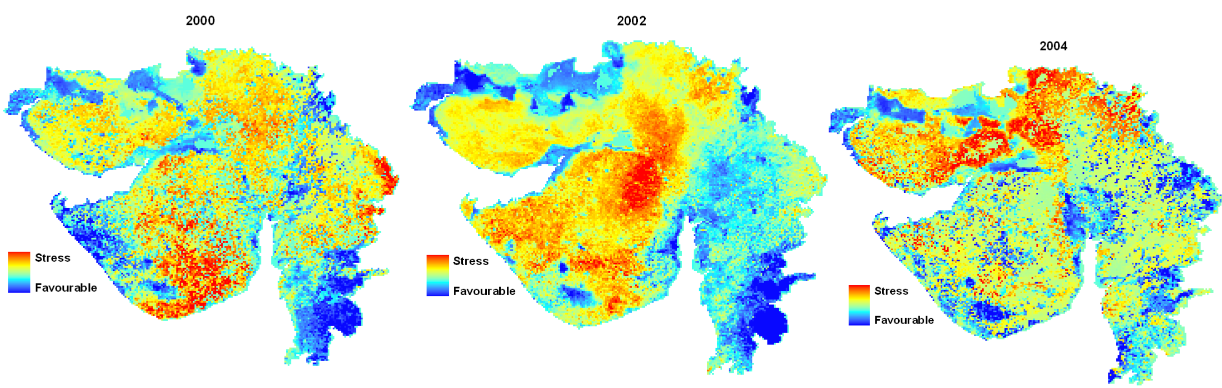


Figure 5.4: Spatial pattern of WDI on 249 JD during 2000, 2002 and 2004 in Gujarat state

The spatial pattern of WDI has been discussed in sub region wise for Gujarat state for 249 JD during 2000, 2002 and 2004. The lower WDI value denotes the favourable condition where as higher VTCI value denotes stress condition in that region and this is just opposite to the VTCI value range. It can be observed that during 2000 and 2002 the spatial pattern of WDI is similar to the VTCI. Although the spatial patterns are similar, WDI gives a distinct class of the condition. In the Saurashtra part of The Gujarat state the stress condition is more during 2002 as compared to 2000.This is due to higher WDI value in Saurashtra. In northern Gujarat the WDI value also high and due to it this showing the entire Northern Gujarat districts are prone to stress. The southern districts showing favourable condition due to lower WDI value during 2002 and in contrast the few districts like Vadodara and Bharuch showing higher WDI value which is as similar to VTCI during 2000.During 2004 the WDI value is higher in Northern Gujarat and shows the stress condition .For other region WDI value is lower as compared to 2000 and 2002.

In overall the analysis shows that based on VTCI as well as WDI the spatial extent of favourable to stress is similar which shows that the year 2000 and 2002 were dominated by stress condition and 2004 was dominated by favourable condition.

5.3. Weekly rainfall and moisture status

A weekly rainfall and crop moisture index relationship has been discussed for Gujarat state for drought year and for non drought year. As spatial pattern of drought indicates that 2000 was the drought year and 2004 was the normal year for Gujarat state and on that basis the rainfall and CMI relation has been done on weekly basis from 22nd to 43rd weeks. The selected meteorological stations are presented for analysing the relationships between weekly rainfall and moisture status. The five selected stations in different region of the Gujarat state has been discussed during 2000 and 2004.The year selected on the basis of drought stress. The year 2000 was affected severely due to drought and on the contrary 2004 was a normal year. In the graph 5.5, weekly rainfall shown in terms of bar graph and weekly moisture status shown in line. In table 5.3, the crop moisture index range has been given for classification of drought.

For 2000

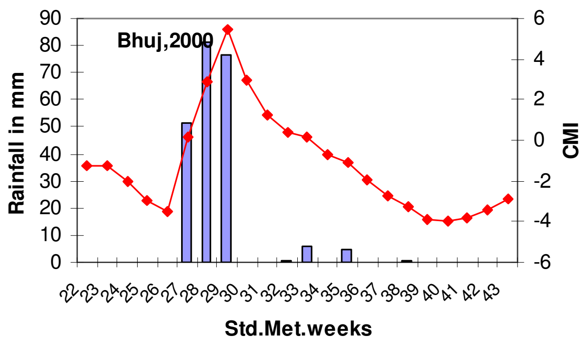
In Northern Gujarat,Bhuj meteorological stations has been taken for analysis .The weekly rainfall received is very scanty and only 3 weeks are having the rainfall more than 50 mm out of total 22 weeks. This shows the scanty rainfall especially during reproductive stage of the crop that is from 35th week to 43rd week. Due to scanty rainfall the moisture status is low across the weeks. In general the crop moisture index less than 1 represents the starting point of dryness and as value of CMI decreases from 1 the drought stress increases. The result shows that the moisture status is very low during 2000 except 28-30th week. This indicates this region is very prone to drought.

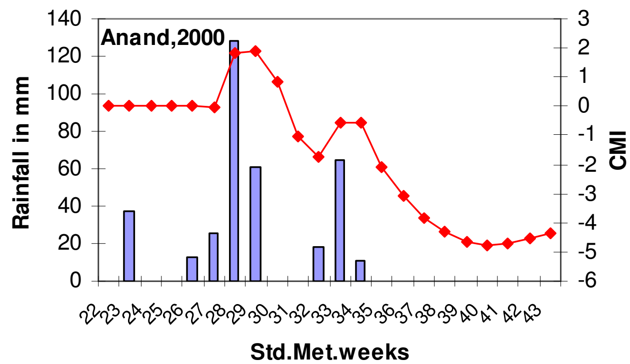
For central Gujarat, Anand stations have been taken for analysis. The weekly CMI shows that from 32 weeks onwards the CMI is less than -2, which shows the stress period. In early period the rainfall has been received but at later stage there is no rainfall. Due to this it shows the late drought in the study area. In Saurashtra part of Gujarat state, it has been observe that the weekly moisture status is less than 1 at Amreli stations, which represents the persistent drought through out the weeks. At Godhra, it has been observed that there is no water shortage at early stage of the crop. From 32 weeks onwards the moisture status is low in that area. In South Gujarat state, it has been observe that the rainfall received is high and it is up to 500mm, which is more as compared to other region like Bhuj, Amreli, and Godhra where rainfall is up to 100mm. Due to high rainfall the CMI values are higher and represents no moisture stress.

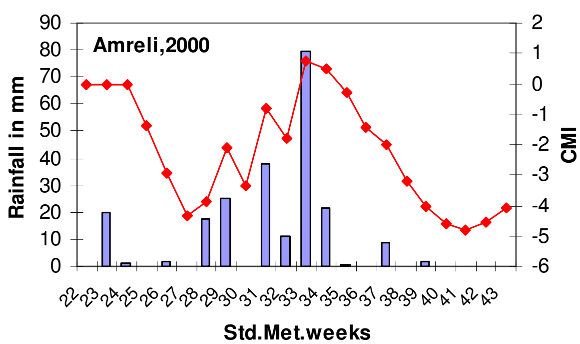
For 2004

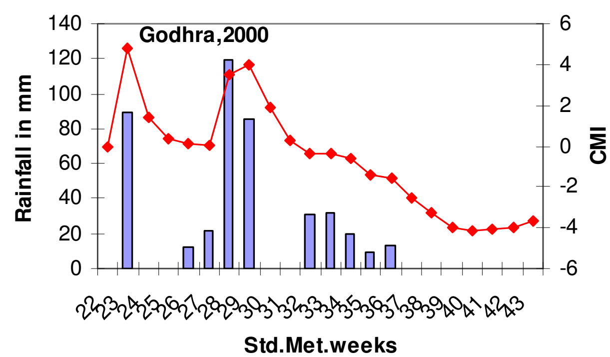
The moisture status at Navsari also high in early period, which shows there are no much impacts of moisture on crops. At Bhuj, it can be observed that moisture status is low and all the periods showing the CMI value less than 1, which represents this region is prone to drought stress. On the contrary moisture status again low at Anand stations except 31-35, where moisture status is high that is more than 1 and up to 12. This implies there is not much impacts of moisture level during 2004. Because the crop can with stand few weeks due to moisture stress and at peak stage again the moisture level increases and hence there is not much impacts on crop. Similarly at Godhra the CMI value is higher at peak stage. At Amreli, the moisture level is near to zero which indicates the slight dry from 22-43 weeks.

In general it can be inferred that the year 2000 is showing less moisture content as compared to 2004 throughout in Gujarat state.









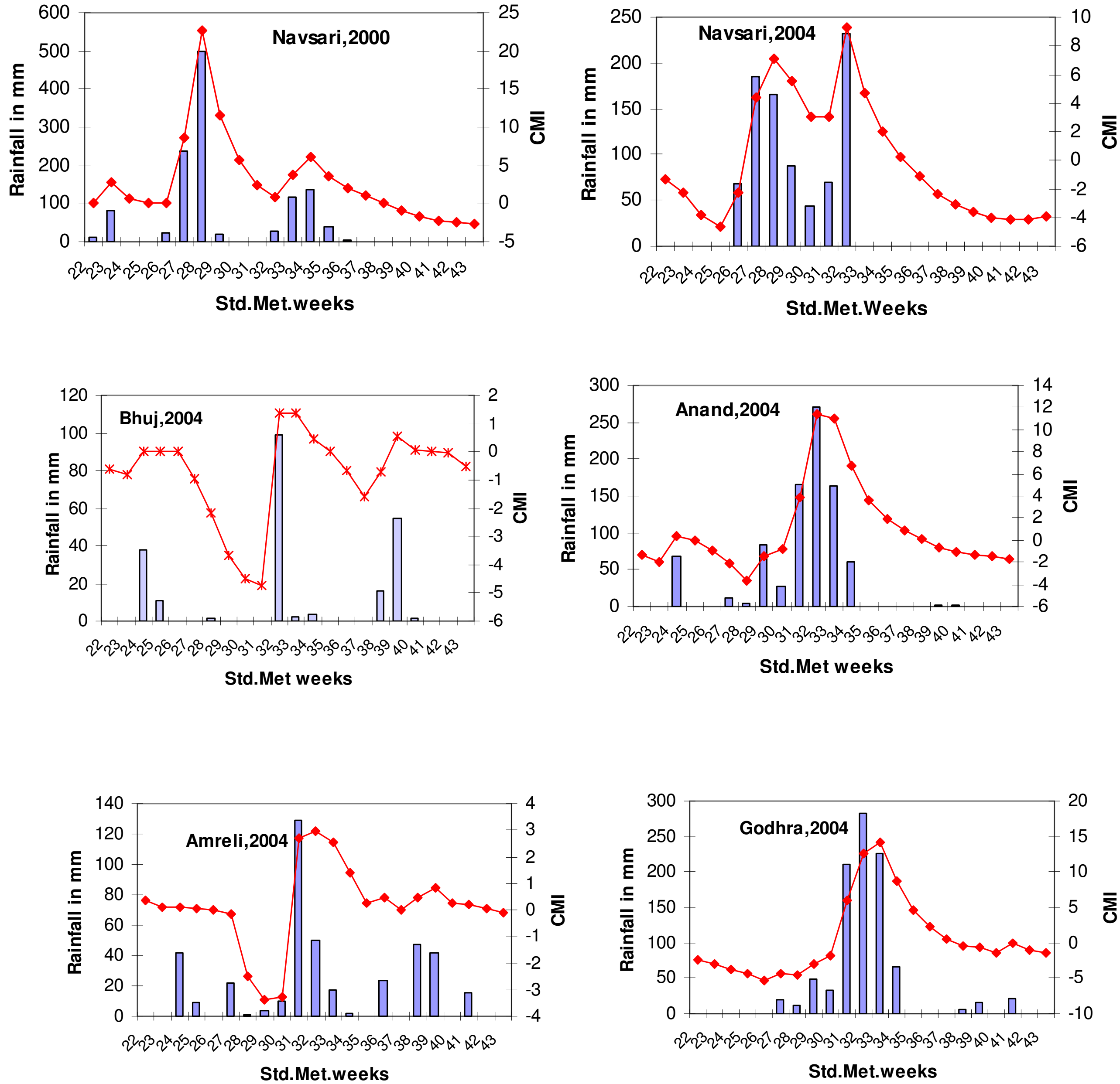


Figure 5.5: The relationships between weekly rainfall and crop moisture index during 2000 and 2004

5.4. Identification of threshold values for different drought indices

An image of 3x3 pixel windows of VTCI and WDI for each period summarising each meteorological stations was estimated to compare with CMI calculated for 20 stations. VTCI and WDI images have been used to extract pixel in model maker for 30 different stations distributed all over the study area. This includes September and October month from 2000 to 2004 in 8 days composite basis, which comprises Julian day of 241 to 297. The resultant 3x3 window pixel value has been used for identifying the thresholds value of VTCI for drought with relation to crop moisture index. Similarly WDI thresholds values have been identified. Further the threshold VTCI value has been used for identifying the duration of drought.

VTCI and WDI images have been used for zonal mean extraction for 25 districts in the study area after masking other features other than agriculture area. This includes September and October month from 2000 to 2004 (JD 241 to 297) in 8 days composite basis. For analyzing the drought on agriculture, all the pixels related to the water, salt pans, forest and fallow land has been discarded from the VTCI and WDI images. The resultant zonal VTCI and WDI mean pixel value has been used to establish the relationships between crop yield and VTCI. The threshold value of VTCI and WDI has been applied to the agriculture masked based VTCI and WDI for reclassifying them into different drought classes.

Crop Moisture Index:

Crop moisture index has been used for identifying the threshold VTCI and WDI value for drought stress. The linear regression trend has been drawn between the CMI and VTCI by taking the all the points of weather stations for each year. VTCI value has been used based on the 3x3 pixel window size surrounding all the stations and on the contrast CMI has been computed for each station based on the last 25 years meteorological data. CMI value has been classified into four types of drought namely normal, slightly stress, moderately stress and severely stress. Similarly WDI threshold value has been identified by drawing the linear regression trend between CMI and WDI value.

Table 5.3: The crop moisture index range for drought classification

+ 1.0 and above	Normal
-1.0 to +1.0	Slightly stress
-2.9 to -1.0	Moderately stress
-3.0 or less	Severely stress

5.4.1. Relationships between satellite based indices with crop moisture index

Linear relationships between VTCI and WDI with CMI were developed for each year. The temporal observations of VTCI and WDI were linearly regressed against corresponding CMI for each year. The results are given in the table 5.4. It was found that the there is a significant positive relationships between VTCI and CMI for particularly on the correlation a negative relationships was noticed between WDI and CMI. This shows that higher WDI values represent greater degree of moisture stress. Despite R square value of coefficient of determination is less the relationships are significant.

Table 5.4: The linear regression equation for defining the VTCI threshold for stress (N=140)

Year	VTCI(y)	R^2	Adjusted R square	Std.Error of the Estimate	F change	Sig.F change
2000	y = 0.0402CMI + 0.5206	0.191	0.185	1.62	32.35	.000
2001	y = 0.055CMI + 0.431	0.188	0.183	1.35	31.63	.000
2002	y = 0.0355CMI + 0.4176	0.311	0.306	2.14	63.24	.000
2003	y = 0.0239CMI + 0.3963	0.146	0.147	2.05	22.51	.000
2004	y = 0.0216CMI + 0.3915	0.105	0.098	1.8	15.29	.000

Table 5.5: The linear regression equation for defining the WDI threshold for stress (N=130)

Year	WDI (y)	R^2	Adjusted R square	Std.Error of the Estimate	F change	Sig.F change
2000	y = -0.057CMI + 0.4495	0.126	0.118	1.54	17.12	.000
2001	y = -0.0406CMI + 0.465	0.179	0.173	1.38	28.57	.000
2002	y = -0.0362CMI + 0.6213	0.406	0.402	1.98	96.56	.000
2003	y = -0.0105CMI + 0.5834	0.049	0.042	2.1	6.48	.012
2004	y = -0.0131CMI + 0.543	0.057	0.050	1.82	7.69	.006

The significance (probability) of the F value or the F value itself has been set as 0.05 level (P value 0.05). The entry probability of F value taken is less than 0.05 for significant result. The F probability result shows for all linear regression equation are less than 0.02 (Sig.F change) and hence all the equation for defining threshold value are significant for further analysis. This indicates the integration of both meteorological data and satellite data for identifying the drought stress. Therefore the null hypothesis1 (H0) which shows that there is close relationship between meteorological based indices and satellite derived indices used for identifying severity and duration of drought stress is accepted and alternative hypothesis (Ha) is rejected.

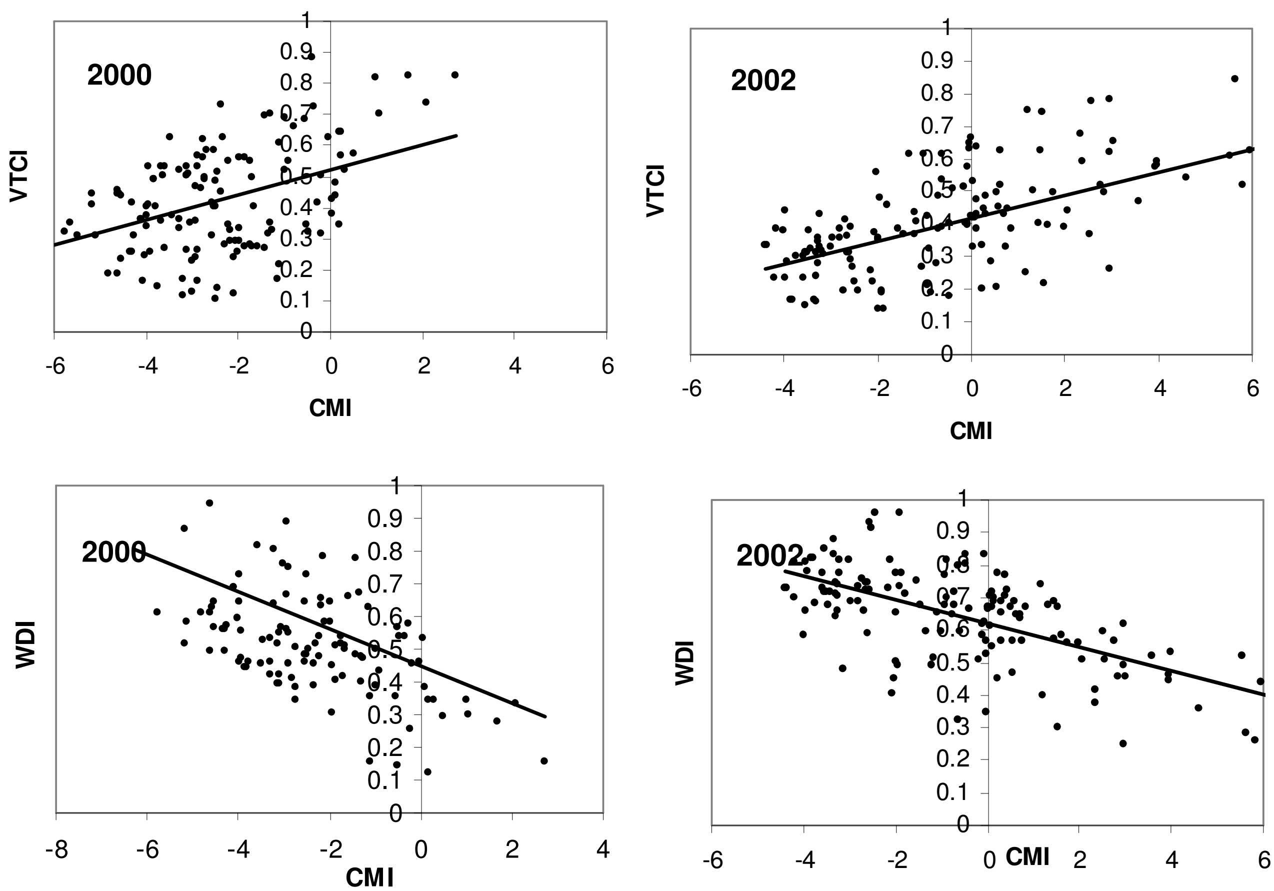


Figure 5.6: The linear regression trend for VTCI and WDI for defining threshold for drought stress

VTCI threshold means the optimum pixel value where agricultural drought stress begins and from that value it starts drought. The agricultural drought stress has been classified into four groups namely normal, slightly stress, moderately stress and severely stress. Crop moisture index value +1.0 and above,-1.0,-2.9 and -3.0 and less has been taken as threshold for normal, slightly stress, moderately stress and severely stress respectively for VTCI as well as for WDI.

Table 5.6: The threshold value for different year from linear regression

Year	Class	VTCI Threshold	Range	WDI Threshold	Range
2000	Normal	0.56	0.56-1.0	0.39	0.00-0.39
	Slightly stress	0.48	0.48-0.56	0.51	0.39-0.51
	Moderately stress	0.40	0.4-0.48	0.61	0.51-0.61
	Severely stress	0.40	0.0-0.4	0.62	0.61-1.0
2001	Normal	0.49	0.49-1.0	0.42	0.0-0.42
	Slightly stress	0.38	0.38-0.49	0.51	0.42-0.51
	Moderately stress	0.27	0.27-0.38	0.58	0.51-0.58
	Severely stress	0.27	0.0-0.27	0.59	0.58-1.0
2002	Normal	0.45	0.45-1.0	0.59	0.0-0.58

	Slightly stress	0.38	0.38-0.45	0.66	0.58-0.66
	Moderately stress	0.31	0.31-0.38	0.73	0.66-0.72
	Severely stress	0.31	0.0-0.31	0.73	0.72-1.0
2003	Normal	0.42	0.42-1.0	0.57	0.0-0.57
	Slightly stress	0.37	0.37-0.42	0.59	0.59-0.60
	Moderately stress	0.33	0.33-0.37	0.61	0.6-0.61
	Severely stress	0.32	0.0-0.33	0.61	0.61-1.0
2004	Normal	0.41	0.41-1.0	0.53	0.0-0.53
	Slightly stress	0.37	0.36-0.41	0.56	0.52-0.56
	Moderately stress	0.33	0.32-0.36	0.58	0.56-0.58
	Severely stress	0.32	0.0-0.32	0.58	0.58-1.0

5.5. Temporal variation of drought indices

According to the crop growth stage, temporal variation of drought has been discussed as drought stress during early stage of the crop and late stage of the crop. CMI and NDVI have been discussed for drought stress in early stage of the crop and in contrast VTCI and WDI have been studied for drought stress in later stage of the crop.

5.5.1. Comparison of drought indices in early and late stage of the crop

Crop moisture index has been computed for different meteorological stations which are distributed all over the study area and based on the CMI value it has classified into four class of drought stress. This index has been computed for entire Kharif season of crop and it includes early stage as well as later stage of the crop. Few selected stations like Anand, Dhanduka, Jamnagar, Surat, Bhuj and Radhanpur CMI are represented in graph (Figure 5.7), which will describe the drought stress pattern in different year and in different region of the study area. In CMI graph the meteorological standard week has been plotted on x-axis, which varies from 22 to 43 weeks. The week no 35 to 43 has been consider as later stage of the crop.

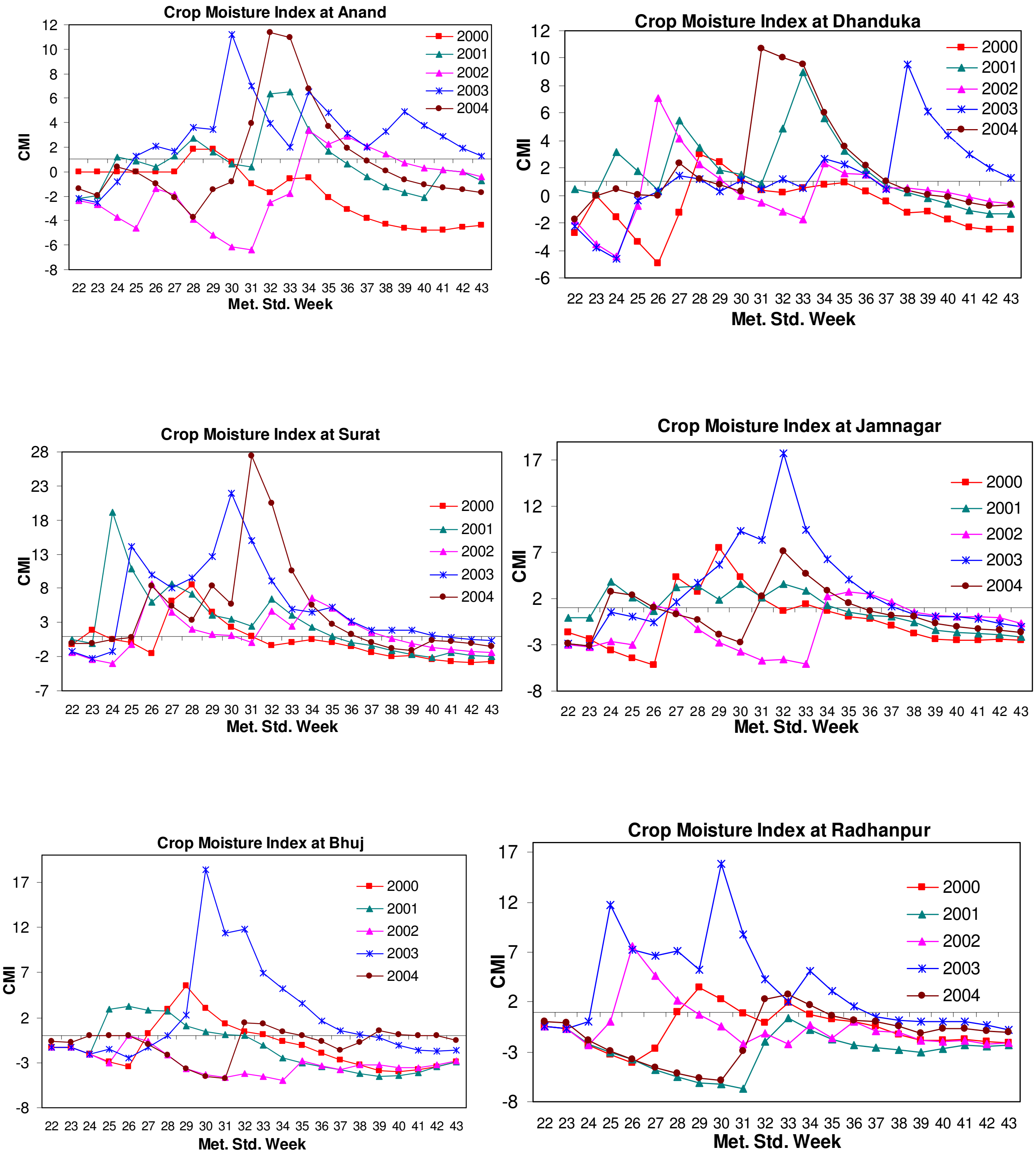
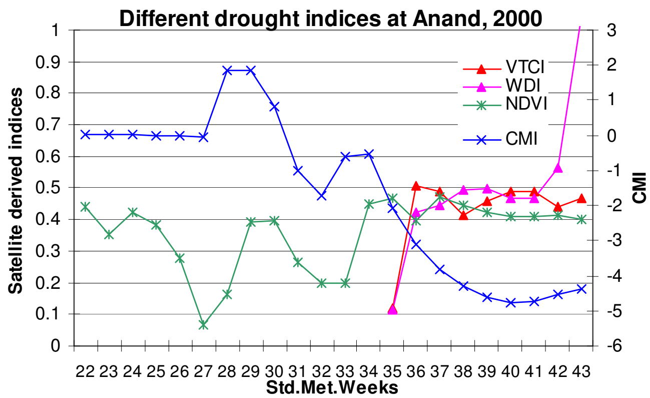


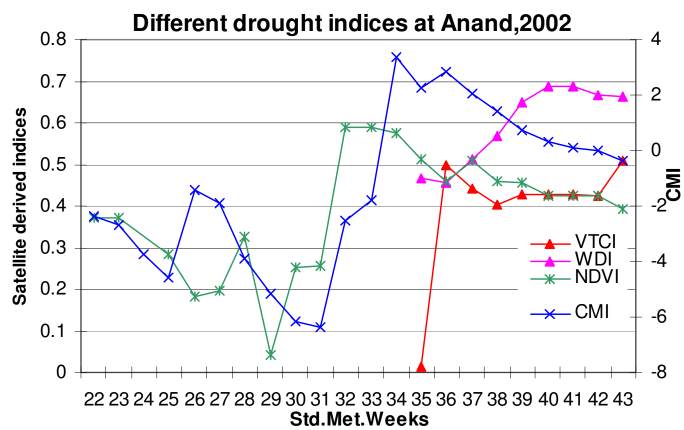
Figure 5.7: The crop moisture index at different stations during 2000 to 2004

CMI value less than 1 is falling under the drought stress and from the above graph it has been observe that majority of the weeks falling under stress for 2000 as well as 2002.This has been proven that specifically this two year was the severe drought stress and in contrast 2001 and 2004 was lesser stress compare to 2000 and 2002.There is another scenario during 2003, where the drought stress is not predominant. This result is exactly matching with the satellite based VTCI spatial drought pattern and it helps to validate the result.

CMI observed at Anand gives a much transparent result of drought stress or pattern for entire duration. In 2000, it can be seen that drought stress is severe in later stage of the crop than early stage and hence year 2000 can be called as "late drought" and in contrast 2002 graph showing the vice versa result, which can be called as "early drought". But this trend may not be same for all the stations and hence it has been generalised that majority of the stations pattern are more or less equivalent for 2000 and 2002.In general northern Gujarat is very prone to drought stress and in this regard drought prone can be better described in Bhuj stations (Kutchch). Except 2003, all the years are under stress and due to this reason this district has been classified under severely drought stress prone area. Therefore the area under this district is always persistent to drought.

In this section the study has been attempted to establish the relationships among satellite derived indices and meteorological computed indices. Selected location namely Anand, Kutchch and Jamnagar has be chosen for establish the relationships among them. CMI and NDVI has been computed for entire period of the Kharif season, mean while VTCI and WDI has been analysed for later stage of the crop period that is from 35 to 43rd standard meteorological weeks. For better explanation of drought pattern in study area, the drought year 2000 and 2002 has been shown here.





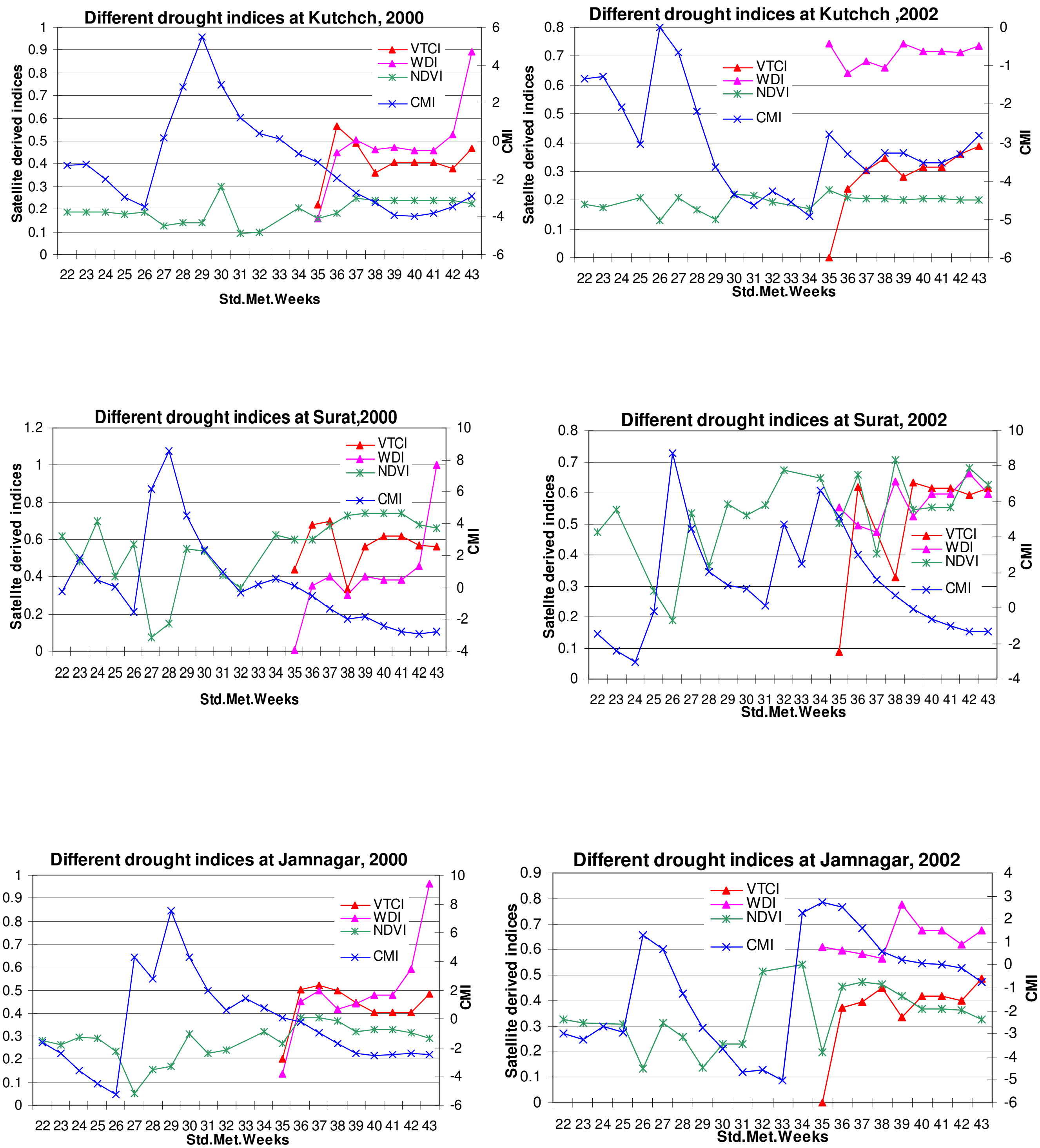


Figure 5.8: The relationships among satellite derived indices and meteorological based index

In Kutchch (Northern Gujarat) it has been analysed that NDVI curve falling under 0.3, CMI also less than 1 for 2000 from 35^{th} to 43^{rd} week, which has been given as threshold value for CMI as stress. In contrast VTCI curve is falling under 0.2 to 0.55 (2000) and less than 0.4 (2002), which connotes that this district is under severe drought stress. Similarly WDI value is more than 0.39 indicates the drought stress for 2000 except the 35^{th} week but in 2002, WDI showing very sharp trend towards the drought stress.

In south Gujarat, Surat the drought pattern is entirely different, except few weeks all the periods falling under the normal and hence no drought. It has been observe that most of the district in south Gujarat has shown the normal condition and very less prone to drought due to irrigation facility.

In Jamnagar, NDVI curve falls under less than 0.4 (2000) and on an average less than 0.45 except few weeks, which describes the pattern of vegetation growth but doesn't gives more explanation about the agricultural drought stress. On the contrary VTCI and WDI give better representation about the drought stress. VTCI curve for 2000 is less than 0.56 (the threshold for 2000) suggests that drought stress is very distinct. WDI also giving the distinct pattern of drought stress that is more than 0.39 (the threshold for 2000) except 35^{th} week. In 2002 both VTCI and WDI is very distinct towards the trend of drought stress.

In Anand also it has been observed that VTCI and WDI curves gives better result of drought stress compare to NDVI as well as CMI. In general during 2000 VTCI value (0.4-0.48) gives the moderate drought stress and WDI gives slight to moderate stress (0.0-0.61) except 43^{rd} week, although meteorological index, CMI gives severely drought stress in later stage of the crop growth. Therefore CMI cannot explain a better way of agricultural drought stress. It implies that although meteorological drought has occurred, there may not be agricultural drought. This may be due to many reasons and among them one important factor may be the residual soil moisture status, soil types and retention capacity of soil moisture etc. In contrast the relationships between VTCI and WDI are very distinct to the drought stress trend.

The above stated results connotes that both VTCI and WDI has got the advantage over NDVI and CMI for agricultural drought monitoring. This is because of land surface characteristics like LST (Ts) which is incorporated in VTCI computation and in contrast ambient air temperature (Ta) and LST in WDI computation. In the other hand NDVI doesn't account land surface characteristics and hence VTCI and WDI is a better index for agricultural drought monitoring.

5.6. Spatial pattern of drought severity based on satellite derived index

Satellite based indices Vegetation temperature condition index (VTCI) and water deficit index (WDI) has been taken for analysis the drought stress on reproductive stage of crop. Based on above mentioned threshold value, the VTCI and WDI for all the period starting from 241 to 297 JD has been classified into four class of drought stress namely normal (no stress), slightly stress, moderately stress and severely stress. The spatial pattern of drought for every 257 JD (14-21st September) during 2000 to 2004 in Gujarat has been shown based on VTCI. This period has shown because this is one of the critical periods for crop out of total period in study area. Similarly the spatial pattern of drought has been shown based on WDI for each year.

5.6.1. Spatial pattern of drought severity based on VTCI

The spatial pattern of drought in Gujarat state has been classified into four classes by masking the forest area, salt pans, water body and other class. The derived threshold of VTCI has been applied to only agriculture area for drought stress classification. Based on this the VTCI has been commuted for each pixel of the study area. However the 2003 and 2004 map showing some portion of the map are covered with cloud, which has been classified under non agriculture area. The different levels of drought pattern in Gujarat state has been discussed under sub region of the state.

Drought in Northern part of Gujarat:
The distribution of drought in 2000 has more severe stress than any of the year. From the map it can be seen that majority of the area under drought stress. The Rann of Kutchch is situated in this region, which is a desert area. The State has two deserts, one north of Kachchh and the other between Kachchh and the mainland Gujarat are saline wastes. Kutchch on the north-east is barren and rocky and contains the famous Rann (desert) of Kutchch, the big Rann in the north and the little Rann in the east. This part showing severely drought stress during 2000, 2001, and 2002 but on the severity has been changed during 2003 and 2004.Even though drought stress has reduced to some extent, this part of the state is always prone to drought.

Drought in Southern part of Gujarat:
The drought stress is absolutely absent in this southern part of the state except year 2000.This is because the agriculture is not depending upon the south west monsoon and the area having the irrigation facility. Hence VTCI value is above 0.5 in this part of the region. The scenario is little difference in 2000 for few districts like Bharuch, Narmada and Vadodara. The drought has occurred in these districts during 2000, this may be due to lower ground water level due to scarcity of rainfall.

Drought in Eastern part of Gujarat:
This part totally has not shown drought stress during 2002, 2003 and 2004 except 2000 and 2001.

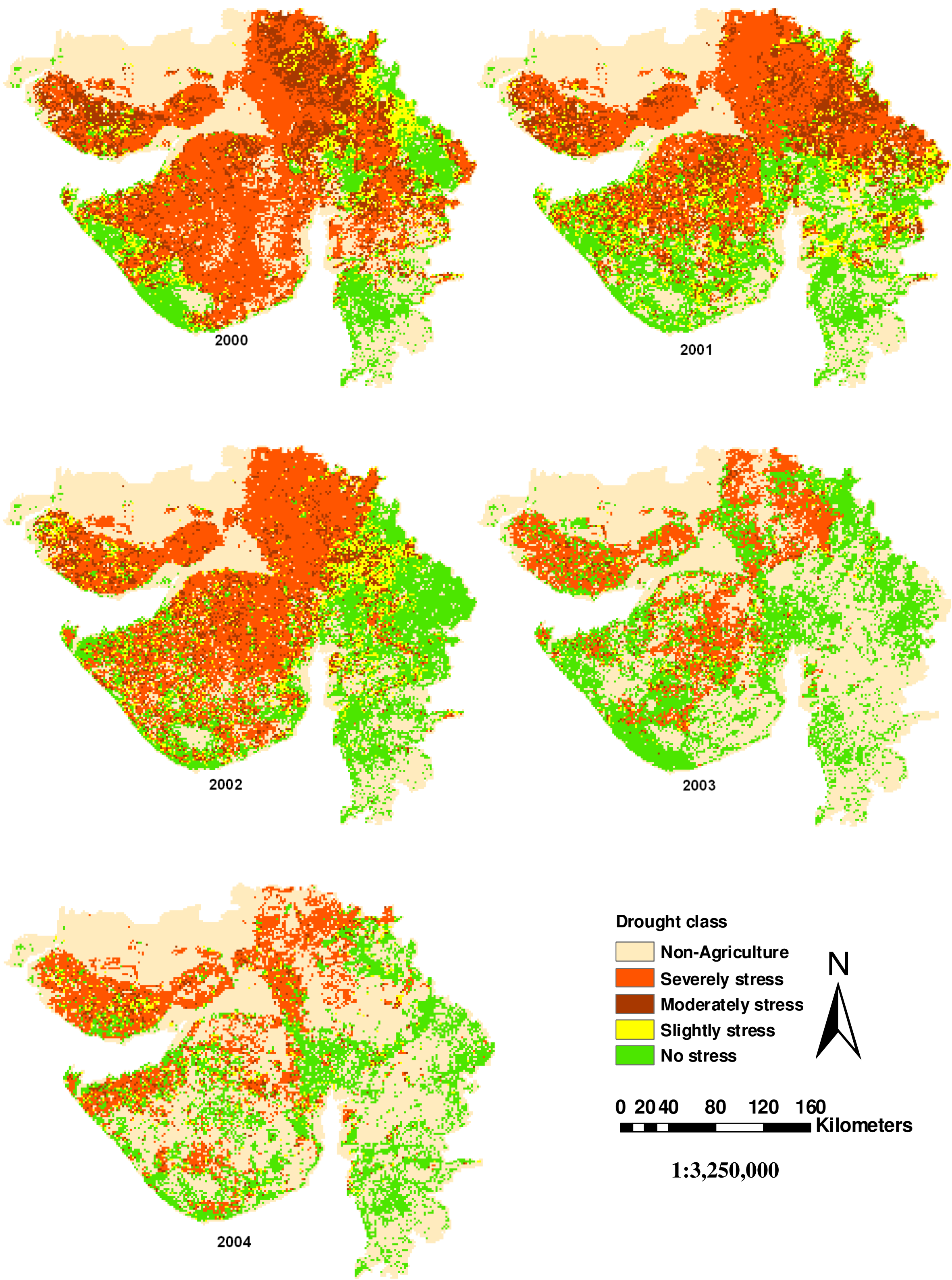


Figure 5.9: Map showing the spatial pattern of drought severity on 257 JD during 2000 to 2004 based on VTCI

Drought in Western part of Gujarat:

The peninsular traditionally known as Saurashtra. It is essentially a hilly tract sprinkled with low mountains. Particularly this part has very important with respect to agriculture .The oilseeds crops like groundnut is one of the important crop in this region .Cotton also more prominent in this area. It has been seen that there is severe drought stress during 2000 and 2002. In 2001 the drought stress has been reduced to some extend as compare to 2000 and 2002. But again the drought stress is absolutely very less during 2003 and 2004.

In general the drought is more severe during 2000 and 2002 and also 2001. The year 2003-04 shows the normal year for entire state except the northern part of the state. As it has been seen that there is a persistent drought occurrence in northern part of the state, this portion of the state could be classified under drought prone area. Using satellite derived drought index VTCI, it is possible to demarcate the drought occurrence in regional level for a specific time. The spatial pattern of drought can be represented for every 8 days basis using this approach. The result showed that VTCI could be the better approach for monitoring the relative drought occurrences and in studying the spatial pattern of drought occurrences in a specific time in specific region. It helps to capture the variation of drought in a specific site and better during later part of the crop growth.

5.6.2. Temporal Variation of VTCI curve

Weekly variability of average VTCI value has been plotted for entire state during 2000 to 2004. This has been done only for two month from September to October (241-297 JD). The average VTCI has been computed from 25 district of the entire Gujarat state. The weekly average VTCI has been compared with the threshold VTCI value for each year for identifying the variability of the drought in time series scale. The threshold VTCI value less than 0.56 causes the drought stress during 2000 and in plotted graph it has been observed that the average VTCI curve falls under 0.56. The threshold VTCI value less than 0.49 causes the drought stress during 2001 and in plotted graph it has been observed that the average VTCI curves falls under 0.49 except 241 JD. For 2002 the threshold VTCI value is 0.45, the 2002 VTCI curve shows it falls under 0.45 except 249 JD. Hence the result remarks that the above discussed year having the drought stress. As the VTCI curve for 2003 is above 0.42, it indicates no drought stress. VTCI curve for 2004 is above 0.41 indicates no stress except 273JD.The above result shows that the average VTCI weekly variability curve in time scale is also similar as spatial distribution of drought, which has been discussed in earlier section.

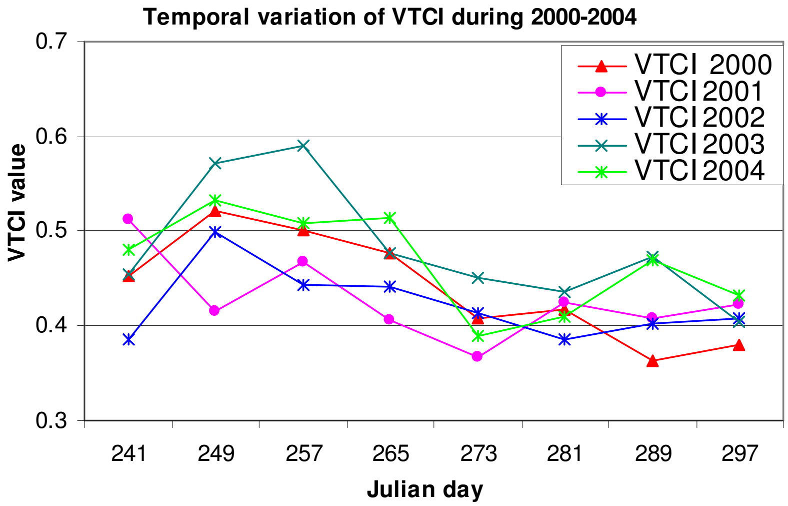


Figure 5.10: The temporal variation of average VTCI curve for Gujarat state during September to October month for 2000-2004

5.6.3. Spatial pattern of drought severity based on WDI

The spatial pattern of drought has been shown based on WDI for each year. The occurrences of drought in Gujarat state has been classified based on water deficit index, which has been shown as similar as VTCI. The WDI has been commuted for each pixel of the study area. The distribution of drought based on WDI has shown in the map for severely drought stress year and for normal year and the result showed that the demarcation of drought stress area is quite similar as VTCI. This study has found that drought stress area based on WDI is lesser than VTCI for all the year and WDI has similar prospective to identify the drought stress during crop growing season for a specific time in regional level. The study doesn't attempt to compare, which one could be the better satellite derived index among VTCI and WDI for identification of drought stress.

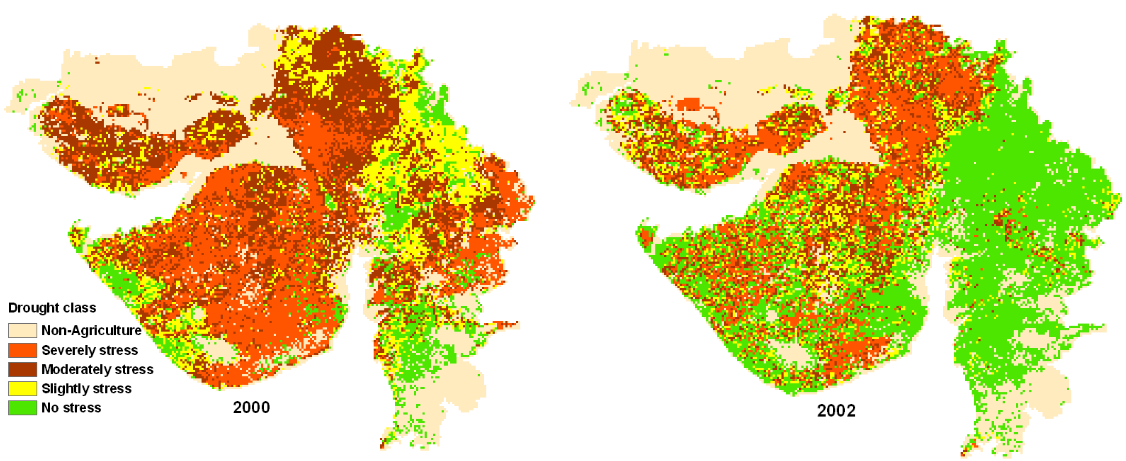


Figure 5.11: Map showing the spatial pattern of drought on 257 JD during 2000 and 2002 based on WDI

5.6.4. Relationships between VTCI based drought duration and crop performance

The agriculture pixel extracted VTCI image has been reclassified into drought stress and non stress based on the threshold value of VTCI. Based on the threshold value drought stress recoded into 1 and non stress is recorded into 0.Non stress has not been highlighted in analysis of drought duration and this class has been merge with non-agriculture area. Non-agriculture area includes forest, water, salt pans, and bare soils, which is constant over the year. Non stress area through out the time can be differentiated from Non-agriculture area with respect to reclassifying them into other number. This has been done for entire duration (241 to 297 Julian days) for 2000 to 2004. Each year having 8 duration of VTCI and all the 8 duration VTCI has been added. The final VTCI image will give the duration of drought in pixel basis, which is ranged from 1 to 8. This duration of VTCI, has been calculated in district wise using the zonal attribute function and it represents the occurrences of drought or duration of drought for particular region over the time span, which means the drought pattern change in every 8 days interval. The duration of drought has been described in the given map.

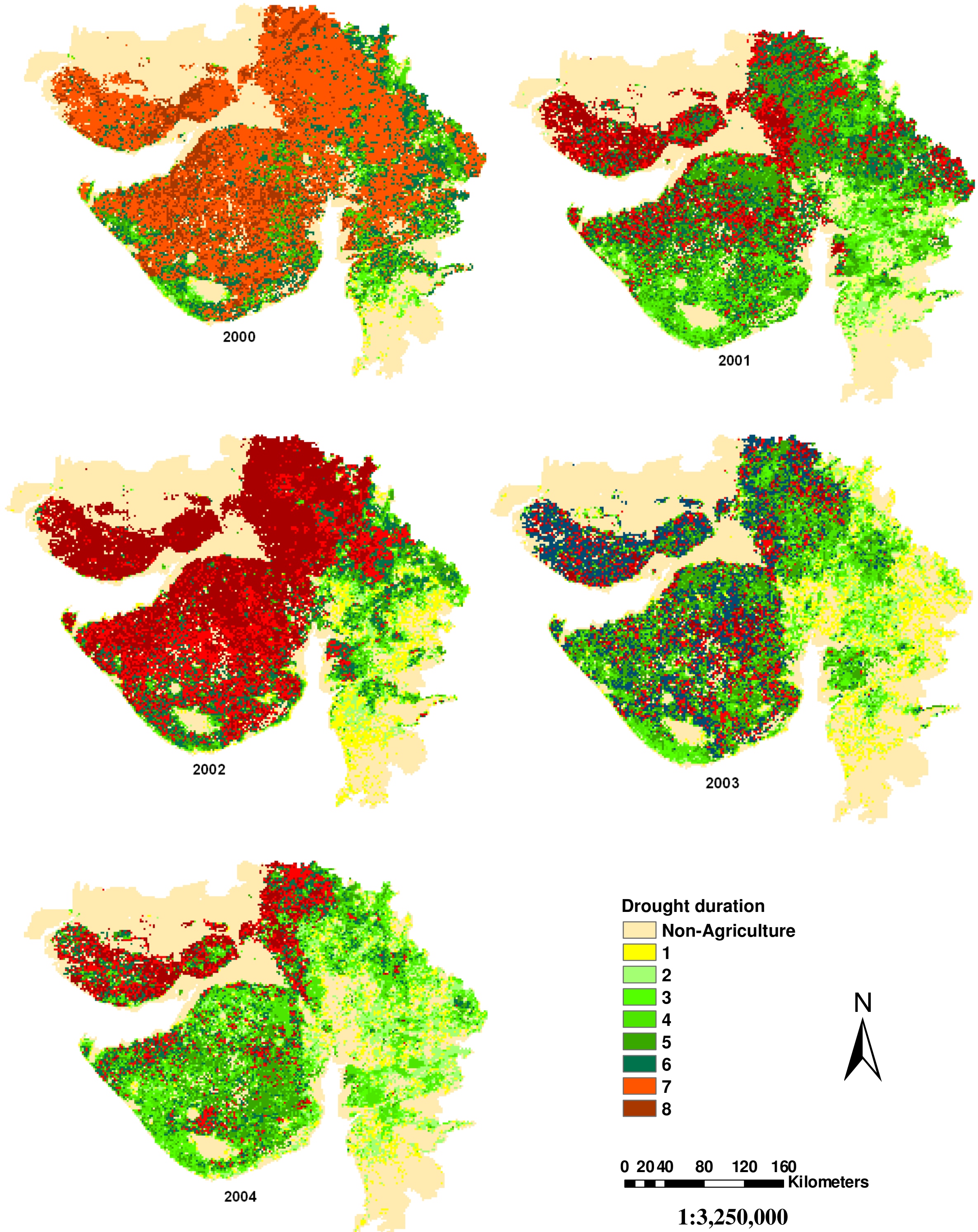


Figure 5.12: Map showing the drought duration pattern in 8 days interval from 241 to 257JD during 2000- 2004 based on VTCI

From the figure 5.12, it can be described as the year 2000 and 2002 was the severe drought stress than other years and due to this reason it has more impacts on yield loss. This facts can be observed in appendix 3 that is the average yield anomaly for food grains is very less during 2000(**-28.17**) and as against 2002 (**-11.20**). This helps to validate the result of drought occurrences or pattern estimated from satellite based indices called VTCI.

The food grain yield and oilseed yield has been correlated with the duration of drought for 2000 to 2003 and it has been observe that crop yield decreases with increase in drought stress period.

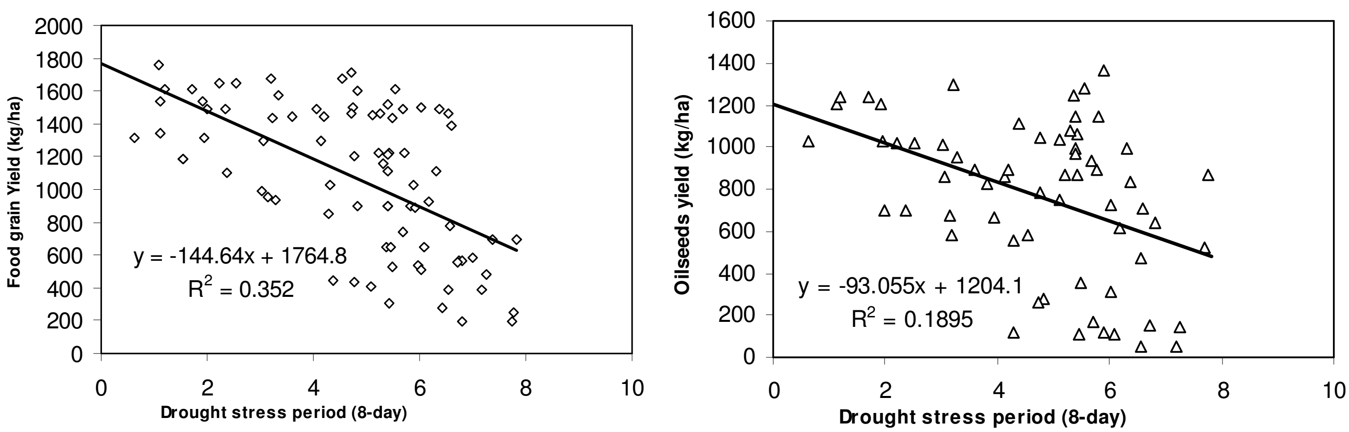


Figure 5.13: The relationship between drought duration pattern with food grain yield and oilseed yield

5.6.5. Temporal variation of Agriculture area under drought class based on VTCI

The total agriculture area has been extracted by masking other features class in the study area and based on VTCI threshold value the different drought class namely slightly stress, moderately stress and severely stress area has been computed only for critical JD for each year. The no stress class has been excluded in the graph. In addition to this the temporal variation (241-297JD) of agriculture area under drought stress has been calculated from 2000 to 2004. The area has further changed to percent area of stress.

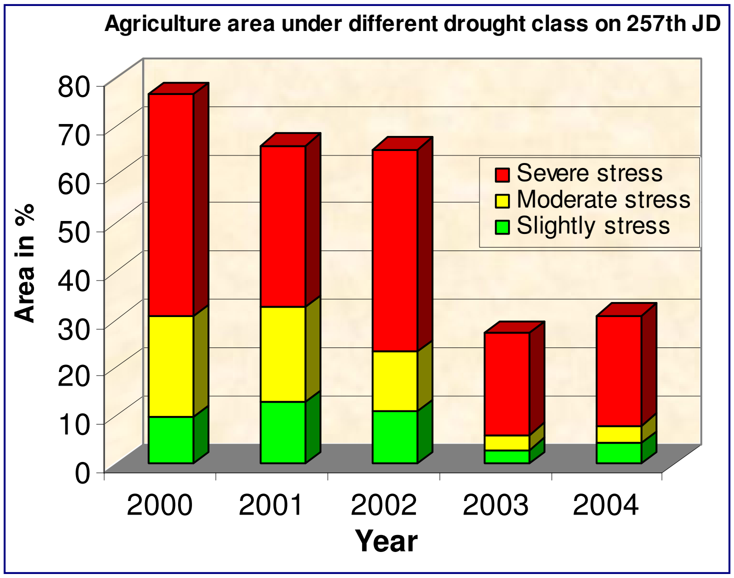


Figure 5.14: The agriculture area under different drought stress on 257th JD

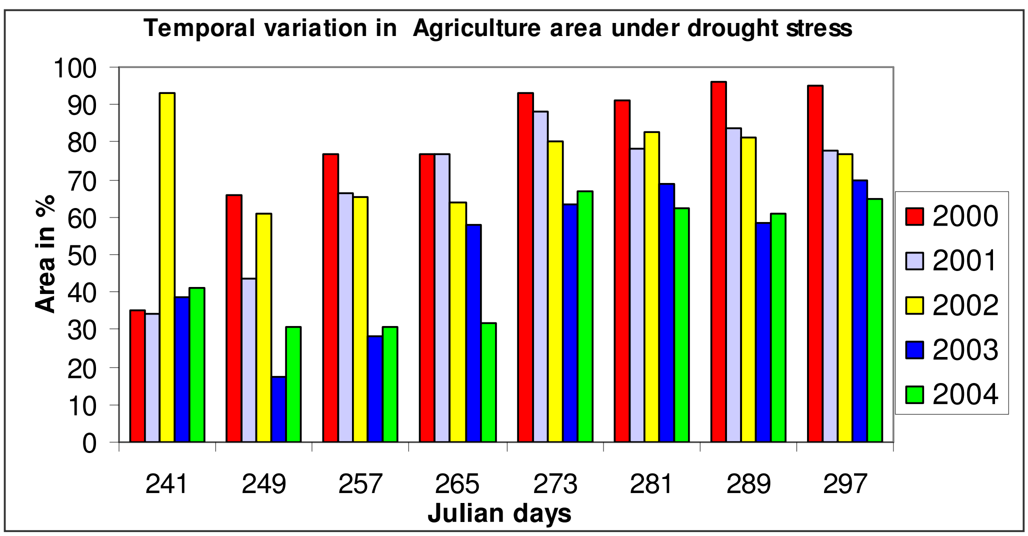


Figure 5.15: The temporal variation (241-297JD) of agriculture area under drought from 2000 to 2004

The result showed in figure 5.14 implies that the overall stress area is less in 2003 and 2004.The highest drought stress occurs during 2000,where the drought stress area showing above 80% of the agriculture area. The temporal change of agriculture area under drought stress has been also observed, which has been plotted in bar graph (Figure 5.15). This has been discussed for each year as follows.

During 2000 the drought stress is in increasing order from 241 JD to 297 JD and compare to other years this gives a highest area in % which is under drought. In 2001 the drought stress area increases from 241-273JD and then it decreases. In 2002 the drought stress area is more on 241JD compare to rest of the JD from 249-297. On 241 JD 2002 gives more drought stress area compare to any year in that period. This indicates the year 2002 was the “early drought”. During 2003-04 the drought area under stress is less compare to 2000-02. From 241-265 JD the drought stress area is less during 2003-04 and subsequently the area increasing from 273 to 297 JD. In general it has been observed that 297 JD represents more % of area under stress for all the year and this is due to lesser value of VTCI. Although the year 2003-04 was not a drought year still the stress indicates. This is due to the senescence of most of the crop during 297 JD. The critical Julian day 257 represents a better result which describes the different drought class area in percentage. It indicates the most of the agriculture area has been affected by drought during 2000-02 where as less area under stress during 2003-04.

5.7. Drought and its effects on crop performance

To know the effects of drought the detrended yield anomaly has been calculated for food grains and oil seed crop. The detrended yield anomaly has been computed from historical crop yield data for each district in Gujarat state. The detrended crop yield from 2000 to 2003 has been in the appendix 3. It is clearly indicated that most of the district having negative food grains yield anomaly trend during 2000 and 2002. Drought has affected the crop performance severely during 2000 and 2002 and in contrast less impact on 2001 and 2003. The average yield anomaly shows that during 2000 the yield loss is more as compare to other year. Similarly yield anomaly has been observed for oilseeds and the result shows that average oil seeds yield anomaly gives negative anomaly value during 2002 (-35.49) and during 2000 (-20.5) due to drought stress on oilseeds crops. This shows the drought severity and the impacts on oilseeds crops but during 2003 the scenario is different, where the oilseeds yield gives positive anomaly (85.15) and indicates no stress (See Appendix 3 for oil seeds anomaly).

5.7.1. Correlation between different satellite derived indices and detrended yield anomaly of food grains and oilseeds during drought years

Table 5.7: The relationships between VTCI, WDI with detrended crop yield anomaly

Indices	Julian day	2000		2002	
		Food grains	Oil seeds	Food grains	Oil seeds
VTCI	241	-0.036	0.033	0.342	0.207
	249	0.233	-0.079	0.451**	0.276

	257	0.273	-0.087	0.330	0.222
	265	0.105	-0.044	0.189	0.238
	273	0.186	-0.075	0.192	0.315
	281	0.138	-0.043	0.212	0.283
	289	0.150	-0.025	0.166	0.319
	297	0.214	0.114	0.241	0.332
WDI	241	-0.133	-0.120	-0.328	-0.132
	249	-0.403*	-0.212	-0.276	0.146
	257	-0.231	-0.024	-0.176	-0.018
	265	-0.128	-0.007	-0.054	-0.033
	273	-0.499**	-0.030	-0.071	0.061
	281	-0.456*	0.067	-0.004	0.051
	289	-0.451*	-0.073	-0.024	-0.010
	297	-0.317	-0.039	-0.047	-0.134

** indicates Pearson correlation is significant at the 0.01 level (2-tailed)
*   indicates Pearson correlation is significant at the 0.01 level (1-tailed)

The table 5.7 indicates that food grains yield has given significant result for few periods and in contrast all the values described non significant. This is due to crop yields, heterogeneity of crop distribution and coarse resolution of satellite data. Crop yields include only food grains and oilseeds in lieu of crop specific yield. In study area other than food grains and oil seeds, there is a lot of other crop exist like sugarcane, cotton etc.

5.8. PS-n based Groundnut yield simulation and cfH2O

Groundnut is the world's 4th most important source of edible oil and 3rd most important source of vegetable protein. In India, groundnut is grown on 5.7 million ha with a production of 4.7 million metric tons, with an average productivity of 0.8 metric tons/ha during the rainy season. Groundnut is raised mostly as a rainfed kharif crop, being sown from June to July, depending on the monsoon rains. In some areas or where the monsoon is delayed, it is sown as late as August or early September. For this study PS-n model has been used for groundnut yield simulation because this is one of the dominant crops in the Saurashtra region of the Gujarat state which includes seven major districts namely Jamnagar, Surendranagar, Rajkot, Porbander, Junagarh, Amreli and Bhavnagar. And hence PS-n model has been used to know the physical drought persistent and simulation of crop yield in that region. Further this simulated crop yield has been compared with the actual crop yield to know the yield gap and to determine the effects of drought on crop productivity. The groundnut variety used for simulation is JL-24 and the pertaining crop parameters have been taken from the literature. The crop characteristic given for yield simulation has been given below.

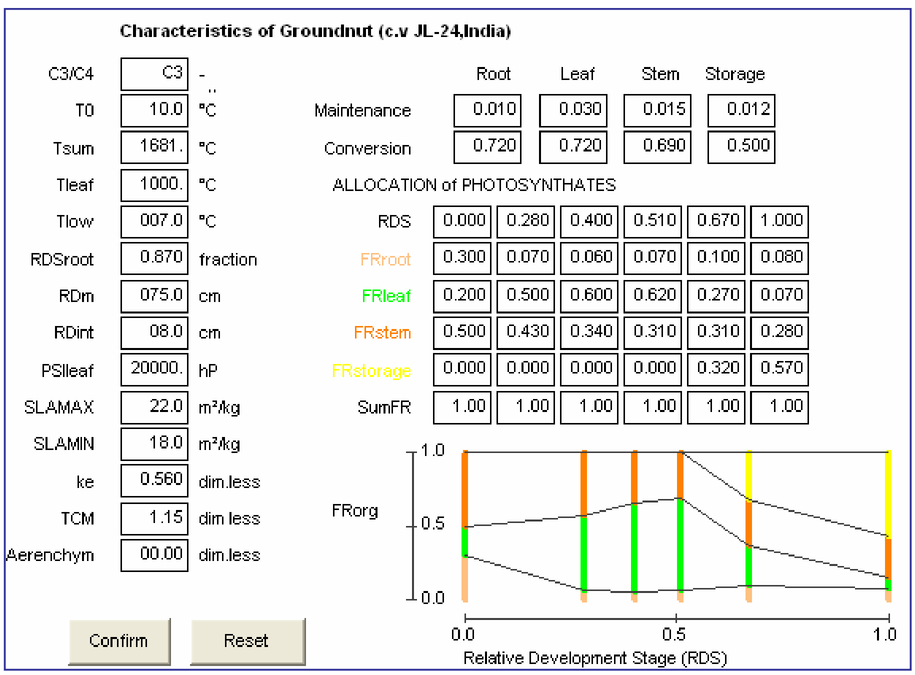


Figure 5.16: The characteristics of groundnut

PS1+PS2: Water limited production Situation in Rainfed conditions

Using PS-n model the crop yield and cfH2O has been simulated. The graph below has been given here as an example for simulation result. This has been derived for Rajkot stations during 2002. The actual yield is 125 kg/ha and the PS-n based simulated yield is 119 kg/ha, which shows the result with in error of 4.8% and for others the error vary. The analysis observed that generally the simulated yield error vary from -30% to 30%. And the assumption has been taken up to 10% error. Provide the error limit with in 30% instead of 10%, the simulated yield can be accepted. With respect to coefficient of water sufficiency index, the results showed that the cfH2O stress has started suddenly from 233 JD to 237JD and again stress has observed from 238 JD onwards, this are marked by vertical grey lines in the graph the. It indicates crop stress has been occurred when crop is at reproductive stage (233JD).

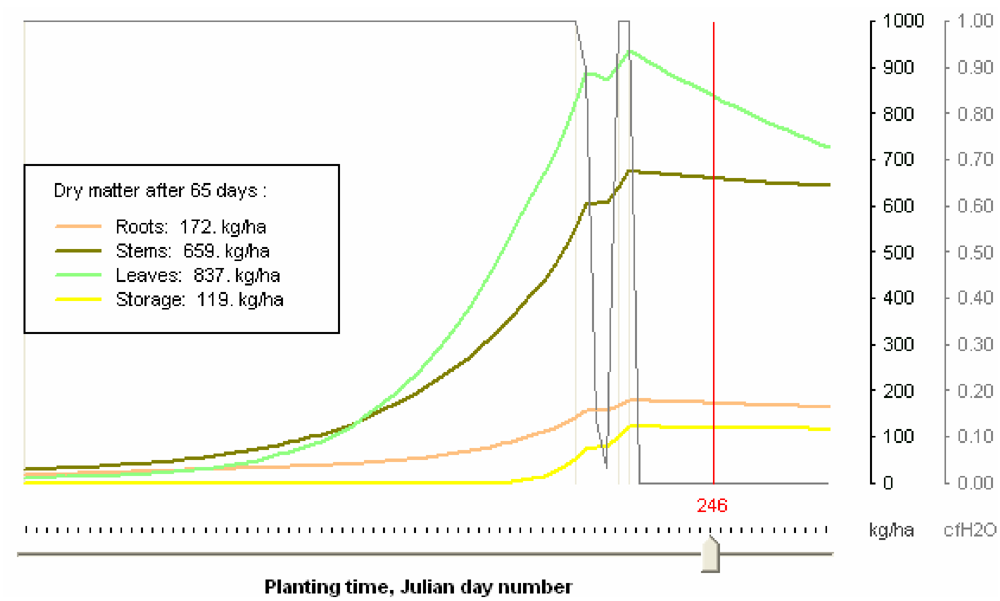


Figure 5.17: The coefficient of water sufficiency index (cfH2O) and dry matter growth curves simulated from PS-n model for Rajkot, 2002

5.8.1. Comparison of simulated and actual groundnut yield at district level

Groundnut yield was simulated using PS-n growth model and the results represented with actual crop yield. The simulated ground yield has been done for four years from 2000 to 2003 and this yield has been compared with actual yield, which has been given in the table5.8. For the analysis the relative deviation and root mean square has been calculated to observe their relationships. Relative deviation in percent has been calculated to know the deviation of crop yield from the actual yield. The relative deviation of ground nut yield has been listed in the table below.

Table 5.8: The actual crop yield and simulated yield

Groundnut Yield (kg/ha)	2000			2001			2002			2003		
District Name	Actual yield	Simulated yield	RD %	Actual yield	Simulated yield	RD %	Actual yield	Simulated yield	RD %	Actual yield	Simulated yield	RD %
Amreli	170	188	10.6	1452	1670	15.0	717	727	1.4	2324	2214	-4.7
Bhavnagar	90	67.3	-25.2	1363	1752	28.5	862	698	-19.0	1211	911	-24.8
Jamnagar	23	41*	78.3	1391	1040	-25.2	36	40	11.1	2155	2248	4.3
Rajkot	57	60	5.3	1265	1016	-19.7	125	119	-4.8	2318	1017*	-56.1
Surendranagar	955	1040	8.9	968	783	-19.1	1200	732*	-39.0	1790	1128*	-37.0

* indicates the simulated yield result is not valid and hence it has not taken for analysis

The relative deviation of ground nut yield at district level is varying from -56.1 to 78.3, which indicates a wide range of yield gap but the few observation are falling in the extreme value of relative deviation. Due to this reason the relative deviation from -30 to +30% has been accepted and more or less than this value has been discarded from the analysis. Due to this reason above mention four results has been removed from the analysis. In Amreli district, the relative deviation of groundnut yield is less which falls within -4.7 to 15.0 in year 2000 to 2003. At Bhavnagar the relative deviation varies from -25.2 to 28.5. Out of four observations in this district from 2000 to 2003 only during 2001, the relative deviation gives positive value. At Jamanagr district the year 2000 result has not considered and remaining year the deviation with in 30%. During 2003 at Rajkot and Surendranagar the relative deviation is more than 30% and due to this it has not considered for analysis.

During 2000 year only the negative deviation of yield has been observed at Bhavnagar district and on the contrary all other district giving a positive deviation which is varying from 5.3 to 10.6. During 2001 the negative deviation observed at Rajkot and Surendranagar district. In 2002 Amreli and Jamnagar district gives a positive deviation but Bhavnagar and Rajkot district showing the negative deviation. In 2003 except Jamnagar district other districts have a negative deviation.

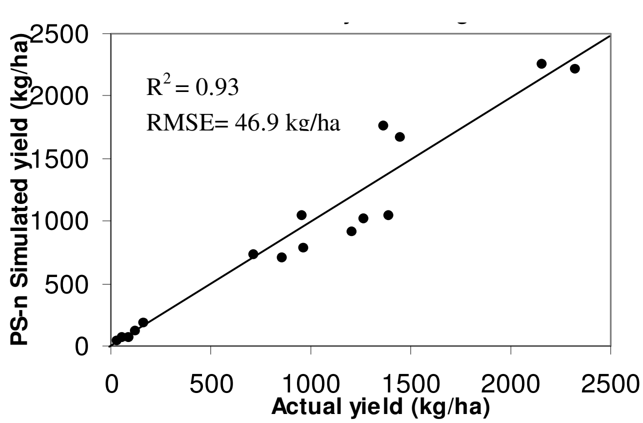


Figure 5.18: 1:1 line comparison between the actual yield and simulated yield of groundnut

Further, 1:1 line plot (figure 5.18) of actual yield and PS-n simulated yield of groundnut shows that the simulated yield and actual yield are in close agreement with high coefficient of determination (R^2 0.93). The RMSE observed between actual and simulated yield of groundnut was 46.9 kg/ha, which is about 4.58% of average actual yield (1023.6 kg/ha). Therefore the null hypothesis3 (Ho), there is systematic difference between observed and simulated crop production at district level is accepted and alternative (Ha) rejected, if the error margin extent up to 30%.

5.8.2. Groundnut yield departure from normal verses simulate yield

The average groundnut yield has been computed from 1981 to 2003 for entire Saurashtra region of Gujarat state. Subsequently Groundnut Yield departure has been calculated for 2000 to 2003 for different district in Saurashtra. Yield departure less than 1 denotes the drought impacts on crop performance where as yield departure more than 1 denotes no drought impacts on crop performance. Subsequently the yield departure has been correlated with the simulated yield.

Table 5.9: The groundnut yield departure during 2000 to 2003

Groundnut Yield departure	Amreli	Bhavnagar	Jamnagar	Rajkot	Surendranagar
2000	**0.20**	**0.12**	**0.04**	**0.09**	1.18
2001	1.74	1.87	2.17	2.04	1.19
2002	**0.86**	1.18	**0.06**	**0.20**	1.48
2003	2.78	1.66	3.36	3.74	2.21

From the table 5.9, it can observe that in the year 2000 the yield departure is very less and less than 1, which indicates the drought stress on crop performance. Similarly during 2002 there is drought stress and has impacts on groundnut crop yield. The yield departure is more than 1 for all five districts during 2003 which implies that there was no drought impacts on crop performance.

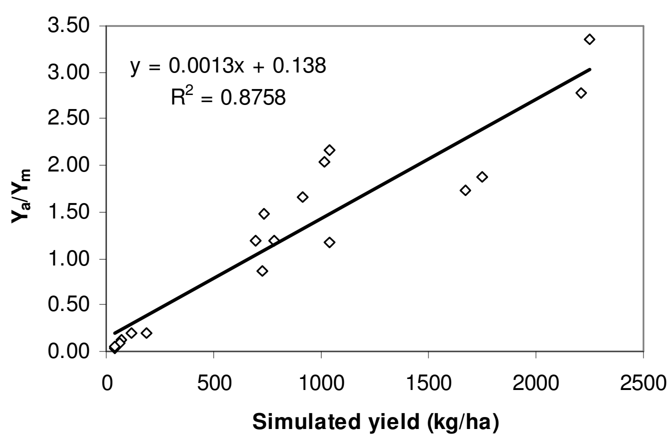


Figure 5.19: The relationships between simulated yield and yield departure

The simulated yield and yield departure has been correlated and it has been observed that the strong relation (R^2 =0.87) exist between simulated yield and yield departure. From the departure of yield and simulated yield it can be observed that the lower the yield departure value, higher is the occurrences of drought stress and there could be significant effects on crop performance.

5.8.3. Relationships between cfH2O and VTCI

The physical drought index called coefficient of water sufficiency index (cfH2O) has been correlated with semi empirical drought index (VTCI) for Saurashtra, part of the Gujarat state during drought year (2000) and non-drought year (2003), especially for the reproductive stage of the crop (241-297JD). The result showed that the relation is insignificant for drought year as well as for non-drought year. For 2000 R^2 is 0.119 and as against 2003 is 0.029.This remarks that PS-n based drought index doesn't represent the crop stress during the later part of the crop growth stage. The poor correlation could be due to the PS-n based model, which requires many parameters like crop, weather and soil. Although the crop parameter has been taken as Indian condition for analysis, on the contrary the soil parameters has been used the default of the PS-n model. The soil parameter seems to be very important for giving erroneous result of cfH2O index for identifying the drought stress.

Table 5.10: The statistical relationships between cfH2O and VTCI

Year	cfH2O (y)	R^2	Adjusted R square	Std.Error of the Estimate	F change	Sig.F change	N
2000	y = 1.13VTCI+0.036	0.119	0.096	0.14	5.13	0.029	40
2003	y = -0.52VTCI+0.57	0.029	-0.009	0.155	0.756	0.393	27

The statistical analysis shows that cfH2O based drought study is irrelevant for identifying the drought stress in the study area and due to this reason the other years has not been further analysed. The correlation value is lower and Sig.F change is 0.029 and 0.393, which indicates the relation is not significant. The year 2003 showing the negative relation between VTCI and cfH2O and due to this result can't be accepted. Therefore the null hypothesis 2 (Ho) there is systematic difference between coefficient of water sufficiency indices and satellite derived indices to detect severity and duration of drought stress has been rejected and alternative hypothesis (Ha) accepted.

6. Conclusion and Scope for Further Research

6.1. Conclusions

An integrated semi empirical approach with meteorological approach appears to be a useful tool for studying land, vegetation and atmosphere interactions. The combination of both remotely sensed land surface reflectance and thermal properties from Terra MODIS gives importance on changes in both land surface temperature and NDVI over a region in real world. The objectives of this study was to demonstrate the use of satellite derived indices from Terra MODIS satellite data for monitoring the agricultural drought with integration of both meteorological data and PS-n based simulated index. In this study the role of satellite derived index for drought detection has been exemplified by integrating meteorological derived index called crop moisture index. Crop moisture index has been computed from last 25 years meteorological data using PDSI programme. A critical analysis of satellite derived indices has been done by relating with crop moisture index for establishing the threshold VTCI and WDI value.

This study has found a significant result for regional drought monitoring by integration of satellite data and meteorological data and this has can be seen in Table 5.4 and 5.5 the linear regression equation for defining the VTCI and WDI threshold for stress. The entry probability of F value taken is less than 0.05. The F probability result shows for all linear regression equation are less than 0.05 (Sig.F change) and hence all the equation for defining threshold value are significant. In this study the direct defining the VTCI threshold and WDI threshold has been avoided by integration of meteorological index called crop moisture index. In literature it has found that in few studies the VTCI threshold less than 0.4 has been taken as a drought stress (Wang, 2001). The present research found that by integrating Terra MODIS satellite data with meteorological data the VTCI threshold value for drought stress is varying from year to year, which is depending upon the in situ data namely rainfall, maximum temperature, minimum temperature, evapotranspiration and in brief soil water balance model. The results remark that the integration of both meteorological data and satellite data for identifying the drought stress has an importance to set the VTCI value or WDI value. Therefore the null hypothesis1 (H0) there is close relationship between meteorological based indices and satellite derived indices used for identifying severity and duration of drought stress is accepted and alternative hypothesis (Ha) is rejected.

Based on NDVI-Ts space relation vegetation temperature condition index (VTCI) has been used as an effective agricultural drought index to monitor the spatial pattern of vegetation over a region. This research attempts to evaluate the drought status in Gujarat state using the vegetation temperature condition index (VTCI) value and compare VTCI with the estimated weekly crop moisture index (CMI) to verify the efficiency of VTCI in agricultural drought monitoring with MODIS satellite data. VTCI is time dependent and usually region specific. It has been developed for drought monitoring at a regional level for specific time period during 2000 to 2004 for crop growing period. This index has been used to monitor the drought occurrences in 8 days composite basis. The satellite derived index VTCI could be crucial tools for study the temporal variation of drought. Temporal variation of drought has been study and observed the drought pattern change over the period in Gujarat state and the drought stress area also changing in every 8 days period. Similarly WDI has been used to evaluate the drought status using WDI value based on an interpretation of the NDVI-ΔT space; and compare WDI with the estimated weekly crop moisture index (CMI) to verify the efficiency of WDI in drought monitoring with MODIS satellite data. In analysis part it has been observe that even though meteorological drought has been occurred spatially, it has not been influenced to agricultural drought due to irrigation facility, better land management practices etc. To study the spatial distribution of agricultural drought, VTCI and WDI approach could be a better approach than meteorological based approach.

The ability of VTCI to detect drought stress has been verified with crop yield data by relating the VTCI based drought duration and the crop yield. The result observed that as duration of stress in 8 days basis increasing the crop yield decreasing.

A sensitivity analysis on VTCI, WDI and CMI shows that the satellite derived indices has more potential for real time agriculture drought monitoring using MODIS satellite data and hence the semi-empirical based satellite index such as VTCI and WDI could be a crucial for early warning of drought in regional scale. In addition to this MODIS satellite data makes easier tools to any drought planner for agriculture drought monitoring in regional scale due to public domain satellite data. The VTCI approach for agricultural drought monitoring integrates the remotely sensed land surface reflectance and thermal properties, and gives the emphasis on changes in both LST and NDVI based on NDVI-Ts space relation. On the contrary WDI approach integrates both remotely sensed land surface reflectance and thermal properties and gives the emphasis on changes in both LST, ambient air temperature and NDVI based on NDVI-ΔT space relation. Temporal variation of drought distribution with respect to crop growth stage for particular region is very indispensable for drought planning, which can be done by analysing the real time series satellite data. This could be a pivotal approach for predicting the near future drought, which could be useful for protecting the farmers from massive loss of crop yield as a consequence of drought.

This study also attempted the PS-n model based physical drought (cfH2O) and crop yield simulation and this study only pertaining to the Saurashtra region of the Gujarat state. The PS-n model has been used for groundnut yield simulation because this is one of the dominant crops in the Saurashtra. This approach used to know the physical drought persistent and simulation of crop yield in that region. Further this simulated crop yield has been compared with the actual crop yield to know the yield gap and to determine the effects of drought on crop productivity. The result shows that the simulated yield and the actual yield are highly correlated (R^2 = to 0.93 and RMSE=46.9 kg/ha) and remarks that the PS-n simulated yield could be used for crop growth modelling. The RMSE observed between actual and simulated yield of groundnut was 46.9 kg/ha, which is about 4.58% of average actual yield (1023.6 kg/ha). To evaluate the relation between PS-n simulated yield and the drought stress, the simulated yield has been relate with the groundnut yield departure for Saurashtra region of the study area. It has been conclude that there is a significant change in crop performance especially groundnut yield due to drought stress during 2000 and 2002 as compare to drought during 2003. Therefore the null hypothesis3 (Ho), there is systematic difference between observed and simulated crop production at district level is accepted and alternative (Ha) rejected, if the error margin extent up to 30%.

The coefficient of water sufficiency index cfH2O also simulated using PS-n model for identifying the drought stress and this index has been correlated with satellite derived index VTCI. The results shows the negative relation between two indices and poor correlation value 0.11 and 0.029 and the Sig. F change is more than the set F probability value 0.02 that is Sig.F change is 0.029 and 0.393, which indicates the relation is not significant. The year 2003 showing the negative relation between VTCI and cfH2O and due to this result can't be accepted. Due to the poor correlation the result has been rejected and remarks that the based on physical drought the drought monitoring is difficult as compared to satellite based drought monitoring. Therefore the null hypothesis 2 (Ho) there is systematic difference between coefficient of water sufficiency indices and satellite derived indices to detect severity and duration of drought stress has been rejected and alternative hypothesis (Ha) accepted.

The methodology developed for drought monitoring in regional scale can be logically conclude that present research gives high spatial information content of the satellite data, which allows for accurate mapping of the spatial extent of drought conditions and temporal variation of drought stress over the time and over the year.

6.2. Scope for Further Research

The following recommendations are made to upgrade the methodology described in this study as an effective tool for drought monitoring as follows.

1. VTCI approach identifies the drought stress very transparently in dryer region compare to wet condition and gives high spatial information of drought stress especially in agriculture drought monitoring. In identifying the threshold value for VTCI by integrating meteorological data and satellite data requires verification with respect to rainfed agriculture and irrigated agriculture rather than a generalised agriculture for agriculture drought monitoring. For further research a detailed study requires in rainfed agriculture and irrigated agriculture separately with the appropriate validation approaches.

2. The future study requires evaluating the better index among the VTCI and WDI for temporal variation of drought stress as well as for spatial pattern of drought in a regional level.

3. Present study realised the presence of clouds in satellite images is a significant obstacle to land surface studies. Clouds in satellite images must thus be precisely identified prior to any further analysis. This cloud contamination in 8 days composite LST and NDVI leads to lowering the accuracy of the results for drought monitoring. It is very important to the reader that satellite observations are often scanty during Kharif season which falls between June to October month in India. Hence there is a lot of scope to use geostationary satellite to overcome this issue.

4. The PS-n based drought index requires experimental study for specific crop for specific soil characteristics and further work can be done to develop a mathematical model for simulating the crop yield.

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Appendices

Appendix 1: The MODIS products LST and surface reflectance Julian days and the respective dates

Julian day for LST and Surface reflectance	8 Days interval date	Julian day for LST and Surface reflectance	8 Days interval date
145	01.06.2004	225	20.08.2004
153	09.06.2004	233	28.08.2004
161	17.06.2004	241	05.09.2004
169	25.06.2004	249	13.09.2004
177	03.07.2004	257	21.09.2004
185	11.07.2004	265	29.09.2004
193	19.07.2004	273	07.10.2004
201	27.07.2004	281	15.10.2004
209	04.08.2004	289	23.10.2004
217	12.08.2004	297	31.10.2004

Appendix 2: The food grain yield and oil seed yield from 2000-03

	Food grain Yield				Oilseed yield			
District Name	**2000**	**2001**	**2002**	**2003**	**2000**	**2001**	**2002**	**2003**
Kuchch	305.0	580.0	250.0	893.0	1061	1317	1097	1366
Banas kantha	282.0	740.0	190.0	1161	1856	1624	863.2	1555
Sabar kantha	650.0	1450	930.0	1438	1244	752.1	616.2	1299
Patan	567.0	1110	690.0	897.0	1617	996.1	1113	1462
Mahesana	567.0	1110	690.0	897.0	1617	996.1	1113	1462
Surendranagar	775.0	1500	10.0	1494	471.5	726.8	521.6	938.0
Ahmedabad	540.0	1520	190.0	1936	1545	968.6	637.6	822.0
Gandhinagar	1464	1610	1750	1572	2080	1282	2011	1726
Panchmahals	411.0	1220	1300	1185	1038	864.4	862.1	15100
Kheda	899.0	1680	1440	1651	1141	577.6	889.5	1019
Rajkot	551.0	1220	480.0	1438	153.4	166.1	144.8	2163
Dohad	411.0	1220	1300	1185	1038	864.4	862.1	15100
Jamnagar	646.0	1030	390.0	1462	113.2	116.8	52.6	2110
Vadodara	445.0	950.0	990.0	1103	1112	671.7	1008	1543
Anand	899.0	1680	1440	1651	1141	577.6	889.5	1019
Bhavnagar	530.0	1600	1490	1939	357.0	275.0	837.2	1074
Bharuch	439.0		850.0	936.0	785.7	666.7	553.6	954.0
Porbandar	646.0	1030	390.0	1462	113.2	116.8	52.6	2110
Amreli	505.0	1500	1390	1213	309.5	263.3	703.9	2100
Junagadh	1204	1492	1988	1712	1042	1603	892.6	2727
Surat	1313	1490	1540	1609	1028	697.5	1202	1241

Navsari	1313	1490.	1540	1609	1028	697.5	1202	1241
The Dangs	620.0	990.0	670.0	1143	360.0	365.9	512.8	2279
Valsad	1392	1800	1340	1763	285.7	500.0	400.0	2264

Appendix 3: The detrended Food grains and oilseeds yield anomaly for different district during 2000 to 2003

	Food grains yield anomaly				Oil seeds yield anomaly			
District Name	**2000**	**2001**	**2002**	**2003**	**2000**	**2001**	**2002**	**2003**
Ahmedabad	-46.31	48.36	-81.79	82.29	5.09	-35.94	-58.96	-48.46
Amreli	-56.62	26.49	15.10	-1.33	-58.46	-64.65	-5.52	181.88
Banaskantha	-3.57	165.87	-28.09	364.22	-0.10	-14.59	-55.65	-21.88
Bharuch	-32.87	-100.00	29.97	43.12	-6.08	-21.40	-35.62	9.48
Bhavnagar	-51.10	44.67	32.08	68.58	-44.56	-57.30	29.99	66.77
Gandhinagar	-21.10	-15.78	-11.06	-22.32	-6.10	-43.97	-14.89	-29.17
Jamnagar	10.78	73.64	-35.35	45.62	-79.75	-79.11	-90.58	277.46
Kutchh	-32.67	28.04	-44.81	-91.94	-24.47	13.50	-38.25	84.50
Kheda	-39.87	10.99	-6.02	6.47	-13.65	4.14	-15.61	2.23
Mehsana	-13.30	69.72	5.50	37.16	18.38	-41.03	-10.59	0.86
Panchmahal	-51.36	44.38	53.85	40.24	-10.26	-45.89	-40.72	-23.73
Rajkot	-16.89	84.01	-27.60	116.89	-11.46	-28.41	-30.59	1082.85
Sabarkantha	-43.97	22.36	-23.14	16.43	-81.58	-80.67	-83.65	137.12
Surat	-20.60	-11.68	-10.49	-8.27	-20.56	-53.49	-63.05	-24.39
Surendranagar	-15.49	56.98	-98.99	44.72	-7.02	-37.85	5.58	7.41
Dangs	-26.93	15.15	-23.07	29.59	-27.50	9.33	-23.39	34.95
Vadodara	-43.24	21.17	26.28	40.69	-53.67	-52.91	-34.00	193.31
Valsad	-12.40	13.28	-15.67	10.95	-8.41	-85.11	-35.57	45.13
Junagadh	-21.8	-5.4	23.1	3.6	-69.24	-46.18	-56.94	143.70
Average	**-28.17**	31.45	**-11.20**	43.85	**-20.50**	-36.22	**-35.49**	85.15

Appendix 4: The meteorological stations and its location used for station air temperature interpolation and for pixel extraction in 3x3 window

Name of the Stations	Longitude(E)	Latitude(N)
Bombay	72.85°	19.11°
Pariya	73.029°	20.409°
Gandevi	73.00°	20.82°
Navsari	72.94°	20.96°
Veraval	70.375°	20.92°
Ubharat	72.746°	21.018°
Surat	72.916°	21.2°
Mangrol	70.13°	21.13°
Mahuva	71.699°	21.199°

Dhari	71°	21.31°
Amreli	71.19°	21.6°
Tancha	73.302°	21.683°
Broach	72.969°	21.701°
Achaliya	73.406°	21.93°
Kandha	73.211°	22.047°
Baroda	73.14°	22.25°
Arnej	72.22°	22.31°
Rajkot	70.7°	22.3°
Dhanduka	71.98°	22.36°
Dhermej	72.797°	22.419°
Anand	72.93°	22.53°
Jamnager	70.07°	22.48°
Derol	73.52°	22.65°
Indore	75.8°	22.71°
Godhra	73.58°	22.78°
Nawgam	72.578°	22.784°
Ahmedabad	72.7°	23.05°
Bhuj-Rudramata	69.66°	23.25°
Vijapur	72.761°	23.558°
Radhanpur	71.36°	23.833°
Khedbrama	73.01°	24.08°
Sknager	72.436°	24.378°
Kota	75.85°	25.15°
Karachi airport	67.13°	24.9°
Hyderabad	68.41°	25.38°
Jaisalmer	70.91°	26.9°

Appendix 5: Crop Moisture Index

The following abbreviations have been used for CMI calculations
AWC: Available water holding capacity
PE: Potential Evapotranspiration - Calculated with Thornthwaite's
ET: Computed 'actual' evapotranspiration
Alpha: Coefficient of Evapotranspiration
CET: CAFEC (Climatically Appropriate For Existing Conditions) Evapotranspiration
R: The total computed recharge
RO: The total computed runoff
Ss: The amount of moisture stored in the upper layer
Su: The amount of moisture stored in the lower layer
M: Percent of field capacity
DE: Relative evapotranspiration anomaly for the week
Y'i: First approximation to Y during the ith week
Yi: Index of evapotranspiration deficit during the ith week

Gi: Index of excessive moisture during the ith week
H: A "return to normal" factor
CMI: The Crop Moisture Index

Appendix 6: Crop parameters for PS-n model

To: threshold temperature
Tsum : heat requirement for full development
Tleaf : heat sum for full development of leaf tissue
Tlow: low temperature (-20 degree C)-NA here
RDS (0 to1): relative development stage
RDm (cm): maximum root development
RDint (cm): initial root depth
PS1leaf : potential in pressure
SLAmax : maximum total leaf area per unit dry leaf mass
SLAmin :minimum total leaf area per unit dry leaf mass
Ke: extinction coefficient for visible light (it is a function of canopy shape position…)
TCM: maximum turbulence coefficient (kc)
Kc: crop coefficient
Aerenchym: air ducts (soil moisture availability)
FRroot: mass fraction of root (o to 1)
FRleaf : mass fraction of leaf
FRstem: mass fraction of stem
FRstorage: mass fraction of storage
RDS=f (fraction of root, leaf, stem, storage)
EC: Coefficiency of conversion for root, leaf, stem and storage
Maintenance: maintenance respiration

Appendix 7: Details on LST science data sets (12)

SDS	Units	Data Type-bit	Fill Value	Valid Range	Multiply by Scale Factor	Add Additional Offset
Daily daytime 1km grid Land-surface Temperature	Kelvin	16-bit unsigned integer	0	7500 - 65535	0.0200	na
*Quality control for daytime LST and emissivity	na	8-bit unsigned integer	0	0 - 255	na	na
Time of daytime Land-surface Temperature observation	Hrs	8-bit unsigned integer	0	0 - 240	0.1000	na
View zenith angle of daytime Land-surface Temperature	Degree	8-bit unsigned integer	255	0 - 130	1.0000	-65.0000

Daily nighttime 1km grid Land-surface Temperature	Kelvin	16-bit unsigned integer	0	7500 - 65535	0.0200	na
Quality control for nighttime LST and emissivity	na	8-bit unsigned integer	0	0 - 255	na	na
Time of nighttime Land-surface Temperature observation	Hrs	8-bit unsigned integer	0	1 - 240	0.1000	na
View zenith angle of nighttime Land-surface Temperature	Degree	8-bit unsigned integer	255	0 - 130	1.0000	-65.0000
Band 31 emissivity	na	8-bit unsigned integer	0	1 - 255	0.0020	0.4900
Band 32 emissivity	na	8-bit unsigned integer	0	1 - 255	0.0020	0.4900
Clear-sky Days	na	8-bit unsigned integer	0	0 - 255	na	na
Clear-sky Nights	na	8-bit unsigned integer	0	0 - 255	na	na

*Quality Control Bit Index

Appendix 8: Details on surface reflectance science data sets (3)

SDS	Units	Data Type-bit	Fill Value	Valid Range	Multiply by Scale Factor
Surface Reflectance for band 1 (620-670 nm)	reflectance	16-bit signed integer	-28672	-100 - 16000	0.0001
Surface Reflectance for band 2 (841-876 nm)	reflectance	16-bit signed integer	-28672	-100 - 16000	0.0001
*Surface reflectance 250m quality control flags	Bit field	16-bit unsigned integer	65535	0-4294966531	na

Appendix 9: Groundnut and cotton in study area