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PROSPECTS FOR AN INTERNATIONAL CHARTER "SPACE AND MAJOR DISASTER" REMOTE SENSING RESPONSE TO DROUGHT DISASTERS – AN ANHUI, CHINA CASE STUDY

by

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PROSPECTS FOR AN INTERNATIONAL CHARTER “SPACE AND MAJOR DISASTER” REMOTE SENSING RESPONSE TO DROUGHT DISASTERS – AN ANHUI, CHINA CASE STUDY

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Western Michigan University, 2012

Remote sensing is often leveraged during the response phase of disaster management to improve the situational awareness of decision-makers. The International Charter “Space and Major Disaster” (Charter) provides remote sensing support to non-spacefaring nations facing disasters such as earthquakes, floods and tsunamis. However, the Charter has never activated for a major drought disaster. Since droughts affect over half of the nearly 3 billion people that suffer from natural disasters annually, this study seeks to determine whether satellite remote sensing can be effectively employed according to the intent, capabilities, and limitations of the Charter to benefit officials responding to a major drought disaster during the response phase of disaster management. A case study of a major drought in 2009, which severely threatened crops in Anhui Province, China, was used to test the methods available to the Charter that could have been used during the response phase of the drought. The analysis demonstrates the benefits, utility and limitations of remote sensing during the response phase of a major drought disaster.

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Joseph Burkhead

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INTRODUCTION

Introduction to the International Charter “Space and Major Disaster”

The International Charter “Space and Major Disaster” (referred to alternately as “Charter” or “the Charter”) is an agreement among nineteen national space agencies and space corporations to openly share satellite remote sensing data free of charge with both signatory and non-signatory countries in the event of major disasters. The charter was established at the Third United Nations Conference on Space Exploration and Peaceful Use of Outer Space (UNISPACE III) in Vienna, Austria, 1999, and promulgated the following year. Since then, the charter has played a crucial role in disaster response, providing critical imagery and situational awareness to nations coping with diverse disasters including floods, earthquakes, volcanoes, tsunamis and fires. Recognizing that no single space-borne platform can provide a complete and adequate response to any given major disaster, and also that many nations across the globe are not yet space-faring and thus lack access to satellite remote sensing data, the Charter has filled one the world’s most pressing human needs when it comes to earth observation applications. In short, the Charter has made valiant contributions in the effort to save lives, property and prosperity during times of disaster for more than a decade.

The text of the Charter encourages the promotion of new methods and areas for innovative and novel applications by ensuring that parties are kept “abreast of new methods being developed in applied research for warning of, anticipating and managing disasters” and that those methods are tested before charter implementation (Charter, 2000). This research intends to meet the spirit of that encouragement by investigating ways in which the charter’s assets can be leveraged in response to the severe and growing hazards brought by major drought disasters. This research also seeks to leverage the capabilities provided by satellite remote sensing measurements of large areas of the earth’s surface conditions. Finally, the research seeks to achieve synergy within the remote sensing and emergency management communities as they respond to global drought disasters with an aim to reduce the negative impact of droughts on humans, property, resources and the environment among both spacefaring and non-spacefaring nations.

The Charter’s versatility in responding to a wide set of disasters is one of its strong points, but it is important to recognize that the scope of the Charter sets specific limits on the type of disasters which permit Charter activation. For example, the Charter has never been activated in response to a drought disaster. The Charter’s acceptance criteria for its own activation have prevented Charter response to “disasters with doubtful/no benefit from space assets such as drought” (Ito, 2005, p. 146). The Charter’s self-imposed restriction from accepting drought disaster missions is very likely influenced by the Charter’s self-imposed fifteen-day activation time limit (Ito, 2005). Since severe drought situations build and persist over long periods of time, Charter activation may be limited in scope in responding to drought disasters.

This research specifically examines whether it is feasible to argue for an adjustment of the current Charter activation acceptance criteria to include major drought disasters, and whether the notion that space-borne remote sensing has "doubtful or no benefit to drought disaster response" is, in fact, justified. The results of the research will also reveal what opportunities remote sensing provides to the Charter and other international disaster response players in their efforts to reduce the impacts of drought hazards as they respond to major drought disasters.

Introduction to Drought Disasters

The International Charter 'Space and Major Disaster', as its name implies, operates squarely in the realm of major disasters. The term "disaster" certainly has different meanings to different people and organizations, so it is necessary to define the term as it is used in this research. "Disaster" is defined as a hazardous event that has gone beyond the capacity of responding agencies, resources and communities to manage and cope with the incident (Joyce et al., 2009).

A "drought" may be defined according to various meteorological, hydrological or agricultural standards, but generally refers to a severe shortage of precipitation sufficient enough to negatively impact water resources, soil health, and vegetation health. Drought is in essence a combination of moisture deficit and land use, wherein the "available moisture is at or below a point where harm is caused to vegetation (including crops) and/or stock and thereby to people and/or animals that depend on it" (Jupp et al., 1998, p. 5). This general definition of a drought will suffice for this research since the major focus of the study is not on developing a definition of "drought", but instead to deal with the issue of a "major drought disaster."

Droughts are among the most severe forms of disaster to affect human activity as well as ecological systems and the environment. They can severely impact food production, life expectancy and economic performance of large regions with influence lasting many years after the incident (Jeyaseelan, 2004). In just the twenty four years from 1967 to 1991, drought affected approximately half of the nearly 3 billion people that suffered from any form of natural disaster and killed 35 percent of the 3.5 million people who lost their lives due to natural disasters worldwide for the same time period (Jeyaseelan, 2004). Heavily populated countries face a growing threat of severe droughts and will likely experience increasingly dry conditions reaching a scale by the end of the century that has rarely, if ever, been observed in modern times (Dai, 2010). In short, most researchers anticipate major drought disasters will become more frequent, more severe and more hazardous.

A "major drought disaster" is defined in this research as a drought event which has exceeded the capacity of responding agencies, resources and community coping capacities. When the capacity of responding agencies at local and state or provincial levels of government have been exceeded, national governments will typically make a national declaration of the disaster to provide additional support to the responding agencies and communities which are unable to cope with the disaster. It is within this realm that this study is focused. The research assumes that if the charter activates in response to a major drought disaster, the affected nation has declared the drought a national disaster. The severity of the drought narrows the focus of the research and the relevancy to the Charter. The timing of the response phase as it fits within the drought management cycle is another issue for narrowing the scope of this research.

The Disaster Management Cycle

Effective disaster management is an integrated and continuous process which transpires before, during and after a disaster incident. It can be symbolized as a continuous cycle composed of interrelated phases of reduction, readiness, response and recovery (see Figure 1.1).

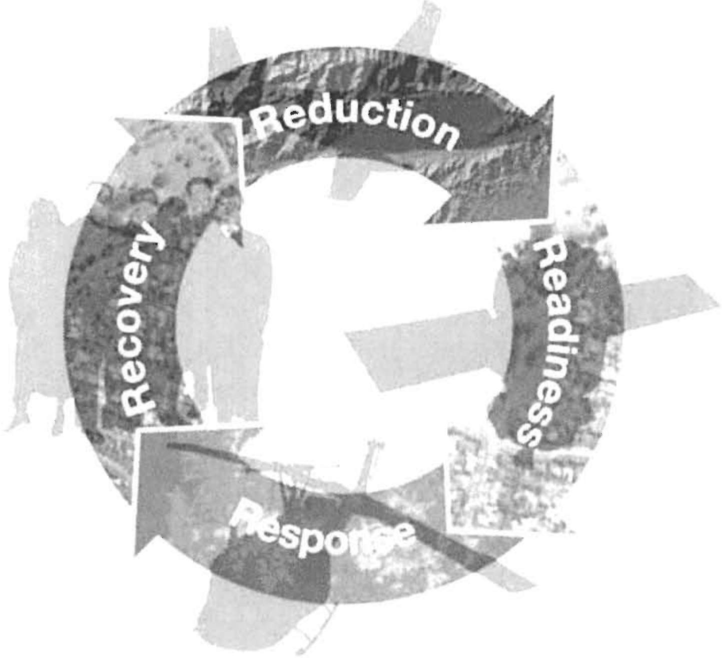

Figure 1.1. The Disaster Management Cycle. (Source: Joyce et al., 2009)

Long before a disaster strikes, emergency managers and the public they serve take steps during the reduction phase to prepare for potential disasters and reduce the risks posed by a disaster. The reduction phase incorporates all measures and planning which reduce the likelihood of a disaster occurring (Joyce et al., 2009). These measures may include modifying the behaviors of individuals and organizations at risk of experiencing a disaster, or modifying the integrity or resilience of structures or assets that are at risk (Joyce et al., 2009). Governments, emergency responders, organizations and individuals take steps to prepare themselves to respond to disaster risks which cannot be eliminated in the readiness phase. This readiness phase is characterized by accepting some level of risk for the communities and implementing measures to ensure that any response to hazards during a disaster is efficient and reduces hazard impacts (Joyce et al., 2009). Once a disaster has struck, people respond to the disaster by taking action, changing behavior and working to minimize or cope with the impact of the disaster during the response phase. Disaster response is the process of coordinated effort to manage resources, including life essentials and personnel, for activities such as relief, evacuation, search and rescue and needs assessments. The recovery phase consists of steps such as restoring life essentials and rebuilding communities both physically and holistically (Joyce at al., 2009).

This research and the work of the Charter are set entirely within the context of the response phase of the disaster management cycle. With the definitions of "major drought disaster" and the "response" phase of disaster management established, the next section will summarize assessments of the prospects of remote sensing and Charter emergency response to major drought disasters. Using a nationally-declared major drought disaster in rural China as a case study, the capabilities and limitations of remote sensing will be evaluated using spaceborne assets available to the Charter and using methods appropriate for the response phase of disaster management. Before introducing the methods and results related to the case study, I will first review the current role and applications of remote sensing during drought events.

CHAPTER II

PROSPECTS FOR A REMOTE SENSING RESPONSE TO DROUGHT

The Role of Remote Sensing in Drought Response

Remote sensing is routinely utilized during droughts in the reduction, readiness and recovery stages of the disaster management cycle. Remote sensing applications for droughts during the disaster response stage, however, have been sparse. Yet the existing technology and capabilities of remote sensing instruments offer the potential to fill a greater role in the response stage. The response stage, as described in the previous section, requires accurate and time-sensitive information and assessments which are often derived from situation maps.

When responding to a drought, emergency managers require information about the spatial extent and severity of the disaster in deciding where to focus the most attention and where to allocate limited resources. Most drought-related data are provided by point-based measurements, such as precipitation measurements from reporting weather stations or soil moisture measurements from agricultural field survey sites. Point-based measurements lack the spatial continuity of measurements across a large area which remote sensing measurements provide. To fill the gaps in data between precipitation or soil moisture probes, scientists typically apply a variety of methods of interpolation among the points to derive estimates of precipitation and soil moisture across large areas. These interpolated values are only estimates and indeed may be incorrect in the particulars, if accurate in general. Satellite remote sensing, on the other hand, offers continuous spatial measurements over large areas where weather stations or other ground-based observations are sparse or non-existent (Brown et al., 2008). It is this capability of measuring land surface characteristics across large continuous areas that makes remote sensing particularly useful in aiding non-spacefaring nations in effectively determining which areas are most adversely affected by a drought disaster. Remote sensing not only reduces reliance on interpolative methodologies for assessing drought conditions, but also may be the only feasible method for making an accurate assessment of a drought disaster in a nation that lacks an extensive network of precipitation or soil moisture measurement stations so common in the developed world.

Remote sensing-derived measurements can inform emergency managers responding to a drought about the meteorological and agronomic conditions that determine locations experiencing “drought exceptional circumstances” through the use of data including rainfall estimates, solar radiation, vegetation conditions, crop yields, thermal measurements, soil moisture, and vegetation stress (McVicar and Jupp, 1998). These variables offer tremendous insight into the spatial patterns and severity of a drought situation. If data can be collected and distributed quickly to decision-makers in the form of an easily deciphered product, remote sensing can play a greater role in the response stage of a drought disaster. Remote sensing products applied to drought events in the past, as reviewed in the next section, help to further demonstrate the potential role for remote sensing in a drought response.

History of Remote Sensing Drought Applications

Several remote sensing applications are useful for the analysis of drought disasters across the globe. Drought effects observable by satellites may include defoliation which results in decreased near infrared (NIR) reflectance, increased visible reflectance, and even sharper increases in short wave infrared (SWIR) radiation (Deshayes et al., 2006). Remote sensors are also sensitive to changes in the physical characteristics of vegetation experiencing water stress. Past observations have included visible/near infrared (NIR) spectrum reflectance changes due to altered chlorophyll and leaf pigments, increased short-wave infrared (SWIR) reflectance due to decreased leaf water content, and increased thermal infrared (TIR) response from stomata closure and reduced transpiration (Deshayes et al., 2006).These applications include efforts to measure vegetation conditions, soil conditions, surface temperatures, thermal signatures and precipitation.

One common and fundamental remote sensing application for drought monitoring is the calculation of the Normalized Differential Vegetation Index (NDVI). NDVI is a measure closely correlated to the biophysical characteristics of vegetation such as green biomass and chlorophyll content (Wardlow, 2009). NDVI is calculated as follows:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Equation 2.1

Where:
NIR = Near infrared band value RED = Red band value

NDVI values range from -1 to +1, with high NDVI values (generally above 0.5) indicating healthy or dense vegetation and low positive NDVI values indicating stressed vegetation. Very low NDVI positive values (0.0 - 0.1) are likely to be areas of bare rock, sand or snow. NDVI may be measured using multiple sensors such as Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectrometer (MODIS), VEGETATION, and others sensors with NIR and Red band collection capability.

There are numerous studies indicating the utility of NDVI for drought estimation. VEGETATION sensor (aboard SPOT-4 and SPOT-5 satellites) data were used to detail severe drought conditions across France and other portions of Western Europe in 2003 using NDVI (Deshayes et al., 2006). The onset of the drought's impact was visible in June's data before the situation aggravated in July and August. It is plausible to conclude that if remote sensing data such as those presented by the VEGETATION sensor in June are provided immediately to emergency management officials and a response implemented (such as a spatially-modified irrigation plan), the negative effects of the increased drought severity as shown in July and August may not have as damaging of an impact than if no response was made in June. For example, a decision to divert resources from the northwest to the southeast of France may have been warranted.

In another study, SPOT High-Resolution Visual Infra-Red (HRVIR) sensor data detailed the impact of the 2003 Western Europe drought on meadows, forests, wheat and maize using NDVI. This demonstrated the utility of remote sensing for detecting changes in the phenological cycle of drought-affected vegetation (Coret et al., 2005).

NDVI used in conjunction with climatic conditions were shown on initial evaluation to be effective in monitoring the impact of drought on vegetation growth and crop production on a global scale through the calculation of a Climatic Impact Index (CII) (Zhang et al., 2004). The index was also found to be useful for drought monitoring and forecasting drought impacts (Zhang et al., 2004).

Another vegetation index was developed which improves upon NDVI called the Enhanced Vegetation Index (EVI). EVI was developed to optimize the vegetation signal with improved sensitivity in high biomass regions and improved vegetation monitoring through minimizing canopy background variations and maintaining sensitivity over dense vegetation (Huete et al., 2002). EVI also utilizes the blue band to remove residual atmosphere contamination caused by smoke and sub-pixel thin cloud clouds (USGS, 2010). EVI is calculated as follows:

$$EVI = G * \frac{NIR - RED}{NIR + C_1 * RED - C_2 * BLUE + L}$$ Equation 2.2

Where:
NIR = Near infrared band RED = Red band $BLUE$ = Blue band
G = Gain factor coefficient = 2.5
C_1 = Coefficient of aerosol resistance = 6
C_2 = Coefficient of aerosol resistance = 7.5
L = Canopy background adjustment = 1

Sensor data from the Medium Resolution Imaging Spectrometer (MERIS) aboard the European Space Agency's ENVISAT satellite detected drought-impacted vegetation during this same 2003 drought by estimating the Fraction of Absorbed Photo-synthetically Active Radiation (FAPAR), (Gobron et al., 2004). FAPAR is measure of the fraction of solar radiation absorbed by vegetation which indicates the presence and state of vegetation cover (Wardlow, 2009). The effect of the drought on vegetation growth left a "definite signature observable from space" as early as March, 2003, some three to five months before the drought's severity reached levels that caused not only agricultural disaster but also intense wildfires in during August of 2003 (Gobron et al., 2004). The FAPAR measurements were also found to strongly correlate with independent surface wetness measurements (Gobron et al., 2004).

NDVI was also used in conjunction with a Vegetation Condition Index (VCI) to monitor drought in Iran and resulted in positive correlation with measured meteorological drought data, showing another example of the potential usefulness of remote sensing in application to visualizing drought conditions (Bajgiran et al., 2008). The VCI approach attempts to quantify and account for weather-related fluctuations in NDVI and is calculated as follows:

$$VCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$

Equation 2.3

Where:
$NDVI$ = Smoothed weekly NDVI
$NDVI_{max}$ = Multi-year maximum NDVI
$NDVI_{min}$ = Multi-year minimum NDVI

VCI ranges from 0.0 to 1.0, corresponding to changes in vegetation condition from extremely unfavorable to optimal. Alternatively, the index can be represented by a percentage from 0 to 100 (Bajgiran et al., 2008).

To adjust for NDVI's weaknesses in timing and shallow surface characterizations, and to improve remote sensing's ability to measure soil moisture conditions at a 0 to 50 centimeter depth, a Cropland Soil Moisture Index (CSMI) was developed and applied to a drought study in Henan, China (Chen et al., 2009). CSMI utilizes the MODIS midwave infrared (MWIR) bands six (1628 nm to 1652 nm) and seven (2105 nm to 2155 nm) to derive the surface water content index (SWCI) and is then factored with NDVI to more accurately measure the soil moisture content at depths of 0 – 50 cm (Chen et al., 2009). The CSMI is derived as follows:

$$CSMI = \frac{NDVI - SWCI}{NDVI + SWCI}$$

Equation 2.4

Where:

$$SWCI = \frac{\text{Band 6 - Band 7}}{\text{Band 6 + Band 7}}$$

CSMI indications of soil moisture closely resembled actual relative soil moisture (RSM) in Henan in 2007 (Chen et al., 2009).

A Modified Perpendicular Drought Index (MPDI) was tested in several places in China including in Beijing and Ningxia Hui Autonomous Region of China (Ghulam et al., 2007). Similar to other indices, MPDI uses the red and NIR spectrum bands of MODIS data while accounting for such variables as vegetation growth, soil moisture, and Leaf Area Index (LAI) and was found to closely correlate to measured and observed soil moisture and drought conditions (Ghulam et al., 2007).

A Normalized Multi-Band Drought Index (NMDI) was developed to account for both soil moisture and leaf water content changes. NMDI was determined by calculating the difference between the 860 nm band (a NIR wavelength sensitive to water content) and the difference between the shortwave infrared (SWIR) 1,630 nm and 2,130 nm bands (water absorption bands), and then dividing by their combinations. Also in China, NMDI was used to analyze Henan Province drought conditions during the 2008 and 2009 severe droughts which supported the claims of NMDI effectiveness in cropland drought monitoring. NMDI data for periods of time for this drought were compared to the 0-50 cm depth soil moisture data from meteorological stations. Correlations between NMDI and soil moisture observations were found to be strong at p = 0.01 significance levels (Zhang, Chen and Shen, 2009).

Leaf Area Index (LAI) is another vegetation index used to evaluate the health or stress of vegetation. More recently in the North Central Plains of China, LAI measurements from the MODIS instrument were used to assess the severity of the 2009 winter drought (Liu et al., 2009). By conducting a comparison of the winter drought vegetation LAI conditions to a historic time series analysis of MODIS data, it was shown that LAI was effective in identifying the actual locations of heavy drought as well as the spatial extent of the potential impact of the drought.

The Vegetation Health Index (VHI) was used in combination with the Palmer Z-scale meteorological drought index to highlight spatial distribution of vegetative (VHI) and meteorological (Z-scale) drought conditions and the declining trends in soil moisture availability in northern China from 1981 to 2008. A moderately positive correlation between the Z-index and VHI was found for croplands and forests during the growing season. However, irrigated areas did not result in significant correlations between the two indices, leading the researchers to conclude that VHI is a better measure of vegetative drought than the Z-index. Specific study areas throughout China included Hebei, Henan and Shandong Provinces, and Beijing and Tianjin Municipalities (Zhang et al., 2009).

A Vegetation Temperature Condition Index (VTCI) was developed in China using NDVI and Land Surface Temperature (LST) data to monitor droughts (Wang et al., 2001; Wang et al., 2003). The VTCI effectively reflected the severity of drought across the Guanzhong Plain of central Shaahxi Province in China and an Auto-Regressive Integrated Moving Average (ARIMA) model applied to VTCI accurately predicted drought conditions across the plain during March, 2006 (Han et al., 2009).

The Temperature Vegetation Dryness Index (TVDI) is another index developed for regional drought monitoring and provides a higher temporal resolution for the evaluation of vegetation health. This measure, a ratio of the properties of NDVI and LST, yielded moderately positive results in assessing drought conditions across Sichuan Province. Positive correlations between TVDI and temperature along with negative correlations between TVDI and precipitation were confirmed. However, the strength of these associations was moderate to weak depending on the time period analyzed (Zhang et al., 2007).

Several notable efforts have been made in operationalizing some of the previously discussed remote sensing applications to assist government and emergency response officials in assessing drought impacts. One such effort was accomplished in India. After investigating historical trends in NDVI across India using Wide Image Field Sensor (WiFS) data from the Indian Remote Sensing Satellite (IRS), a deficit year (1999) was compared to a standard year (1998) to derive measures of crop health and drought severity classifications (Krishna et al., 2009). A land use map was digitized and classified, and land areas of crops (specifically paddies) were estimated by using a combination of land use data and NDVI data. The total area of crops was used to calculate an agricultural drought assessment for each region of the Palar Basin, southwest of Chennai, India, classified by order of severity. The calculated paddy areas from both 1998 and 1999 images were compared to calculate the changes between the two, showing that in 1999, 60% of the basin area experienced paddy area reduction during the Samba season (August to October) and 75% of the area experienced paddy area reduction during the Navarai season (December to January).

In similar fashion, Hartmann, Di Bella and Oricchio (2003) integrated multi-spectral satellite remote sensing into a GIS analysis of the southeastern counties in the Buenos Aires Province of Argentina. However this approach also incorporated operational management theory by seeking a low-cost, rapid and effective decision-making tool for government to implement in the midst of a drought disaster. In this case, AVHRR data from NOAA satellites were used to derive NDVI. Just as in the India example, land use data were used to filter out areal coverage not relevant to the decision-maker. Precipitation data were also incorporated in the model and analyzed in comparison with time-series historical analysis. Instead of comparing the drought year against a pre-determined average year, as was the case in the Krishna et al. research for India, the drought year (2001) was contrasted with a time series average from 1996 to 2000. The NDVI values were then used to derive five categories of crop conditions in similar fashion to the India case study. As another step beyond the scope of the India case study, the Argentina work also incorporated LANDSAT TM imagery into the process to allow analysts to make an additional higher-resolution assessment for the areas experiencing poor or very poor crop conditions. While the LANDSAT imagery analysis was done in an informal and interpretive manner, the context for the study entailed the requirement for government decision-makers to make quick and low-cost decisions about where to focus resources (particularly for taxation and credit applications) during what was deemed to be an extended emergency drought incident in 2000 and 2001. The study concluded that despite the prevailing notion of drought circumstances, the methods employed showed that crop conditions were healthy overall. Operationally, the study concluded that analysis by multi-spectral remote sensing was useful in evaluating crop conditions, and that incorporating higher-resolution imagery interpretive analysis with the lower-resolution NDVI quantitative analysis afforded an effective and rapid process for making the required assessments during a drought disaster.

Research by Sheng et al. (2003) in Anhui, China developed a systematic structure for implementing drought monitoring while also positing additional quantitative approaches for assessing drought conditions in the late 1990’s using AVHRR sensor data. One method used was the Vegetation Water Supply Index (VWSI), which is a ratio of crop canopy temperature to normalized NDVI. Another method employed was to measure the thermal inertia of the earth's surface which, in theory, indicates the propensity of the surface to resist temperature change and thus indicate healthy and moist conditions, or potential drought conditions (moist soils will have relatively higher thermal inertia than dry soils). Like the case studies in India and Argentina, the researchers classified the remote sensing results by severity for the 1997 and 1998 years. Finally, a regional drought condition index was derived based upon growing conditions during periods of drought and flooding, and a moving-average annual crop yield estimation model was formulated. The authors concluded that results from the GIS and remote sensing analysis matched observed field conditions in Anhui during the 1997, 1998 and 2001 drought seasons.

While remote sensing is frequently applied for direct measurement and assessments of drought situations as in the examples above, analysis of remotely sensed data is also promising when applied to fire hazards. Fires pose a secondary disaster risk to lives and property throughout an area affected by drought, and the combination of a fire disaster during a major drought disaster complicates and compounds an already volatile situation. Recognizing that remote sensing was not typically applied to fire risk evaluations in China, researchers investigated whether remote sensing could provide synoptic frequent information for wide areas which could effectively generate fire indexes (Guo and Zhou, 2004). To accomplish this, MODIS LST data from the Terra satellite were found to be useful for identifying areas of increased fire risk (Guo and Zhou, 2004). Land Surface Temperature (LST) readings were found to significantly increase as many as three days in advance of fires (Guo and Zhou, 2004). Additional efforts to use remote sensing for evaluating fire hazards were conducted using AVHRR data (Burgan et al., 1988).

In addition to using MODIS data to highlight areas of increased fire hazard risk, wildfire management agencies in the United States have also utilized thermal IR MODIS data to provide synoptic, 2-4 times-daily hot-spot detection of fires for estimates of regional fire distributions (Joyce et al., 2009).

Bulgaria's Aerospace Monitoring Center (ASMC) implemented a system for detecting and monitoring droughts and fires using both MODIS and AVHRR sensor data. NDVI was used for drought monitoring while thermal IR anomaly measurements were used for fire detection. ASMC found the remote sensing applications for drought and fire detection to be effective tools and explained that the remote sensing-derived drought detection products correlated with their own ground observations (Frantzova et al., 2010).

This discussion of the history of remote sensing methods applied to droughts bears evidence of the broad utility remote sensing provides to government officials responding to a drought. In the examples cited above, numerous possibilities for measuring vegetation health or stress, soil moisture and wildfire vulnerability were presented. Innovative examples of emergency management through the integration of remote sensing data, geo-spatial data (such as land use data) and existing system architectures to assess drought situations and provide products useful for aiding in the decision-making process were also presented. Building on these important and innovative studies, this discussion will now turn to an assessment of the current status of remote sensing applications to the response phase of a drought disaster.

Assessing the Present Status of Remote Sensing Drought Response Applications

No single Earth observation system is currently fully dedicated to monitoring and quantifying the impact of extreme droughts (Deshayes et al., 2006). Space-borne sensors such as the Tropical Rainfall Measuring Mission (TRMM), which attempts to directly measure precipitation, do not provide reliable enough data to enable accurate remote sensing of rainfall (Lensky and Levizzani, 2008). Thus the present status of remote sensing drought applications centers on the use of diverse satellite platforms not designed specifically for drought monitoring to derive the drought, vegetation and soil moisture indices described above.

When several of these drought-related indices were tested and compared to one another in Mongolia, results showed that several indices characterized the drought impact with spatial patterns that were at times inconsistent with one another (Bayarjargal et al., 2006). Such conflicting results suggest that the present condition of drought monitoring using remote sensing is still an evolving science, and thus any assessments made of drought conditions by use of remote sensing applications will continue to rely heavily upon the incorporation of complimentary sources of data made available to emergency responders or government officials, including their own local knowledge.

Still, numerous vegetation and drought indices offer a wide range of feasible tools to monitor and respond to drought incidents (a summary is provided above in Table 2.1). However, most of these studies were either conducted long after the response phase of drought disaster management was over, or they were conducted simply for the sake of improving on previous drought-related remote sensing indices without addressing operational solutions.

The closest examples of operational use of remote sensing products during the response phase of a drought disaster were found in the work of Hartmann et al. (2003) and Frantzova et al. (2010). Hartmann et al. developed a low-cost, rapid decision-making tool for Argentine government officials to monitor drought conditions in a way that incorporated NDVI data and high-resolution imagery. Frantzova et al. integrated the use of NDVI and thermal IR anomaly data to aid Bulgarian government officials in identifying areas experiencing drought or wildfires. Conclusions made by the authors of both examples cited satisfaction and confidence in the utility of the operational methods they employed to quickly assess the drought conditions in their respective countries.

Table 2.1
Cited Examples of Remote Sensing Drought Applications

Application	Sensors	Location	Author
NDVI	VEGETATION HRVIR AVHRR MODIS ETM+ WiFS	France / Western Europe Argentina India	Deshayes et al. 2006 Hartmann et al., 2003 Krishna et al., 2009
EVI	MODIS	Global	Heute et al., 2002
VCI	AVHRR	Northwestern Iran	Bajgiran et al., 2008
TVDI	AVHRR	Sichuan Province, China	Zhang et al., 2007
MPDI	MODIS ETM+	Beijing, China Ningxiahui Autonomous Region, China	Ghulam et al., 2007
NMDI	MODIS	Henan Province, China	Zhang, Chen and Shen, 2009
VHI	AVHRR	Hebei, Henan, Shandong Provinces and Beijing and Tianjin municipalities, China	Zhang et al., 2009
CSMI	MODIS	Henan Province, China	Chen et al., 2009
FAPAR	MERIS	Global	Gobron et al., 2004
VTCI	AVHRR	Shaanxi Province, China	Han et al., 2009
LAI	MODIS	North China Plain	Liu et al., 2009
LST	MODIS	China	Guo and Zhou, 2004
Thermal IR anomaly	MODIS	Bulgaria	Frantzova et al., 2010

Nearly all of the remote sensing experts responsible for assessing and monitoring their respective droughts in the previous studies found it necessary and beneficial to classify different levels of drought severity using vegetation data derived from orbiting satellite sensors. Such practice has become routine but should not be taken for granted. The classification of drought severity is important methodologically in that it focuses the attention of disaster responders on the locations most severely affected by drought which in turn leads to more effective use of limited resources during a time of emergency. Thus remote sensing's present value added to drought response is the spatial situational awareness provided to responding officials that other forms of measurement either do not provide, or if they do, are lacking in accuracy (such as those methods of measurement which rely on point-based measurements, spatial interpolations, and/or non-locational reporting of events).

In summary, the present status of remote sensing applied to drought response is a condition reliant on spaceborne sensors developed for purposes other than drought monitoring. The capabilities are still evolving from a technical infancy and it is still largely a scientific, non-operational endeavor. However, remote sensing is providing unique and critical spatial situational awareness to individuals monitoring droughts in ways that other data collection systems are unable to provide. Therefore, the prospects for developing operational methods that utilize remote sensing tools in aiding disaster management officials as they respond to a major drought disaster are positive.

Prospects for Remote Sensing Drought Response

Benefits of remotely sensed data during the response stage of a disaster include: 1) assessing the intensity and extent of a drought; 2) measuring stress of vegetation, impact on agricultural yields, and impacts associated with disease; 3) determining potable water availability; 4) analyzing demographics and infrastructure in the drought affected areas; and 5) aiding in decision support, among other applications (Jeyaseelan, 2004).

The work of Deshayes et al. (2006), Gobron et al. (2004), Zhang, Chen and Shen (2009), and Liu et al. (2009) serve as excellent examples of how remote sensing technology has already been used to characterize or predict drought conditions. Each of the drought-related indices reviewed demonstrate how remote sensing satellites are used to assess the intensity and extent of a drought, as well as the persistence of vegetation stress. The work of Krishna et al. (2009) and Hartmann et al. (2003) both demonstrated effective efforts to estimate the impact of drought on agricultural yields. Hartmann et al. (2003) and Frantzova et al. (2010) both demonstrated seminal efforts to use drought-related remote sensing indices as an operational aid in the decision-making process. Conclusions drawn from the remote sensing studies largely correlated with other drought assessment methods. As importantly, government agencies from multiple continents expressed confidence in the utility of the remote sensing methods employed.

Although the results are promising, existing studies typically focus on a singular method, and are not carried out in an operational manner restricted to the tight time constraints requisite of the Charter activation limits or the drought response timelines required in this project. The current research will help determine if it is feasible to apply these drought-related remote sensing methods during the response phase of disaster management and also within the operational limitations of the Charter. Given the historical methods and the present status of remote sensing discussed in the previous sections, the prospects are plentiful and promising, but the limitation on time restricts these prospects.

Droughts develop and persist over long periods of time, lasting weeks, months and sometimes years in duration. Herein is the challenge in developing an effective use of remote sensing for any drought disaster response. Monitoring a drought event over a long period of time as the drought develops and recedes is already a common and useful practice. Employment of remote sensing as a means to improve emergency management procedures during the response phase of a drought disaster in the spirit of international aid and cooperation is new and challenging territory. Given the grave and growing consequences of drought disasters, however, the journey into this new territory is warranted.

The goal for emergency managers responding to a drought who are using remote sensing products is not to scientifically debate the definition of drought, nor develop a breakthrough in identifying the best index and formula for characterizing or forecasting a drought. These are noble and important pursuits, to some extent outside the scope of this study, but the pragmatic interest of an emergency manager is to simply make rapid use of the tools and methods of analysis which already exist. The goal is to determine which spatial areas are being most severely affected by drought so that limited response resources may be most effectively utilized to mitigate damages. While this review of the literature reveals overwhelming breadth and numerous positive prospects for the application of remote sensing in drought response, it also reveals two common needs in drought response. First, the measurements and spatial visualizations of vegetation health or soil moisture are key drought situational awareness products. Second, the spatial awareness and classification of varying degrees of drought severity emerged as a common theme for officials and scholars monitoring droughts. Meeting these two common needs, within a limited period of time, are the key prospects for remote sensing's contribution to drought response and serve to shape the methods for emergency drought response described in the next section.

CHAPTER III

METHODOLOGY

Defining Remote Sensing's Utility in Drought Disaster Response and Charter Operations

To determine whether remote sensing potentially serves to benefit drought disaster response, and whether it is justifiable to recommend drought disaster response as a new service provided by Charter activation, the utility of remote sensing during a drought disaster must be explored. The International Council for Science (ICSU), consisting of representatives from 134 countries, frequently fulfills a global leadership role in conducting research to reduce the loss of life or property from disasters through its Integrated Research on Disaster Risk program (ICSU, 2008). The (IRDR) program seeks to facilitate the world's enhanced capacity to address hazards and make informed decisions to reduce their impacts. The hazards from drought are apparent from the discussion of drought disasters above, and in discussion of a specific drought example in China below. IRDR believes that humans can adjust or adapt behaviors to reduce their vulnerability and increase resilience during disasters. The utility of remote sensing during a drought disaster should be defined by determining whether the application of the technology can enhance officials' capacity to address hazards, make informed decisions to reduce drought impacts, and modify human behavior to increase the affected population's resilience during a disaster. If the use of remote sensing can effectively contribute to these key areas of reducing the impact of a drought disaster during the response phase of disaster management, the use of remote sensing as a disaster response mechanism is warranted.

Emergency response officials typically have limited resources and manpower for responding to disasters; therefore it is critical for these decision-makers to obtain situational awareness that will help them prioritize locations that need focused effort and to what degree help is needed. Emergency managers responding to a drought disaster require situational awareness of soil moisture content, vegetation health, fire hazard locations, hydrological data and meteorological data. Understanding soil moisture content and vegetation health conditions enables decision-makers to not only understand the physical dynamics of a drought event, but also serve as an important dataset in helping to predict the spatially disparate agricultural and economic impacts that emerge in drought-affected areas. Spatial knowledge of these conditions is fundamental to a response official's decision matrix. Areas that are experiencing severe drought may or may not be of concern to the official directing response resources depending on the land use of the areas affected. For example, if severely stressed vegetation occurs in a desert area where no cropland exists, the response official would not dispatch irrigation resources or implement precipitation enhancement operations (such as cloud seeding) over the affected area. However, if a drought-affected area is primarily composed of cropland in the midst of the growing season, the dispatch of resources and authorization of coping to reduce the drought's impact may be warranted. Without the necessary spatial data on land use, vegetation conditions, and soil moisture, emergency managers' decisions are less-informed and response resources may be wasted or misapplied. The premise of this research is that remote sensing can provide the necessary spatial data for drought conditions when combined with additional available government data and statistics, such as land use data, that will enable an improved emergency response to a drought disaster. Additionally, disaster management officials are concerned with "secondary" disaster hazards which may further complicate and compound an already severe disaster incident. For example, in the case of drought, fire hazards represent one of the most dangerous secondary disaster threats. Therefore, the evaluation of remote sensing's utility during a drought disaster response should also include an evaluation of remote sensing's capacity to provide information which can help response officials know which areas affected by drought pose the most severe fire hazard. Although the future for spaceborne hydrological and precipitation monitoring is promising, those applications have not been as reliable or as extensively validated as applications involving vegetation health, soil moisture, and other land surface monitoring. Therefore the methods of this research will rely heavily upon studies related to vegetation and land surface data.

If remote sensing is found to offer some benefit to drought disaster response, the second test of this research is to determine whether the implementation of the remote sensing applications found beneficial to drought response are suitable for integration into Charter activations. The end goal for such integration is to leverage the assets of space-faring nations in coming to the aid of non–spacefaring nations experiencing the terrible effects of a severe nationally-declared drought emergency. The utility of remote sensing applications in the context of the Charter can be determined by answering whether the remote sensing applications found to be beneficial in drought response can be easily executed under the current Charter intent, organizational capacity, structure and limitations. Even if remote sensing is found beneficial for drought response efforts, the Charter may not be the answer to improving remote sensing drought response. Although the Charter is recognized as a premier international humanitarian organization leveraging remote sensing assets to respond to major disasters, the Charter may not be capable of supporting drought response activations from an organizational or operational perspective.

This research employs a case study using two general methodologies to evaluate remote sensing's utility for drought response and Charter drought response. The first methodology is operational and the second organizational. Operational remote sensing methods were developed and tested for an area which experienced a severe, nationally-declared drought disaster in north China. An organizational assessment of the Charter's capacity to respond to drought disasters and a consideration for available alternative organizations was also studied.

Although China is a spacefaring nation with an impressively advanced and aggressively progressing space program that operates remote sensing satellites of their own, China's winter drought of 2009 was chosen as the case study drought event for testing the utility of remote sensing drought response applications. This decision was made for a number of reasons. First, the drought's severity is readily measured by spaceborne sensors. Second, this drought affected millions of persons and was declared a national disaster; therefore it qualifies as a "major disaster" for the purposes of a justifiable Charter consideration for activation. It posed a severe threat to agricultural and the Chinese economy. The availability of media reporting was also a consideration for conducting research using secondary sources. The province had previous experience in receiving support from Charter activation during a flooding emergency. The author's own familiarity with the area's language and customs was convenient for conducting the research. Finally, the individual provinces of China are also useful scales for a case study given the areal extent of its provinces and counties and the populations and sizes of government bureaucracies which often can equal or surpass the areas, populations and sizes of government bureaucracies of non-spacefaring nations. Thus a province of China serves as a good preview to a future remote sensing response to major drought disaster in a non-spacefaring country. To become more familiarized with the case study area of Anhui

Province, the next section provides useful background information before turning to methods employed in the case study.

Anhui, China Case Study Area Familiarization

The study area selected is Anhui Province due to its drought history, Charter activation history, important agricultural value and proximity to economically-strong east coast provinces. According to the official government figures, Anhui has a population of over 64 million people across an area of 139,600 square kilometers (Anhui Government, 2009). That equates to an average population density of approximately 458 persons per square kilometer. Over 5 million hectares of land in Anhui are used sown to grain (Anhui Government, 2009). The Yangtze and Huai Rivers pass through the Province. The Dabie and Qiuling Mountains enclose Anhui on the southwest and south respectively (see Figure 3.1). China's fifth largest freshwater lake, Chaohu, is situated at the center of the Province, south of the capital, Hefei. The climate is classified as warm and moist temperate to sub-tropical with an average of 800 – 1800 mm of rainfall a year. The Huaihe River is commonly used as a boundary reference between the southern sub-tropical humid climate region and the warm-temperate, semi-humid monsoonal climatic region to the north.

Due to improvements to water control and management systems, Anhui's grain output steadily increased to over 30 million tons during the past three decades (see Figure 3.2; China Statistics Press, 2009). Anhui is now China's 6th largest producer of grains and the rural population remains heavily dependent on agricultural production for their livelihood (see Figure 3.3). Given these figures, drought disasters in Anhui have a very damaging effect on China's overall agricultural output, food security and the regional economy. Therefore, this research focuses on Anhui's crop production areas and excludes non-agricultural areas throughout the province.

Croplands throughout Anhui Province are characterized by large double-cropped open fields with winter crops of wheat, rape and barley, and summer crops of corn, soybeans and ride (see Figure 3.4). Some farmers also practice summer season intercropping where strips of corn and soybean are sown in the same field. For example, it is common to see corn and various types of bean crops all planted in the same field as farmers make more effective use of land resources.

Farmland in Anhui is also characterized by a vast network of irrigation canals that weave through the crop fields and provide irrigation from rivers or local reservoir sources (see Figure 3.5). Irrigation is largely controlled by local water bureaus in China, as apparent from one farmer's comments to the media during Anhui's drought when he said, "You can see the wheat is a bit yellow already, but we're not allowed to irrigate here until after the Lantern Festival" (Harby, 2009).

Figure 3.1. Anhui Province Reference Map

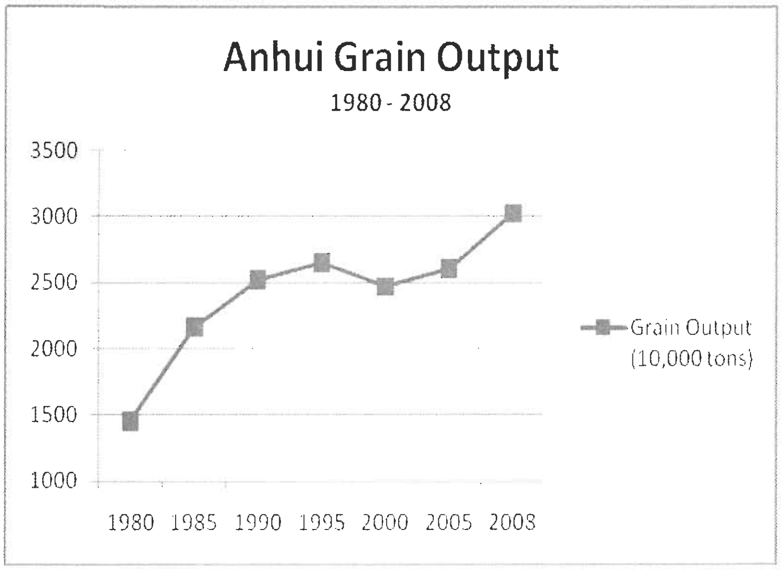

Figure 3.2. Anhui Grain Output. (Source: China Statistics Press, 2009)

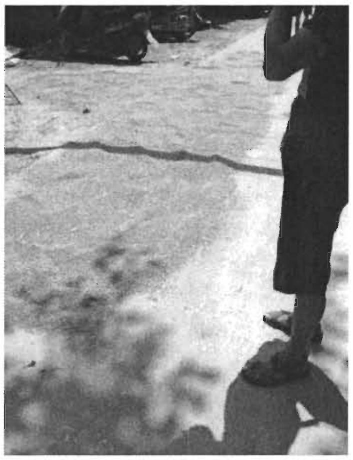

Figure 3.3. Grain on Street Near Chengjiaji, Anhui, China. (Source: Burkhead, 2010)

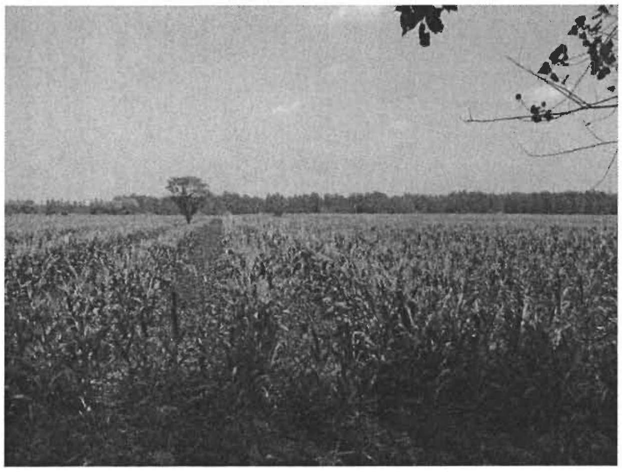

Figure 3.4. Crops in Anhui Province, China. (Source: Burkhead, 2010)

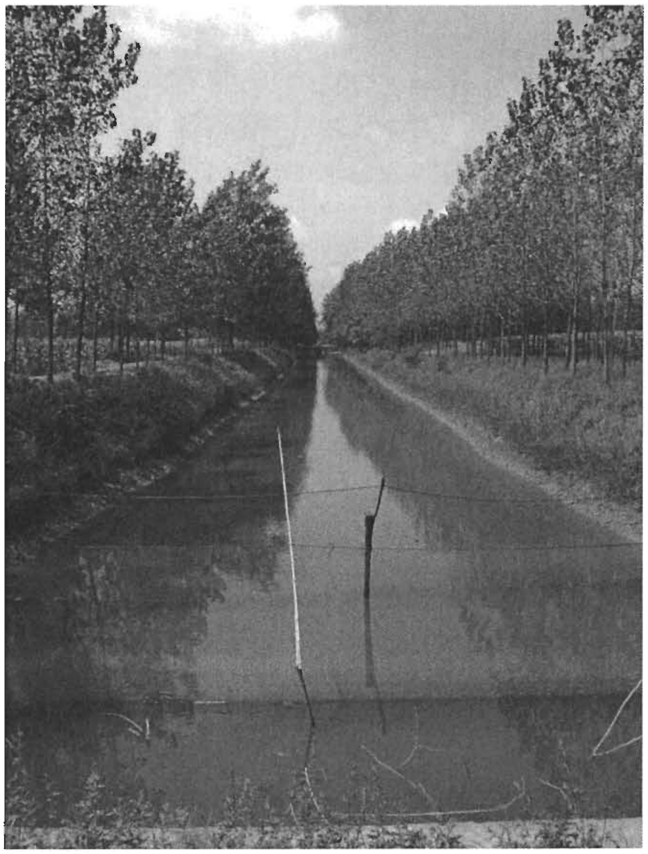

Figure 3.5 – Irrigation Canal in Northern Anhui Province, China. (Source: Burkhead, 2010)

Anhui also has previous experience in activating the International Charter for Space and Major Disaster when floods struck the areas surrounding the Huaihe River in 2007 (Charter, 2007). The Charter promptly provided situational awareness products that highlighted which areas were affected by flooding along the Huaihe River (Charter, 2007). With this background on Anhui Province established, attention can now be turned to the winter drought of 2009 that severely threatened Anhui's agriculture and population.

China's 2009 Winter Drought

China has identified drought as its most severe type of natural disaster, indeed more severe than typhoons, insect plagues, earthquakes, floods or storms. It is not hard to see why China's government feels more threatened by drought than any other major disaster after considering the far-reaching consequences of China's drought experiences in the North China plain during 2008 and 2009. In these two years of droughts, precipitation in impacted areas was reduced 50 to 80 percent. Over four million people and two million livestock were left without adequate drinking water, and nearly eleven million hectares of wheat were affected (USDA, 2009). Almost half of the wheat growing areas across the region were threatened in what China's Office of State Flood Control and Drought Relief (SFDH) called a drought "rarely seen in history" (CBC, 2009). Media broadcasts showed images of dry, cracked farm fields and withering vegetation (CBC, 2009). The cause of the drought was attributed by one Chinese meteorologist to a series of cold fronts that stopped rain clouds from the Bay of Bengal from reaching China (Moore, 2009).

One of the provinces hardest hit by the drought disaster in 2009 was Anhui Province where a government analyst expected a 20 percent decline in wheat yields (Hornby, 2009; USDA, 2009). The government's mobilization to counter the drought was rapid and aggressive, but given the major scale of drought conditions experienced, human suffering and damaged crops persisted through the province.

It was reportedly North China's worst drought experienced in 50 years (Florcruz, 2009).

When issuing its "red alert" of the 2009 drought, the Anhui Meteorological Bureau forecasted that Anhui's crops north of the Huaihe River would be plagued by the drought (Yan, 2009). After the drought event was elevated to what China classified a "Level-2" emergency, Zhang Zitong, the Deputy Chief of the SFHD, directed local officials to fight the drought, protect seedlings, and expand irrigation coverage (Hornby, 2009). China's State Council (China's highest executive organ of State power and administration) declared the drought a national disaster on February 4th, 2009, raising the emergency to "Level-1" alert (Xinhua, 2009). In doing so, China's President, Hu Jintao, and Premier, Wen Jiabao, ordered government officials in the affected areas to make drought relief their top priority, enhance farmland management, expand technical services, expand irrigation efforts, implement precipitation enhancement measures, deliver emergency drinking water supplies, implement plant disease and pest prevention measures, monitor and fight forest fires, and increase readiness and response capabilities (Xinhua, 2009).

According to a United States Department of Agriculture report:

> "Officials sent 279,000 experts and technical personnel to fight the drought, trained 19.7 million farmers on drought-resisting technology, and mobilized 31.7 million people. Within weeks, an estimated 9.33

> million hectares of wheat fields had been irrigated, about 84 percent of the drought-affected area and more than 42 percent of the total wheat sown area" (USDA, 2009).

To induce precipitation, the government launched thousands of shells of silver iodide into the atmosphere that may have helped to trigger widespread rain and snow showers during the second week of February (USDA, 2009). The government also authorized over 400 million Yuan (approximately 63 million U.S. Dollars) in emergency funding to fight the drought and to provide additional economic aid to poverty stricken persons in rural areas (Xinhua, 2009). Some of this emergency funding was used to compensate for the lost income of grain producers in the affected areas (Sulekha, 2009).

The severity of China's 2009 drought with its harsh humanitarian and economic impacts and the government's resultant actions serve as compelling examples in justifying the need to search for additional technologies which can more effectively reduce the impact of a major drought during the response phase of disaster management. Despite the vast resources available to the Chinese government and the levels of funding and support committed by the central government to respond to the drought, the emergency response was challenging. When the very safety and livelihood of persons living in a drought-affected area are threatened by lack of the most fundamental resources for sustaining life, such as water, grain and livestock, it is important to leverage whatever technologies and resources can be brought to bear in minimizing the effects of the devastation. When government officials directly order the leverage of technologies, monitoring of the situation, and implementation of measures to irrigate and conduct precipitation enhancement efforts, a strong case can be made for the use of remote sensing for assessment and planning. In order for Chinese officials to most effectively irrigate with limited water resources, they must know which areas require the greatest need of irrigation to salvage some portion of the crop. One official in China's Irrigation Research Center expressed frustration during the drought response because water was being wasted since the use of mature irrigation technologies were not possible due to a lack of funds. Further, the drought underscored the fact that investment in irrigation infrastructure was insufficient (Yang and Zhang, 2009). Remote sensing analysis could have been utilized to reduce water waste by identifying those areas affected by the drought that most require irrigation and which require the least. In addition to remote sensing's utility for responding to the primary hazards of the drought, it may also be useful in response to the secondary hazard of a drought posed by fires.

A fifty-year old resident of northern Henan Province expressed concern over the fire hazard during the 2009 drought, saying, "The wheat grass gets so dry that it catches fire! I've never seen this in my whole life" (Yang and Zhang, 2009). Indeed, many areas impacted by the Anhui drought ran the risk of a secondary disaster from fire. In order for officials to monitor the threat from fires, they need to know which areas are most vulnerable to fires starting. Remote sensing may also provide this situational awareness of fire hazard.

The Anhui drought experience illustrates some compelling examples of the potential for remote sensing methodology to be put to effective use in directly satisfying the needs of government officials and the public in response to a major drought disaster. Those specific methods are outlined next, beginning first with a summary of the types of data found applicable to a remote sensing response to drought.

Case Study Data

Since the aim of this project was not just to evaluate spaceborne remote sensing's capacity to contribute to drought response, but also to assess the Charter's capacity to respond to a major drought disaster, data for this project needed to be provided by satellites either already available for Charter utilization, or from satellite data that are freely accessible to the public. Additional government statistical data may also be integrated since a nation requesting Charter support would presumably provide whatever government statistical data could be used to enhance the Charter's end products.

As seen in the review of drought-related remote sensing literature in Chapter Two, the MODIS sensor on board the Terra and Aqua Earth Observation System (EOS) satellites has been commonly used to measure vegetation and soil moisture conditions during droughts. Between the two satellites, MODIS sensor data offer twice-daily coverage of the earth's surface features across 36 spectral bands. MODIS sensor data from EOS satellites are available to the Charter and the public at 250 meter to one kilometer resolutions. The public can easily download this data using NASA's Land Processes Distributed Active Archive Center (LP DAAC) search tools or the U.S. Geological Survey's (USGS) Global Visualization Viewer (GloVis) data navigator available at glovis.usgs.gov. Given this ease of accessibility, and the fact that EOS systems already routinely support Charter activations when requested, MODIS data was chosen as a suitable data source for the case study.

In testing a notional Charter remote sensing response to drought, two general types of MODIS data were utilized: 1) drought-related vegetation data in the visible band; and 2) near-infrared bands and land surface thermal data. The MODIS vegetation indexed data permits assessment of vegetation conditions using drought-related vegetation indices such as NDVI and EVI. The thermal MODIS data permits assessment of fire hazards and fire locations.

As noted above, MODIS offers NDVI and EVI products for download. NDVI and EVI measurements from the MODIS sensor are available via a 250-meter daily product (MOD09GQ), an eight-day composite product (MOD09Q1) and a 16-day composite product (MOD13Q1 [Terra] and MYD13Q1 [Aqua]) at a resolution of 250 meters using MODIS band 1 (620-670 nm) and band 2 (841 – 876 nm) (USGS, 2010). These vegetation index products are estimates based on the surface spectral reflectance as measured at ground level assuming no atmospheric scattering or absorption, and corrected for the effects of atmospheric gases and aerosols (Vermote et al., 2008). MODIS drought-related indices including NDVI and EVI have been extensively validated, and the ease of use with data that has already been processed and corrected for atmospheric effects and bi-directional reflectance (BRDF) adds value to its utility given the limited response time for disaster management (Liu L.Y., interview, August 2010). For example, the BRDF mask for MODIS NDVI and EVI products filters out water, clouds, heavy aerosols, and cloud shadows for the data user (USGS, 2010).

The use of MODIS thermal data for fire hazard mapping included LST data (MYD11A2) and an active fire detection data product. The MODIS sensor was chosen for its better temperature precision (1 Kelvin) when compared with the less-precise AVHRR sensor (Guo and Zhou, 2004). The MYD11A2 product is a composite image created from daily clear-sky averaged inputs from MODIS LST (MYD11A1) at 1 km resolution (USGS, 2010). The MODIS active fire detection eight-day composite product (MOD14A1 and MOD14A2) was used to map active fire locations.

An annual classification of land cover types over the surface of the earth is also provided by the MODIS sensor. MCD12Q1 data offer land cover classification using the International Geosphere Biosphere Programme (IGBP) format as well as additional formats at 500-meter spatial resolution (USGS, 2010).

In addition to the remotely sensed data described above, Chinese statistical data can also be incorporated in the spatial analysis of the drought incident. Chinese government statistical data were extracted from the 2010 Anhui Statistical Yearbook to make drought impact assessments and to evaluate the reliability of the conclusions made by the products created in the case study simulation.

In summary, MODIS vegetation, MODIS thermal anomaly, and MODIS-derived land cover data were integrated together to create geo-referenced, operationally-feasible drought response products for the fifteen-day time period following China's declaration of the 2009 winter drought national disaster. The operational methods employed with this data are detailed in the next section.

Case Study Methods

Data products described in the previous section for the fifteen-day time period immediately following China's declaration of a drought national disaster on February 4th, 2009, were used to simulate a notional Charter remote sensing response to Anhui's drought disaster. For reasons given in Chapter One, the case study is thereby restricted only to satellite data made available to the Charter. For the purposes of simplification and due to the benefits that MODIS offers as described above, only MODIS sensor data from EOS satellites was used. As mentioned in the Introduction, the Charter practices a policy of activating for no longer than fifteen days. Since this case study evaluates the operational feasibility of a Charter response to a drought disaster, the simulation must carry the same fifteen-day limitation. Therefore the simulation only employed use of the fifteen days of available data from February 4th, 2009, until February 19th, 2009. However, some archive data preceding February 4th freely available to response officials was also utilized for creating the initial situational awareness products.

As discussed previously, officials in every nation have limited resources and manpower for responding to disasters; therefore it is critical that these decision-makers obtain situational awareness that will help them prioritize which locations need focused effort and the degree of attention warranted. The Charter has discovered through the course of numerous disaster response missions that “users are interested in maps and not in images”, and “a first processing step is to bring actual images into adequate geographical projection systems” (Charter, 2003, p. 10). Therefore the key task of this simulation was to take the remotely sensed imagery and sensor data available to the Charter and use it to create geospatially accurate situational awareness maps.

In the case of a drought, remote sensing may provide officials with situational awareness of soil moisture content, vegetation health, fire hazard locations and active fire locations. Therefore, the notional simulation of a Charter response to China's 2009 winter drought conducted in this case study created products that specifically meet those very needs. The approach adopted is similar to that exercised by Bulgaria's ASMC where remote sensing was used to monitor both the vegetation conditions and the wildfire situation to provide robust situational awareness during a period of intense drought (Frantzova et al., 2010).

As an initial step, the research first "visualized" vegetation health using NDVI and EVI. MODIS MOD13Q1 data were downloaded from the NOAA GloVis website. The MOD13Q1 data are 16-day composite, 250-meter resolution NDVI products. Since the drought was declared by the Chinese government as a national disaster on February 4th, 2009, MOD13Q1 data were downloaded from a day as close as possible preliminary to the February 4th disaster declaration date in order to visualize the vegetation health at the beginning of the simulated fifteen-day response period. A MOD13Q1 NDVI product was created for February 2nd, 2009, just two days prior to the declaration. In order to obtain coverage over the case study area (Anhui Province) in its entirety, three separate MOD13Q1 image tiles were required for download. These images were then imported into ArcGIS, re-projected, mosaiced together as one image, and then clipped to the Anhui Province vector (map) boundaries. Next, NDVI was classified and symbolized according to common classification schemes found in other NDVI products wherein snow was filtered, water was symbolized, average to healthy vegetation symbolized at NDVI values above 0.35, and stressed vegetation symbology was applied to NDVI values less than 0.35. This map projected NDVI estimates across Anhui Province. The next required step was to generate NDVI estimates exclusively for the arable land in the province.

To mask out non-croplands areas (such as urban areas) for the NDVI situational awareness map, agricultural land cover was obtained by downloading MCD12Q1 land cover data from the MODIS sensor. The MCD12Q1 data product was chosen for its global utility. Although China certainly has more accurate and higher-resolution land cover and land use data available at its disposal, many of the non-spacefaring countries that could become benefactors of a Charter drought response may presumably lack accurate land cover or land use data. Therefore, this research made use of the global MCD12Q1 land cover data that are freely available. These data were then imported into ArcGIS, converted to a TIF file format to permit creation of an attribute table, and then symbolized by land cover type. The land cover TIF raster was then reclassified to create a croplands mask. The mask was applied to the NDVI raster through a map combination operation in ArcGIS, and subsequently symbolized. The final product was a situational awareness map of NDVI for only the cropland areas in Anhui Province.

An additional map was created using zonal statistics operations for the NDVI data. A mean NDVI calculation for each county-level administrative area in the province was produced and visualized on the provincial map. The end result was a county-level choropleth map indicating the mean NDVI value for each county-level administrative area within Anhui Province. The procedures to create both map products using NDVI data were repeated using the EVI data as well. As a result, two NDVI and two EVI situational awareness maps for February 2nd, 2009 were created: NDVI and EVI of Anhui Province croplands, and mean NDVI by county in Anhui Province.

All of the above steps were repeated for data collected by the MODIS sensor on February 18th, 2009, to provide a situation update. The Charter has found through its experience that robust but simple change detection products are useful and preferred over sophisticated change detection products (Charter, 2003). Therefore this research implemented a simple but useful change detection methodology to highlight situational changes through the course of the Charter activation. An NDVI change detection product was created for areas of severe vegetation stress by reclassifying NDVI products to only include severely stressed vegetation, and then applying a change detection operation in ArcGIS to the severe vegetation rasters from both dates. The change detection product highlighted areas where severe vegetation stress spread from February 2nd, 2009, to February 18th, 2009.

To monitor and evaluate the potential secondary disaster risk from fires during the drought, MODIS Land Surface Temperature (LST) data (MYD11A2) were also downloaded for February 2nd, 2009, and visualized to create LST situational awareness products depicting areas of highest LST. LST data from February 10th, 2009, and February 18th, 2009, were also visualized to provide updates throughout the notional Charter activation. The areas of high and increasing LST represented potentially increased vulnerability to fire hazard risks.

MODIS active fire detection eight-day composite products (MOD14A1 and MOD14A2) were used to map active fire locations for February 2nd, 2009, February 10th, 2009, and February 18th, 2009. These products were then symbolized by order of low confidence, medium confidence and high confidence levels for the location of active fires.

Each product was created to be easily interpreted by a decision-maker. Time spent on creating the products was monitored to ensure that the total hours of work did not exceed a fifteen-day activation limitation given the Charter's restriction on its duration of activation. Government statistical data for the year 2009 was joined to the spatial data for Anhui Province to indicate the potential impact of the drought disaster. Actual 2009 drought affected areas at the county level were compared to the situational maps to determine whether conclusions made from the drought response simulation products agree with the actual results of the 2009 drought

CHAPTER IV

ANHUI CASE STUDY RESULTS AND FINDINGS

General Results

Several geo-referenced remote sensing-derived situational products were created using MODIS sensor data in conjunction with the methods discussed in the previous chapter. Situational awareness products indicating degrees of vegetation stress, spread of severe vegetation stress, land surface temperature extremes, and areal coverage for areas experiencing fires were created during the fifteen-day notional Charter activation. These products were created to be easily interpreted by emergency management and government officials responding to the major drought disaster, and are intended to provide information that will aid in the responders' decision making process in prioritizing where to allocate limited resources and which county-level administrative regions require the most attention. Areas experiencing the most severe drought impacts as measured by vegetation stress and absolute land surface temperatures were highlighted as well as areas to which severe vegetation stress had spread. In addition to the products created in the simulated response, actual map products created during the drought disaster by China's Center for Earth Observation Digital Earth (CEODE) were also reviewed and were considered by this analysis as useful aids in assessing the drought response. The simulation products and the actual products developed by CEODE both demonstrated the utility of remote sensing during the response phase of drought disaster management.

Drought Response Simulations Results

The simulation period began on simulation day one, as if it were February 4th, 2009, the day China declared the drought a national disaster. The simulation period terminated fifteen days later, hypothetically February 19th, 2009. This is the day that Charter activation would have ended if it had initially activated on February 4th, 2009. All products assembled in the case study were created during the simulation and were well within the Charter limitation of a fifteen-day activation period. Products using sixteen-day composite MODIS MOD13Q1 Normalized Differential Vegetation Index (NDVI) data at 250-meter resolution of Anhui croplands were created for two days. The first was created on the first day of simulation (as if it were created Feb 4th, 2009, using MODIS NDVI data from February 2nd, 2009) and the second was created on the fourteenth simulation day (as if it were created Feb 18th, 2009, using MODIS NDVI data from the same day). The same process was used for creating Enhanced Vegetation Index (EVI) products from the MOD13Q1 data. The sixteen-day products required the greatest most amount of time to create during the simulation period, taking approximately two hours per product to create. This time included time to download, reproject, mosaic, clip, mask and integrate with vector data in ArcGIS, and to create an easily interpretable final layout. Figure 4.1 is the final map depicting NDVI for Anhui Province croplands at the beginning of the simulated activation period. Cropland areas are symbolized and colored according to their NDVI measurement. Areas that are not classified as cropland are displayed by the brown background color.

As readily apparent from the map, most of the croplands in Anhui Province are located in the northern and central portion of the province as indicated by the NDVI-symbolized colors. This is due mostly to the hilly and mountainous terrain found in the southern portion of Anhui. For convenience, a reference map of the county-level administrative regions and topography within Anhui Province is provided as Figure 3.1.

In regards to the drought's impact, any emergency manager analyzing this product can make an important conclusion quickly. As noted in Chapter Three, the Anhui Meteorological Bureau forecasted the drought to severely impact the crops north of the Huaihe River in Anhui Province. However this remote sensing product yields a contradictory conclusion in estimating the actual drought impact. MODIS data showed that cropland areas with the most severe vegetation stress were

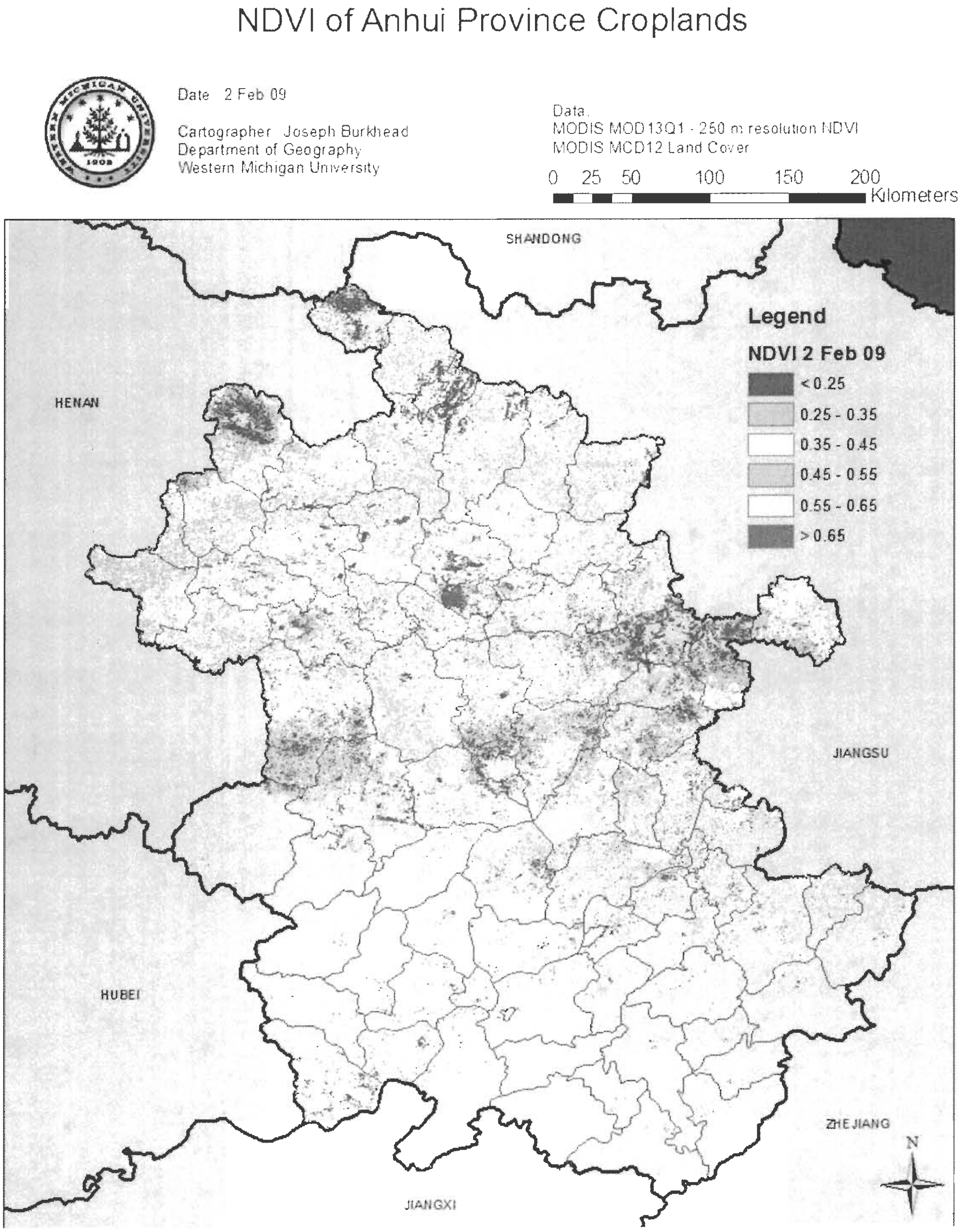

Figure 4.1. NVDI of Anhui Province Croplands, 2 Feb 09

located not just in the north, but also within central counties of the province. Severe vegetation stress in the north was prevalent primarily in three county-level administrative regions in Bozhou Prefecture-Level City, Dangshan County, and Huaiyuan County. An area of severe vegetation stress was also prevalent along the quad-county border areas of Suixi, Suzhou, Xiao and Huaibei. According to the MODIS NDVI data product, the croplands in the central regions of Anhui were no less-spared from the drought than the regions north of the Huaihe River.

From the very start of the notional Charter activation, remote sensing provided a new level of situational awareness that was not clear from government meteorological forecasts and media reporting. The day one NDVI product also indicated croplands in proximity to large urban areas were experiencing more severe vegetation stress than fields farther away from urban areas. Areas of dense vegetation stress in cropland areas are apparent in several central Anhui county-level administrative regions, in a ten kilometer circular area approximately 100 kilometers north of the capital Hefei in Huaiyuan County, and in the two extreme northern areas of Bozhou Prefecture and Dangshan County. Among the central counties, vegetation stress was estimated as most severe in the central-eastern regions of Laian County (sometimes “Lai’an”), eastern Dingyuan County and Mingguang City. These areas of particularly severe vegetation stress span wide areas of croplands in central Anhui and in the more isolated pockets of northern

Anhui are areas that emergency managers would likely turn their attention to first for allocating limited resources in response to the disaster.

A product indicating the mean-NDVI value at the county level was created to serve as a quick reference for emergency managers to assess which county-level governments were impacted most severely by the drought seen as Figure 4.2. This was accomplished by calculating the pixellated NDVI average value within the boundaries of each county zone. The map indicates that it is the central county-level governments that would be struggling most as a result of the drought impacts as opposed to the northern county-level governments as reported in the popular press.

Another NDVI product was created for Anhui's croplands for February 18th, 2009 (see Figure 4.3). This updated map of vegetation stress indices across Anhui sixteen days after the initial map discussed above indicated some significant changes fourteen days after the start of the simulated Charter activation. Overall the vegetation stress across the province was estimated to be more severe than at the beginning of the simulated activation. Most croplands experiencing severe vegetation stress on February 2nd, 2009, had not improved, and there was a significant spread in severe vegetation stress across the province. In particular, the MODIS data indicated a large area of central-western Anhui croplands that had reached severe levels of vegetation stress (indicated by red areas on the map).

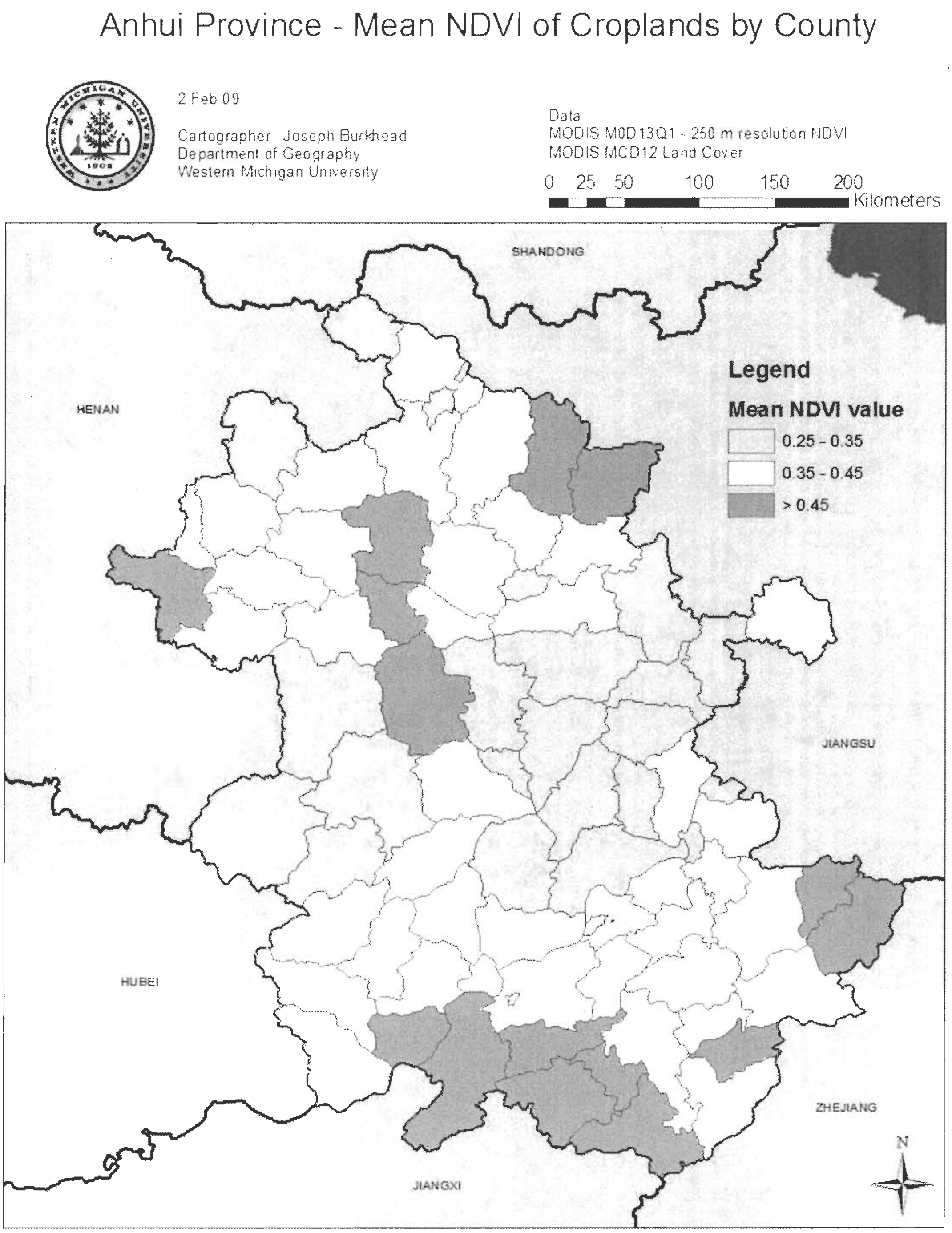

Figure 4.2. Anhui Province Mean-NDVI of Croplands by County, 2 Feb 09

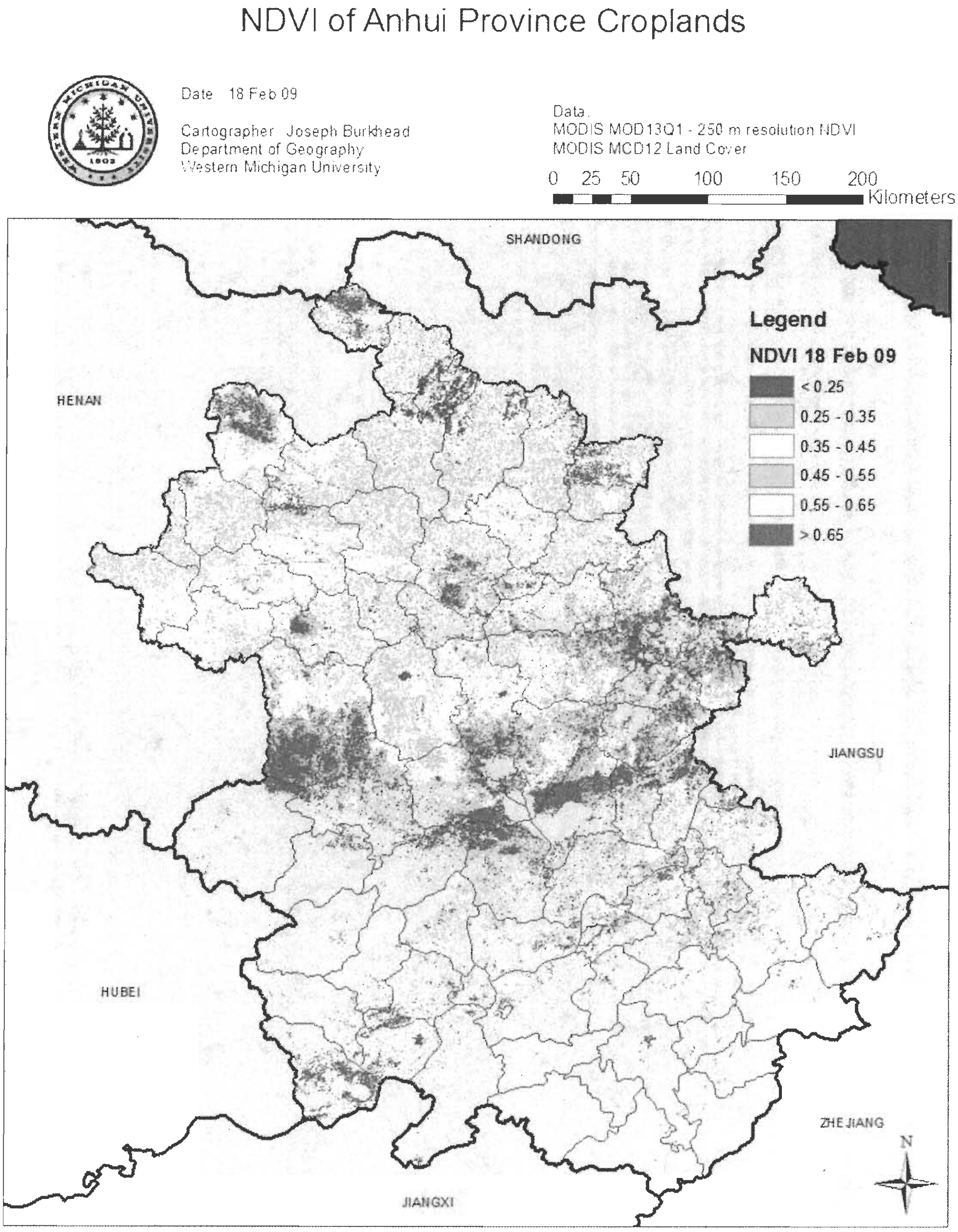

Figure 4.3. NDVI of Anhui Province Croplands, 18 Feb 09

One flaw in the data existed, however, in a narrow band of indicated severe vegetation stress spanning east to west across central Anhui. This thick band of indicated severe vegetation stress was likely due to cloud interference over the two week period, as is also apparent later in assessing the land surface temperature. Therefore some limitation in the effectiveness of remote sensing at this scale is apparent. However, the general conclusions made from the first day of the simulated response hold true two weeks later. Central regions continued to experience severe drought impacts to vegetation health in the province while most areas north of the Huaihe River had relatively healthy vegetation conditions. The four exceptions in the north portion of Anhui, Bozhou City, Dangshan County, a portion of Huaiyuan County, and the quad-county border areas between Suixi, Suzhou, Xiao and Huaibei continued to face severe drought for the entire period.

Another quick-reference product indicating mean-NDVI was created for February 18th, 2009, and is presented as Figure 4.4. Although the result of the calculation of means for the counties indicate a spread of drought severity in the southern county-level administrative regions, the arable land within southern Anhui are limited when compared to the vast area of croplands in the central and northern regions of the province. Results for Chaouhu County and Shucheng County are suspect due to extreme cloud coverage on the image.

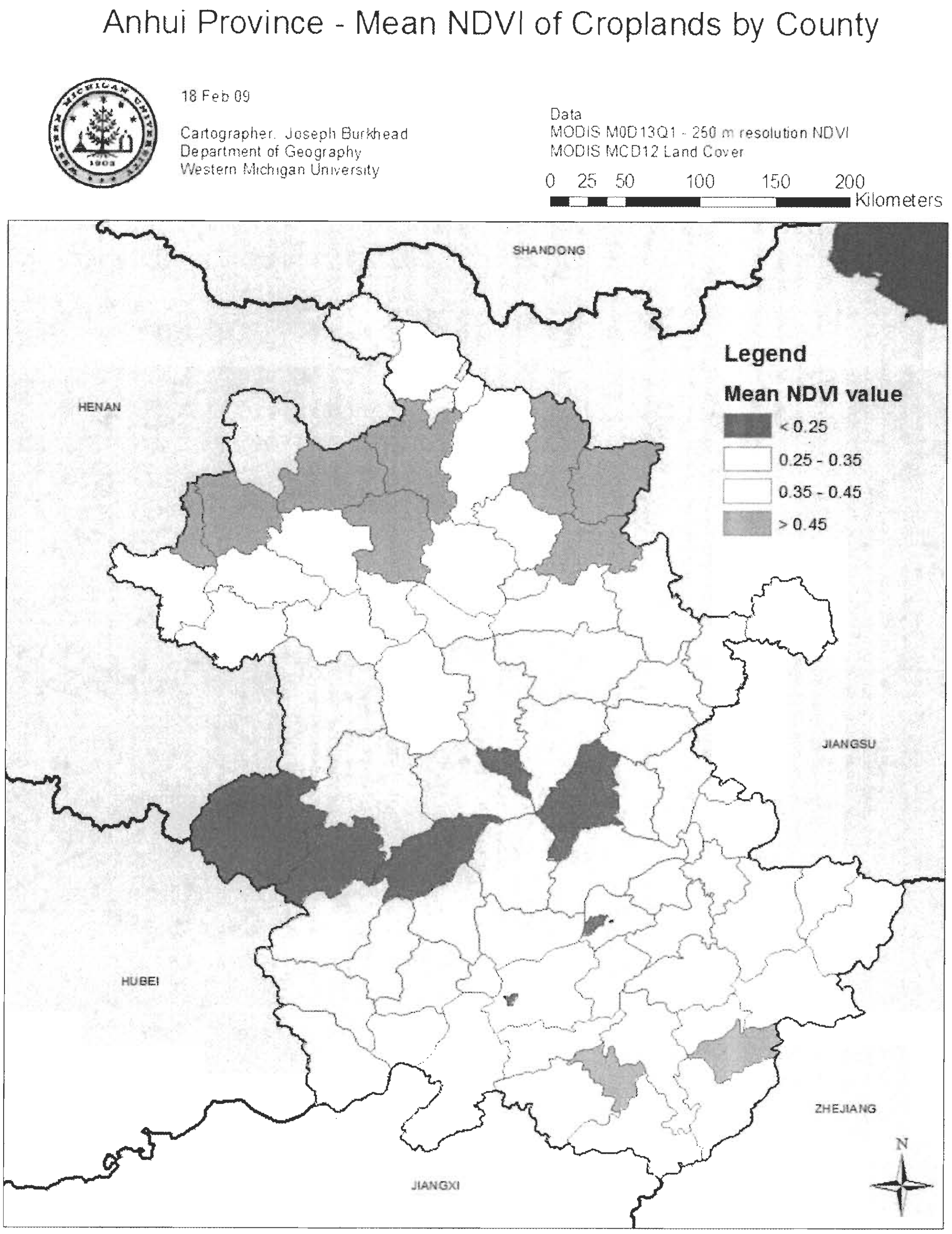

Figure 4.4. Anhui Province Mean-NDVI of Croplands by County, 18 Feb 09

To indicate the spread of severe vegetation stress across the province, a change detection product was created for cropland areas that were not impacted by severe vegetation stress at the onset of the simulated Charter response but were impacted with severe vegetation stress by February 18th, 2009. Severe vegetation stress was classified for cropland areas with values of NDVI less than 0.25. The result is a useful product that shows the potential spread of the drought disaster as seen in Figure 4.5. Based on an evaluation of Figure 4.5, it can be seen that the severe impact of drought had spread to the central-eastern regions of Huoqiu County, northern Jinzhai County, and Liuan Prefecture. Severe vegetation stress clearly expanded across several central regions. The narrow, dense band of severe vegetation stress in the center of the image can be discounted due to the likelihood of cloud interference in the February 18th NDVI composite data.

Products indicating vegetation stress using the Enhanced Vegetation Index (EVI) were also created to verify the NDVI products and in attempt to provide vegetation stress maps with less atmospheric interference than the NDVI products given EVI’s inherent advantages as described in Chapter Two. Like the NDVI products, an initial product was created at the beginning of the simulated Charter activation, and another was created approximately two weeks later. Figure 4.6 shows the estimates of vegetation stress using EVI from the MODIS sensor for February 2nd, 2009 data, and Figure 4.7 displays the February 18th, 2009 EVI data.

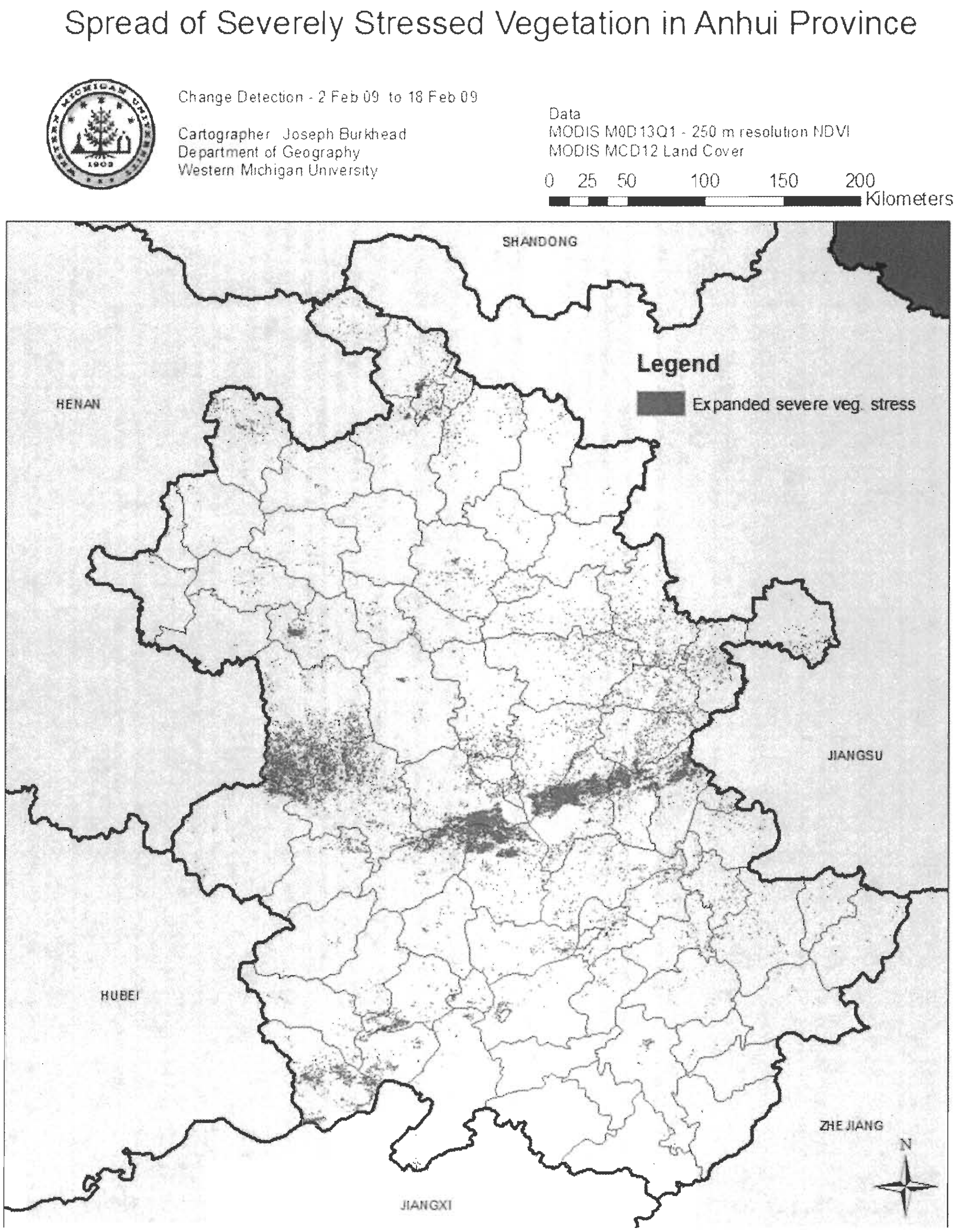

Figure 4.5. Spread of Severely Stressed Vegetation from 2 Feb 09 to 18 Feb 09

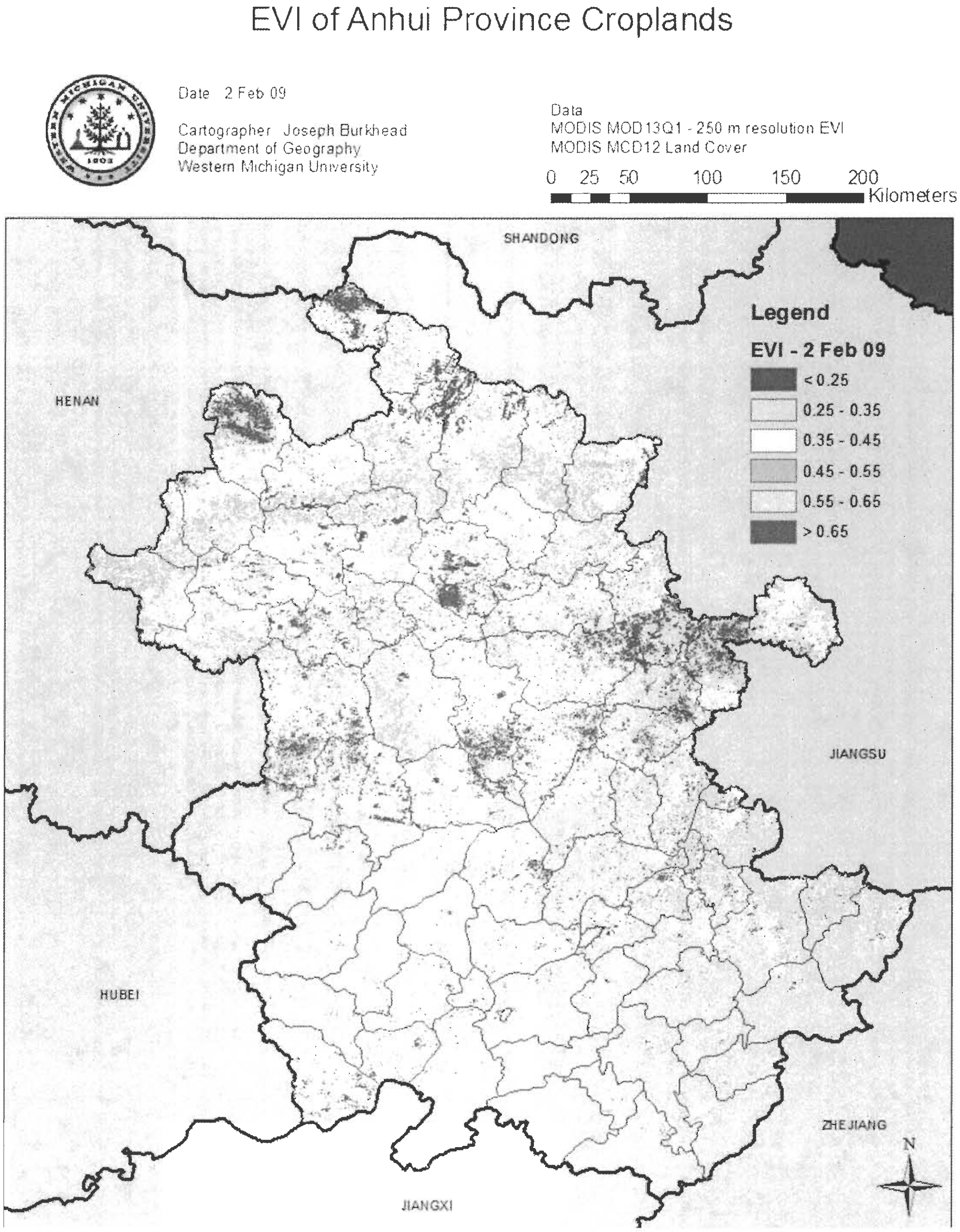

Figure 4.6. EVI of Anhui Province Croplands, 2 Feb 09

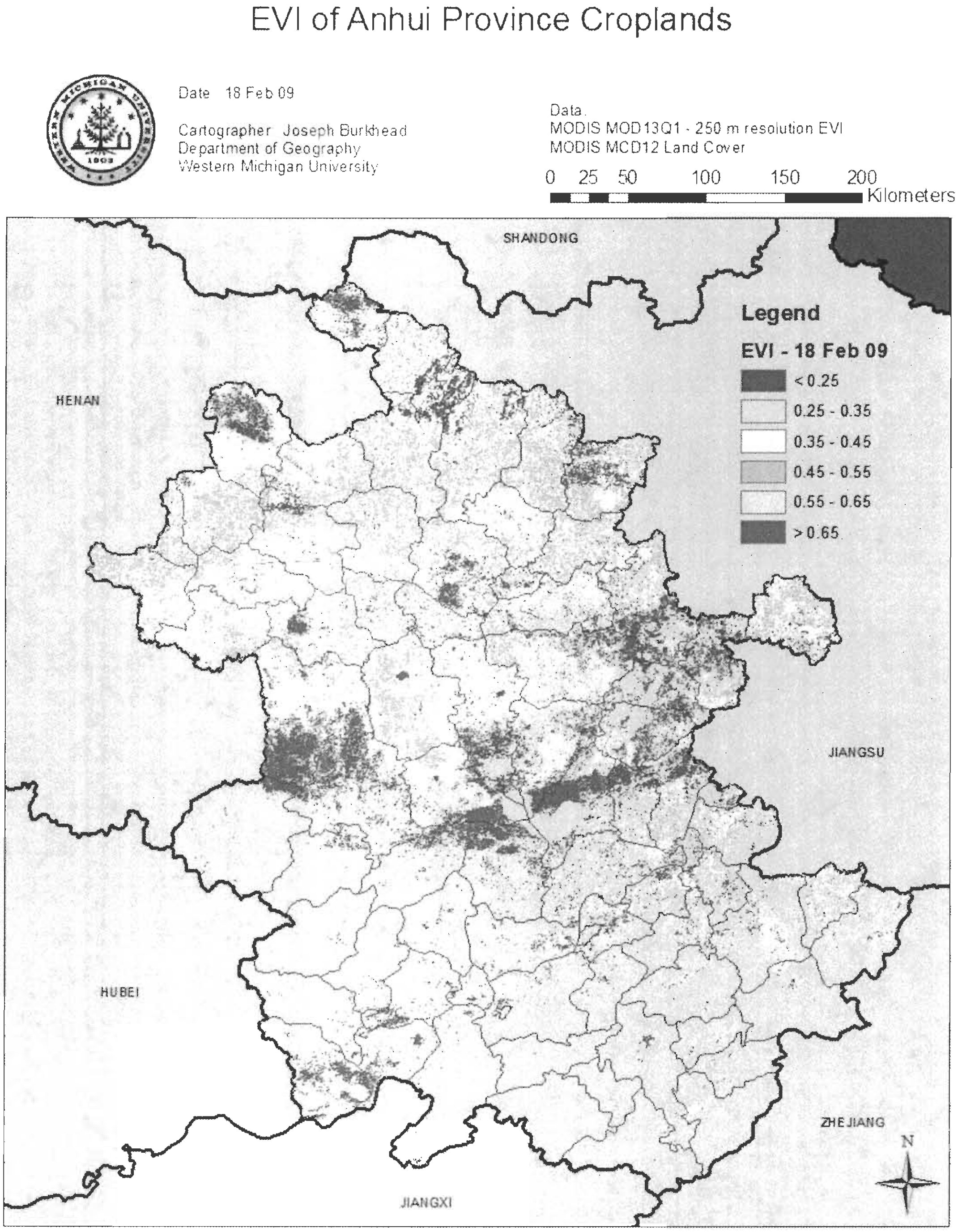

Figure 4.7. EVI of Anhui Province Croplands, 18 Feb 09

As discussed in Chapter Two, high and/or rapidly increasing Land Surface Temperature (LST) can serve as one indication of potential fire hazard. Therefore the LST for Anhui Province was also mapped. LST products showing temperature in Kelvin on February 10th, 2009, and February 18th, 2009, respectively are provided as Figures 4.8 and 4.9. Active fires were also detected by the MODIS sensor's MYD14A2 data on February 10th, 2009 as depicted as Figure 4.10.

Results of an Actual Remote Sensing Response to the Anhui 2009 Winter Drought

As cited in Chapter Two of this study, China's Center for Earth Observation Digital Earth (CEODE) initiated an emergency remote sensing project in response to the 2009 winter drought disaster in the North China plain to monitor drought developments using Charter-associated satellite platforms (including MODIS) to serve national efforts in mitigating the impact of the disaster (CEODE, 2009). CEODE used MODIS Leaf Area Index (LAI) estimates along with historical LAI time-series calculations in conjunction with point-based measurements as a means to indicate change in North China plain drought severity over time (Liu et al., 2009). CEODE's drought disaster response efforts enabled situational awareness of wheat in-season growth conditions, estimates of LAI and a water shortage index (CEODE, 2009).

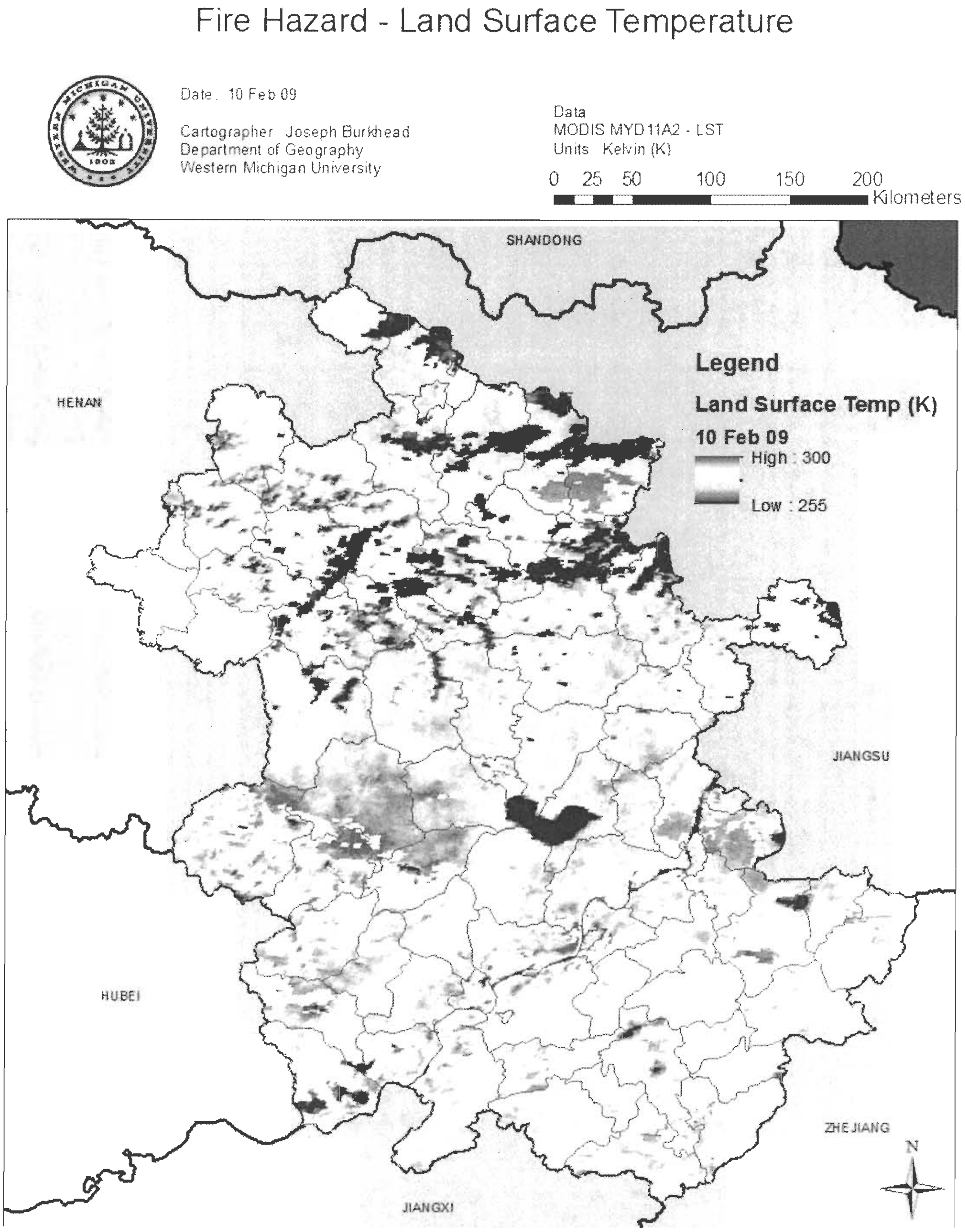

Figure 4.8. Fire Hazard, Land Surface Temperature, 10 Feb 09

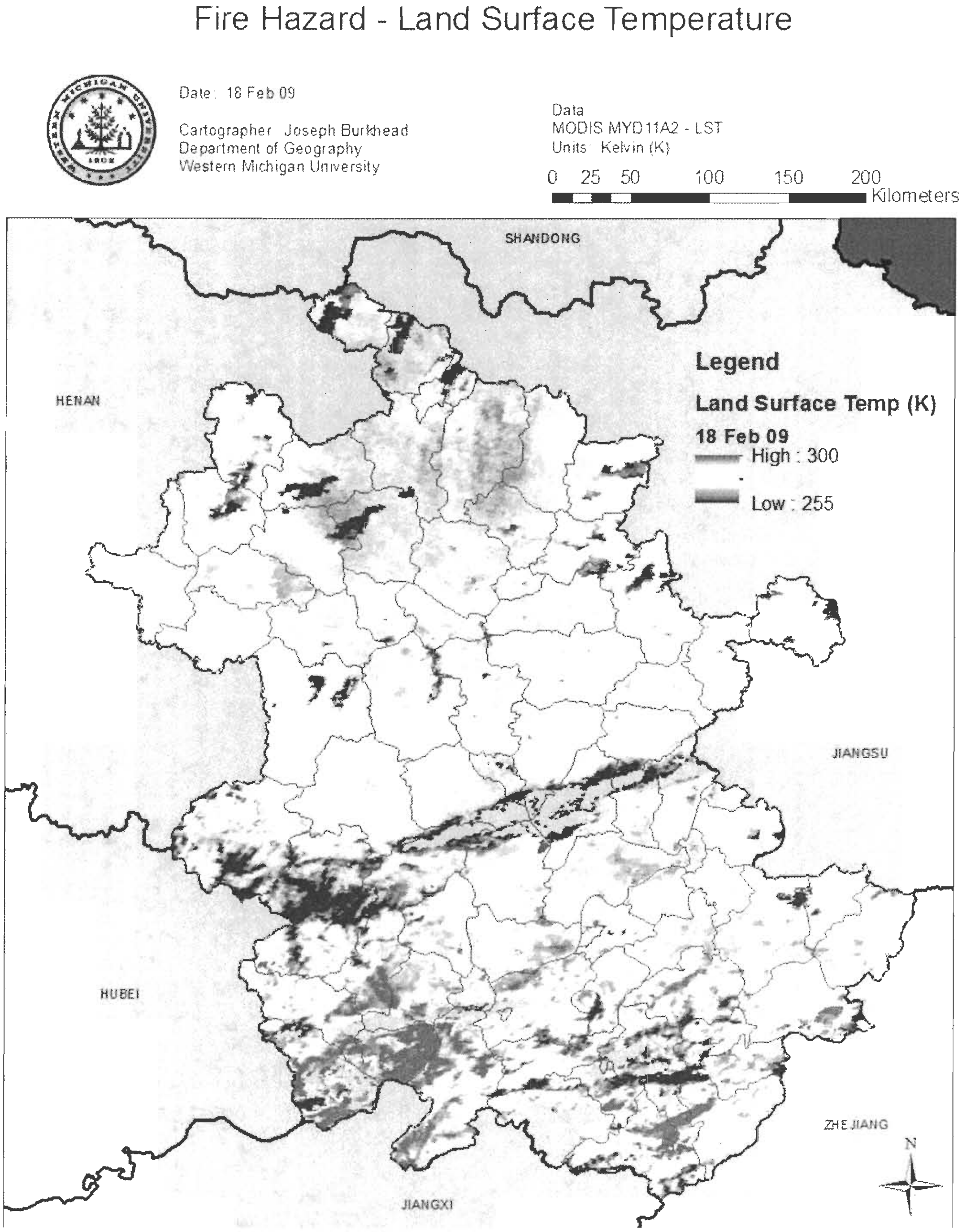

Figure 4.9. Fire Hazard, Land Surface Temperature, 18 Feb 09

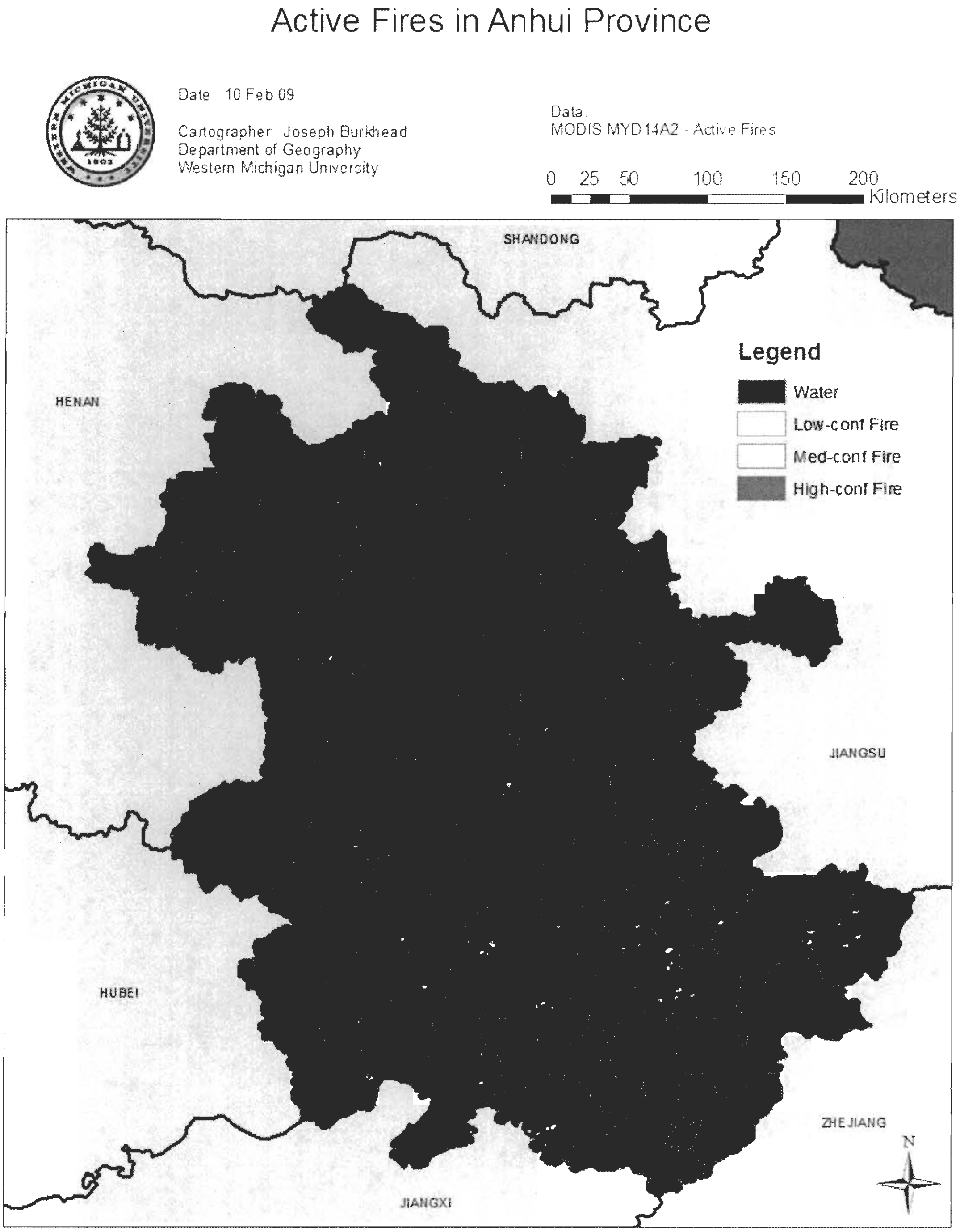

Figure 4.10. Anhui Province Active Fires, 10 Feb 09

Through this analysis, CEODE discovered that in the last ten days of January, just prior to China's declaration of the drought as a national disaster, the soil moisture content was low (CEODE, 2009). Wheat seedlings were turning green amidst rising temperatures, arid weather plagued the province, and the situation was deteriorating in the wheat growing regions of Fuyang and areas north of the Huaihe River (CEODE, 2009).

CEODE posted remote sensing-derived situational awareness products on CEODE's public website during the drought disaster and coordinated data sharing between CEODE and affected local agricultural research institutes (CEODE, 2009). Remote sensing data from CEODE were also provided to the Chinese Academy of Science (CAS) according to routine practice (Guo, H.D., interview, March 2011). An example of the drought situational awareness products for the period immediately preceding the national declaration of drought disaster can be seen as Figure 4.11.

The spatial patterns revealed in CEODE's analysis resulted in similar conclusions to those yielded by the NDVI and EVI vegetation stress products created for Anhui Province in the previous section. Bozhou and Dangshan in the extreme north, and east-central counties experienced the hardest impact of the drought while most vegetation elsewhere north of the Huaihe River was relatively healthy. Exceptions to this were in Linquan and Funan where LAI measurements indicate heavy drought, but where NDVI and EVI indicate healthy conditions.

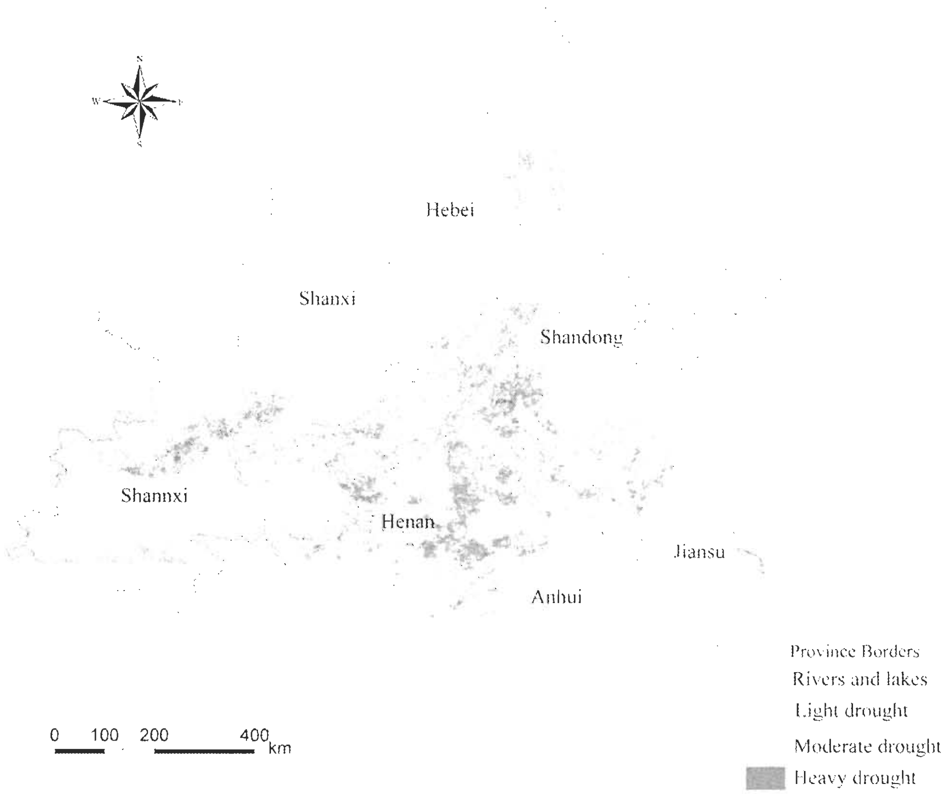

Figure 4.11. LAI over North China during 2009 winter drought.
(Source: Liu et al., 2009)

Actual Impact of the 2009 Winter Drought

An assessment of the actual impact of the 2009 winter drought in Anhui is difficult to accomplish since direct causal links between the drought and agricultural production are not clear. However, statistical data made available by the Chinese government at the county-level administrative scale offers some insight into the disaster's impact. From the meteorological data, Bozhou City immediately stands out as having experienced the greatest shortage of precipitation compared to 2008 with a deficit of approximately nineteen percent (China Statistics Press, 2010). The regions with the next closest deficit margins were Huaibei with a seven percent deficit from 2008, and Fuyang with only a three percent deficit (China Statistics Press, 2010). All other regions finished the year 2009 evenly or in surplus compared to the precipitation received in 2008 (China Statistics Press, 2010). Over 15,000 km^2 of the approximately 136,000 km^2 of total land area in Anhui were reported to have been affected by drought during 2009 (China Statistics Press, 2010). Just as in the case of precipitation data, the government data on drought affected areas show Bozhou to have suffered the worst impact from the drought. Bozhou reported 1,246 km^2 of land area affected by drought. Suzhou, Guoyang, Lixin and Suixi were not far behind, each having over 1,000 km^2 of land area affected by drought (China Statistics Press, 2010). A map depicting only the county-level regions that reported over 100 km^2 of land area affected by drought is depicted in Figure 4.12.

In regards to Bozhou, the remote sensing products created during the simulated response agree with the government's report of Bozhou's suffering from the drought in 2009 (China Statistics Press, 2010). NDVI and EVI measurements during the simulation consistently highlighted Bozhou as an area experiencing severe vegetation stress. Results from the simulation for northwestern counties of Anhui are also supported by the government's reports. Vegetation in these northwestern counties were assessed to be generally healthy during the simulation while the government reports for 2009 shows that those counties were not as severely affected by droughts in 2009 compared to other northern and central

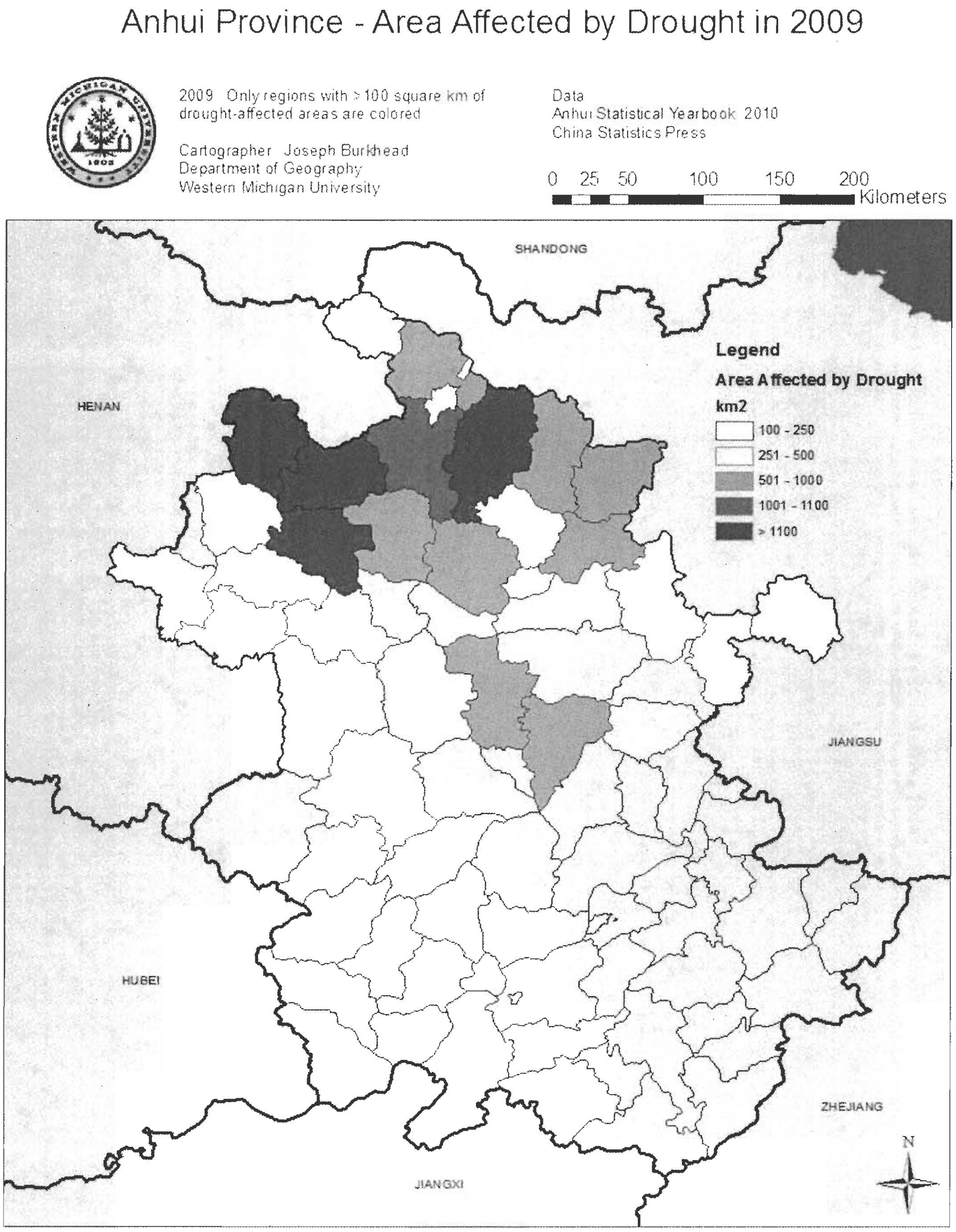

Figure 4.12. Anhui Province - Area Affected by Drought in 2009

counties. The 2009 drought impact data also highlighted a band of counties heavily impacted by drought along the central counties just south of the Huaihe River. Areas that raised concern during the simulation to include Huaiyang, Bengbu, and Huoqiu counties were also reported by the government to have been severely affected by droughts in 2009 (China Statistics Press, 2010).

Two major discrepancies exist between the government's reports of drought affected areas in 2009 and the remote sensing products created during the simulation. First, Dongshan County was reported by the government to have been minimally-impacted by drought compared to other provinces in the north. The MODIS measurements during the simulation indicate widespread and severe vegetation stress in Dongshan. The same type of discrepancy is also apparent in the extreme east-central regions of Mingguang and Lai'an. MODIS measurements indicated Guoyang and Lixin's vegetation to be relatively healthy, but government data for 2009 show both endured widespread drought circumstances (China Statistics Press, 2010).

While comparisons between the government-reported drought impacts in 2009 and the simulated response products are insightful, attempts to directly correlate the two are not possible since the two datasets are at different temporal scales and work from different land cover data. The government data are based on the government's own system of land cover classification to determine which areas are affected by drought, not the MCD12 land cover data used in the simulation. These land cover variations may explain some of discrepancies between the government reporting and the simulation products. The government report includes areas affected not just by the winter drought, but all droughts that may have occurred during 2009. Since the products produced during the simulation are only a snapshot in time within a narrow fifteen day window of analysis, whatever conclusions that could be made from them can only serve a decision-maker's immediate concerns. Since droughts dynamically evolve over time it is not surprising that some discrepancies exist between government drought reports for all of 2009 and the snapshot in time estimates of the drought impacts produced in this case study. Despite these differences, the 2009 government data generally lends support to the conclusions made from the simulation products.

From the Charter's Perspective

Charter documents have stated there is "doubtful or no benefit" from satellite remote sensing in responding to disasters such as droughts (Ito, 2005). Furthermore, Charter activation in response to drought disasters would not comply with the Charter's current mandate, which excludes sustained monitoring (Mahmood and Shokr, 2008; A. Mahmood, personal communication, February 9, 2012). According to the Charter Policies and Procedures Document, the definition of an "emergency" situation warranting Charter activation is "an urgent need for space services associated with a unique and important event, when something unanticipated suddenly occurs and requires prompt action, beyond normal procedures to prevent or limit injury to persons or damage to property" (Mahmood and Shokr, 2008). Therefore, the Charter does not activate in response to droughts "in order to preserve its uniqueness as the source of high priority data provision in response to sudden events that defy preplanning" (A. Mahmood, personal communication, February 9, 2012). The Charter also carries the perspective that droughts are disasters without a "response phase" that would necessitate emergency data acquisition planning and spacecraft tasking (A. Mahmood, personal communication, February 9, 2012). Since the priorities of the Charter emphasize response to sudden crises, the Charter restricts its activation period for an individual disaster incident to fifteen days maximum. Charter activation is highly constrained in time and limited resources currently prohibit the expansion of its mission to accept drought disaster activations (A. Mahmood, personal communication, February 9, 2012). The Emergency On-Call Officer handling incoming Charter activation requests may immediately decline a request for Charter support for a drought disaster based on the assessment that there is doubtful or no benefit from space assets for a drought response (Mahmood and Shokr, 2008).

Given the Charter's prioritization of suddenly occurring crises, its current mandate, organizational constraints, and its limited resources, it is understandable why drought missions have not been incorporated into the Charter's operations.

The Charter's perspective is convincing when its mission, constraints and priorities are all considered. However, the discussion in Chapter Three of the Chinese government's dramatic response to the 2009 winter drought, and the CEODE's emergency response to the drought reviewed in this chapter, suggests that in some cases drought disasters do have a "response phase". The choice to respond is a choice made by the decision-makers coping with drought affects. In situations where a response to a drought disaster is deemed necessary, the scholarship and operations reviewed in Chapter Two, and the results of this chapter's simulated Charter response should remove doubts over the potential benefit that spaceborne remote sensing assets can provide to drought response efforts. Remote sensing should be considered a potentially beneficial resource for decision-makers to leverage during major drought disasters. The Charter's current priorities and limitations, however, suggest that another vehicle for delivering those resources needs to be leveraged.

Limitations of the Case Study

The case study was limited in scope in terms of the use of sensors, use of remote sensing analytical methods, use of supplementary data, spatial resolution, and the operational restrictions. As summarized in Chapter Two, there are a number of Earth-orbiting sensors capable of providing data to improve situational awareness and decision-making during a drought disaster response. This case study restricted analysis to the use of only the MODIS sensor aboard the Aqua and Terra EOS satellites. Therefore, the case study did not provide examples of alternate products that could be used in a drought response from sensors such as the Advanced Very High Resolution Radiometer (AVHRR), Medium Resolution Imaging Spectrometer (MERIS), or Enhanced Thematic Mapper Plus (ETM+). Since the only sensor employed in the study was MODIS, the study was conducted strictly within the visible and near-infrared spectra, limiting situational awareness to what the weather of the day afforded. There was no use of all-weather instruments, such as Synthetic Aperture Radar (SAR) sensors; therefore the study was severely limited by cloud coverage. It is the cloud coverage problem that explains why composite images were used instead of daily data. As with most passive sensor techniques, the obstruction of clouds and other atmospheric or physical environmental dynamics within or surrounding the locations of measurement can cause significant skewing in the results or present problems while collecting a measurement. The vegetation and Land Surface Temperature (LST) composites on February 18th, 2009, demonstrated this limitation with the narrow band of skewed data (as in the vegetation products) or missing data (as in the LST products). The temporal resolution was also affected by this limitation. Clouds also obscured LST data over the majority of Anhui Province at the onset of the simulated Charter response, thus preventing the creation of a February 2nd, 2009, LST product. Daily updates proved problematic due to widespread cloud coverage and therefore the study utilized eight day and sixteen day composite products instead of daily products. These sensor-related limitations certainly altered the temporal resolution of the spatial analysis.

With respect to analytical methods, only the most basic and rudimentary operational remote sensing methods that could be applied to drought analysis were employed in the case study. While NDVI has been shown to offer an important assessment of vegetation health, it is only one measure among many other drought-related measures that can be made. Drought-related indices such as MPDI or other applications cited in the literature review were not tested for their applicability to a drought response.

The study was also very limited in terms of the use of supplementary data since the main objective was to focus on what situational awareness remote sensing alone may provide during a drought response. The formula for assessing the impact of a drought is as much a land-use problem as it is a physical environment problem. Land cover data for agricultural land initially provided by Chinese counterparts did not include vast agricultural areas that the author personally visited in northern Anhui Province. The land cover data used in the case study was not provided by the Chinese or Anhui governments and was very coarse, therefore the accuracy of the visualizations can only provide rough or relative estimates. An affected country would presumably offer higher resolution land cover or land use data to technicians responding to the nation's drought. However, as noted previously the possibility exists that not all nations will have reliable land cover or land use data, thus the case study was conducted within that limitation. The MODIS MCD12 land cover data produce only estimates of land cover based on an algorithm and are therefore not entirely accurate. This was apparent in the vegetation-related products used in this case study where some urban areas were classified by the MODIS land cover algorithm as croplands and therefore the vegetation stress products indicated severe vegetation stress in areas that are actually urban areas. The very definition of drought assumes specific, physical environments and land cover combinations. Without adequate land cover data, an accurate assessment of the drought is fleeting. The study also did not incorporate additional ground-based measurements of precipitation data, agricultural near real-time data, climatic data, or time series data. The absence of *in-situ* measurements limits the study by preventing critical soil moisture, precipitation or field observational data from being included in drought severity assessments. These variables could have contributed to a richer and more accurate spatial analysis of the drought's impact. Future efforts in integrating remote sensing into drought response should seek to incorporate the highest quality land cover data and in-situ measurement data available. Without the integration of these types of data, the scope and depth of assessments made in this study were limited.

The spatial resolution of the study was 250 meters at best. This resolution affords national and provincial decision-makers a broad and generalized perspective, but this resolution begins to lose its utility for emergency managers at the sub-county (township) scale. By limiting the case study to lower-resolution spaceborne sensors, the study was only able to demonstrate applications for county, provincial and national level decision-makers, but not local level decision-makers. Higher-resolution analysis from capable sensors is required to demonstrate the full potential of satellite remote sensing as a drought response tool.

Since the project evaluated not just remote sensing as a technology for drought disaster response, but also the capability of the Charter to contribute to drought disaster response within its restricted activation period, the remote sensing analysis products used in this analysis was limited to a fifteen-day period of work and the use of remote sensing data during, and immediately preliminary to, that period. The operational restriction of a fifteen-day time limit for Charter activation served as the largest obstacle in adequately assessing the drought situation. Droughts develop and persist over long periods of time, often lasting several months, as was the case with China's 2009 winter drought. The effects of the drought persisted long after the end of the simulated activation conclusion on February 19th, 2009, and extended until May, 2009. Therefore the products produced in the case study were only a snapshot in time in the grand scheme of the drought disaster. The assessments made using the operational methods described above would likely be useful only for a short period of time. This temporal limitation of the study is actually a result of the Charter's limitation to exclude sustained monitoring, not a limitation for drought monitoring using remotely sensed products.

Despite the numerous limitations of the case study's methodology, the project demonstrated a degree of utility found in remote sensing's toolbox when applied to a non-spacefaring country's major drought disaster. That utility was apparent in the situational awareness products, CEODE's response to the drought, and the data for drought affected areas in Anhui for 2009.

Summary of the Results and Findings

The spatial patterns of vegetation stress throughout the agricultural land of Anhui Province apparent from remote sensing analysis differed from the spatial patterns indicated by Chinese government forecasting and media reports during the 2009 winter drought disaster. According to the remote sensing analysis, Anhui's agricultural land north of the Huaihe River had generally healthy vegetation conditions with the exception of Bozhou Prefecture, Dangshan County, Hauiyuan County, and the quad-county border areas between Suixi, Suzhou, Xiao and Huaibei. Rather, areas with the most severe and far-reaching vegetation stress were not limited to the northern portion of the province but also included the central counties of Anhui. Mean vegetation stress values across the central counties of the province varied from moderate to severe. Vegetation stress conditions became more severe less than two weeks after the drought was declared a national disaster. Croplands surrounding urban areas commonly suffered severe vegetation stress which may be attributed to either inaccurate land cover classification from the algorithm used to create the MCD12 land cover classifications, micro-climatological phenomena, soil quality, or other undetermined causes. Areas of severe vegetation stress spread to new areas across Anhui during the activation period, primarily to locations in the central-western regions of Huoqiu County, Jinzhai County, Liuan City, and other central cities or counties. Interestingly, Land Surface Temperature (LST) analysis indicated that the central and southern regions of the province were more prone to fire hazards than the northern counties. MODIS active fire detection products identified fires occurring primarily in the southern half of the province.

An actual remote sensing emergency response to the drought disaster by China's Center for Earth Observation Digital Earth (CEODE) produced analytical products based on Leaf Area Index (LAI). The project yielded similar conclusions to those of this research regarding the spatial patterns of drought impact in Anhui Province. Chinese government reports of 2009 drought impacts revealed that several northern and central county-level regions were severely affected by the drought, with Bozhou City havin endured the most severe conditions in the province.

Although this operational analysis produced meaningful results in assessing impacts of the drought disaster, qualitative analysis of the Charter's suitability for implementing drought disaster response suggest that the Charter is not currently capable of incorporating drought response into its operations.

CHAPTER V

CONCLUSIONS

Utility Confirmed, Operational Options Considered

This project evaluates the utility of a range of remote sensing products during the response phase of a major drought disaster, and to also evaluate whether the Charter, the world's premier organization for providing satellite remote sensing support to non-spacefaring countries during times of disaster, is well suited for expanding its mission activations to include responses to major drought disaster. The case study was successful in creating remote sensing-derived products that would improve the situational awareness of decision-makers responding to a major drought disaster. Even when using very basic and routine processes with easily accessible data from spaceborne sensors, remote sensing was efficiently employed to create easily interpretable situational awareness products related to changes in the land-cover and physical environmental assessments that would be useful for emergency management officials and other government officials responding to a drought. The remote sensing products created during the case study's simulated response highlighted areas across Anhui Province that would demand the prioritization of limited resources to mitigate local impacts of the drought. Vegetation stress, fire hazards, and active fire locations were located using satellite remote sensing data available to the Charter as depicted in the previous section, so there is clear utility in using remote sensing for drought disaster management.

As indicated above, however, some have argued (including the Charter), that drought does not have a true “response phase” in the disaster management cycle since droughts develop, sustain, and recede over such lengthy periods of time lasting weeks or months. This case study in China, however, demonstrated the aggressive actions government officials and China’s remote sensing agency (CEODE) implemented just prior to and immediately after national politicians declared the drought a national disaster. Orders from the central government were sent to the provincial and sub-provincial governments to make a quick response to the drought their top priority, and orders to provide increased authorizations for irrigation, subsidization, drinking water rationing, and additional logistical and financial support were issued. CEODE executed an emergency project using remote sensing to assess severity and extent of the drought and to make impact assessments. CEODE then published those findings quickly and distributed widely via their public website, the China Academy of Science (CAS), and through relationships with local-level agricultural experts. The nationally-declared drought disaster was met with a national-level response of uncommon energy. The severe drought was eventually alleviated rapidly by intensive and timely irrigation in February (Liu et al., 2009). The case study of China’s experience in coping with their major drought disaster suggests that when the impact of a drought reaches an unacceptable level for decision-makers, a clear and aggressive response phase in managing the drought disaster may very well be taken.

The question as to whether or not satellite remote sensing can provide any benefit to responding officials was easily answered using the simple remote sensing techniques that were the foci of this thesis. However, the prospects of the Charter serving as the vehicle for delivering that kind of remote sensing response to major drought disasters occurring in non-spacefaring countries in the future is not promising despite the Charter's heroic successes in responding to other forms of natural and man-made disasters. Charter documentation and the author's communications with Charter leadership further clarified that the Charter's current mandate restricts the use of limited Charter resources for prioritizing suddenly occurring crises that do not require "sustained monitoring". Although the products created in this case study were produced well within the fifteen-day simulated activation period as would be required by the Charter's self-imposed restriction, China's response efforts to the drought continued well beyond the fifteen-day period since the drought persisted into May, 2009. Although China's response was most aggressive in February immediately after the drought was declared a national disaster, it was not until May, 2009, that the drought finally ended and response efforts were concluded (Liu et al., 2009). For responding officials to effectively manage limited resources (such as irrigation and water resources) for drought response through the end of the incident, continued remote sensing measurements from space would be required for optimal response. Therefore, although the Charter certainly is capable of utilizing remote sensing assets to respond to droughts by providing useful spatial products to officials within the operational limitations of the Charter's activation restriction, such a short-term commitment to such long-term disaster is neither optimal nor advisable.

For remote sensing to be more fully leveraged in drought disaster response, one of two options may be pursued. One option is for the Charter to modify its activation criteria to permit longer sustained periods of monitoring major drought disasters when such support is requested. This is not a likely outcome given the Charter's focus on suddenly occurring crises and its intention to make Charter services available for such crises anywhere in the world at any time using limited resources and labor. The other option seems more feasible, which is to seek out another vehicle for delivering remote sensing services to drought disaster response.

There are multiple global initiatives in remote sensing for disaster management outside of the Charter. One of the most promising efforts for integrating remote sensing into global drought monitoring is the Global Drought Monitoring Portal (GDMP) project. The GDMP is a prototype portal intended to provide international drought information and serve as the foundation for a Global Drought Early Warning System (GDEWS) (Brewer et al., 2011). Based on the National Integrated Drought Information System's (NIDIS) North American Drought

Monitor (NADM) and the United States Drought Monitor (USDM) systems, the GDMP seeks to incorporate both *in situ* and remotely sensed drought-related indices such as soil moisture, evapotranspiration, and vegetation indices into the portal displays (Brewer et al., 2011). Remote sensing data is deemed particularly important to the GDMP project since there are parts of the world where *in situ* data are difficult or impossible to obtain (Brewer et al., 2011). The NADM and USDM portals which serve as the inspiration for GDMP include the integration of not just *in situ* and remotely sensed data, but also media reporting, drought impact planning, relief and recovery information, ancillary data, and other important drought-related information (Brewer et al., 2011). Given the nascent phase of the GDMP project's development at present, there is ample time and opportunity to incorporate operational remote sensing methods for drought disaster response into the GDMP system. Project managers for the GDMP portal have enthusiastically sought additional drought-related data from international sources to populate the portal server. Further work remains for remote sensing experts to find optimal solutions in integrating remote sensing into global drought disaster response efforts and the GDMP portal project provides a promising vehicle for making new headway in that task. Additional research and operational testing also remains in smaller-scale integration of remotely sensed data from airborne and in-field sensors for drought response and precision irrigation applications. Future scholars and remote sensing operators can build and improve upon this case study by employing remote sensing as a means to proactively monitor the development of droughts while also operationalizing remote sensing within drought response or relief networks and agencies. Building user-friendly, near real-time capabilities for situational awareness of drought impact is another important role that remote sensing may fulfill.

In light of the Charter's encouragement to seek additional opportunities in finding new methods and applications to utilize Charter assets, this research highlighted remote sensing methods that could be applied to droughts; a type of major disaster which the Charter has never responded to but which threatens lives, food, water, and economies across the world. Results show that remote sensing not only offers important capabilities to responding officials, but the spatial information provided by satellite platforms are in high demand during drought disasters. Analysis of imagery can provide data on the physical nature of the drought between *in situ* measurements and in places where *in situ* measurements are not available. This is commonly the case in countries lacking the technical and logistical capacity to operate their own space program. A government bearing the burden of a major drought disaster must allocate limited resources such as irrigation and financial support to the locations where the support will have the most positive impact in preventing further loss of life or property. Remote sensing was shown to be an effective tool in providing information that aids in that decision making process. However, in the course of considering the Charter's capabilities and role in the context of drought disasters, this research ultimately concludes that the Charter is not the best answer for leveraging remote sensing for drought disaster response efforts despite the technical capability of the Charter and its gallant history of aiding nations in distress. Instead this research recommends the pursuit of other opportunities to integrate remote sensing in international drought disaster response efforts. The GDMP is one option going forward, while other options may yet arise. Although this research offers only a basic foundation to build upon, whatever further work is accomplished in the spirit of this case study and in the spirit of leveraging remote sensing for drought disaster response should be accomplished hastily given the forecasts of increasing severity and frequency of droughts in the coming decades. As the Latin proverb goes, “we are the authors of our own disasters.”

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