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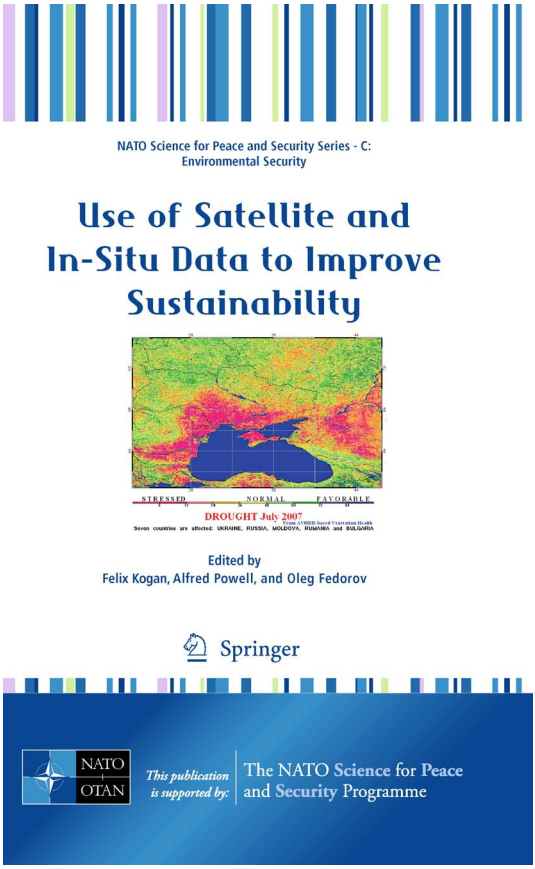

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Early Detection and Monitoring Droughts From NOAA Environmental Satellites

Felix Kogan and Wei Guo

Abstract With nearly 30 years of the accumulated AVHRR data which were collected from NOAA operational polar-orbiting environmental satellites, the area of their applications expanded in the direction of monitoring vegetation condition, modeling agricultural production, analysis of climate and global change, resource management, and early and more efficient monitoring of droughts and their impacts on economy and society. This becomes possible due to the development of Vegetation Health (VH) indices. This paper discusses utility of the AVHRR-based VH focusing on monitoring vegetation with the emphasis on early drought warning and drought features.

Keywords Droughts • Environmental satellites • Vegetation Health indices

Introduction

Drought is a typical phenomenon of the earth's climate. The losses from droughts are normally staggering. The average annual cost of drought in the United States of America, a country of the advanced technology, is around $6 billion. However, in extreme drought years such as 1988, the cost of the drought is five to eight times larger. In the recent years, large-scale intensive droughts were reported all over the globe. Developing countries of Africa and Asia were the most affected. For example, the Horn of Africa experienced droughts 6 years in a row which led to serious food shortages. Rangeland in Mongolia have also suffered from a very intensive droughts resulting in a lack of feed for the livestock. Unusual summer

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dryness also affected the new countries (from the former USSR) in the Black Sea and Caspian Sea regions. Western USA experienced drought-induced forest fires for several years. In 2003 and 2007, nearly 20% of the global lands were drought-stricken.

Weather data are traditionally used for drought monitoring. However, weather-derived drought-watch system has shortcomings. Weather data represent point locations rather than an area and meteorological stations are not uniformly distributed. Even in the United States, with a well developed weather network, the density of stations is not sufficient to characterize regional drought. For example, in South Dakota one weather station is normally used for monitoring drought on 1–2 million acres of crop land. In Ukraine, each of the 180 weather stations covers 0.8 million acres of land. The problem of insufficient density of weather stations becomes especially acute in the areas with marginal climatic resources such as Africa, Asia, Central and South America.

This paper discusses a new satellite-based land-surface observing system used for drought monitoring. Principally, satellite data in the form of vegetation indices have been applied for land monitoring since the mid 1980s (Tarpley et al. 1984). In the last 20 years, NOAA has designed a new AVHRR-based Vegetation Health (VH) theory, system and data set (Global Vegetation Index, GVI-x) that showed success when applied to drought detection and tracking (Kogan 1990, 1997, 2001). Unlike other remote sensing techniques, the new method and system uses multi-spectral radiances and the main ecosystem laws for analysis of vegetation health in response to weather changes. During the last 8 years, this method was tested and validated thoroughly against ground data in all major agricultural countries of the world and proved to be of excellent utility for early drought detection, accurate monitoring of its development, affected area and impacts on agriculture, rangeland and forestry (Salazar et al. 2007). This paper presents the results of using the VH for monitoring droughts.

Satellite Data

The GVI-x system was developed based on the NOAA AVHRR Global Area Coverage (GAC) data set. The GAC is produced by sampling and mapping the AVHRR 1-km daily reflectance in the visible (VIS, 0.58–0.68 μm, near infrared (NIR, 0.72–1.1 (μm), and two infrared bands (IR4, 10.3–11.3 and IR5, 11.5–12.5 μm) to a 4-km map. The VIS and NIR reflectance were pre- and post-launch calibrated and the normalized difference vegetation index (NDVI) was calculated as (NIR-VIS)/(NIR+VIS). The IR4 emission was converted to brightness temperature (BT), which was corrected for non-linear behavior of the AVHRR sensor. Daily NDVI and BT were composited over a 7-day period by saving those values that have the largest NDVI for each map cell. The 1981–2010 NDVI and BT weekly time series were processed to remove high frequency noise, identify seasonal cycle and to calculate climatology.

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Vegetation Health Method

A new method is based on the estimation of green canopy stress/no stress from AVHRR-derived indices, characterizing moisture, thermal conditions and total vegetation health (Kogan 1990, 1997, 2001). Unlike the two spectral channels approach (NDVI-based) routinely applied for vegetation monitoring, the new numerical method in addition to NDVI, also uses BT from 10.3–11.3 μm IR4 channel, which estimates the hotness of the vegetation canopy. In dry years, high temperatures, coupled with an insufficient water supply, lead to overheating of the canopy, which intensifies negative effects of moisture deficit impact on vegetation. The three-channel algorithm consists of comprehensive processing of NDVI and BT annual time series, which includes complete removal of high-frequency noise, enhancing seasonal cycle, calculation of climatology and single out medium-to-low frequency fluctuations associated with weather impacts on vegetation (Kogan 1995, 1997,). This procedure was formalized by Eqs. (1)–(3), where climatology was represented by the difference between 22-year absolute maximum and minimum both NDVI and BT values for each pixel and week.

$$\mathrm{VCI} = 100 * \left(\mathrm{NDVI} - \mathrm{NDVI}_{\min}\right) / \left(\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}\right) \tag{1}$$

$$\mathrm{VCI} = 100 * \left(\mathrm{BT}_{\max} - \mathrm{BT}\right) / \left(\mathrm{BT}_{\max} - \mathrm{BT}_{\min}\right) \tag{2}$$

$$\mathrm{VHI} = a * \mathrm{VCI} + b * \mathrm{TCI} \tag{3}$$

where NDVI, $\mathrm{NDVI}_{\max}$, and $\mathrm{NDVI}_{\min}$ (BT, $\mathrm{BT}_{\max}$, and $\mathrm{BT}_{\min}$) are the smoothed weekly NDVI (BT), their multi-year absolute maximum and minimum, respectively; a and $b = 1 - a$ are coefficients quantifying a share of VCI and TCI contribution in the total vegetation health. The VCI (Vegetation Condition Index), TCI (Temperature Condition Index) and VHI (Vegetation Health Index) are indices estimating cumulative moisture, temperature and total vegetation health conditions, respectively on a scale from zero (extreme stress) to 100 (favorable condition) with 50 corresponding to the average condition.

Global Droughts

The VH system has been used successfully for monitoring vegetation health, including drought-related vegetation stress around the world since the 1990s. These data were presented at http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_currentImage.php. Examples of vegetation health (condition) in mid 2007 and 2008 are shown in Fig. 1. As seen, intensive summer drought-related vegetation stress were observed in the western USA, southern Ukraine and Russia, Mongolia (Northern Hemisphere, summer) and in Argentina (2008), western Australia, Brazil and Southern Africa (Southern Hemisphere, winter). These estimates are supported by in situ observations (Le Comte 2008, 2009).

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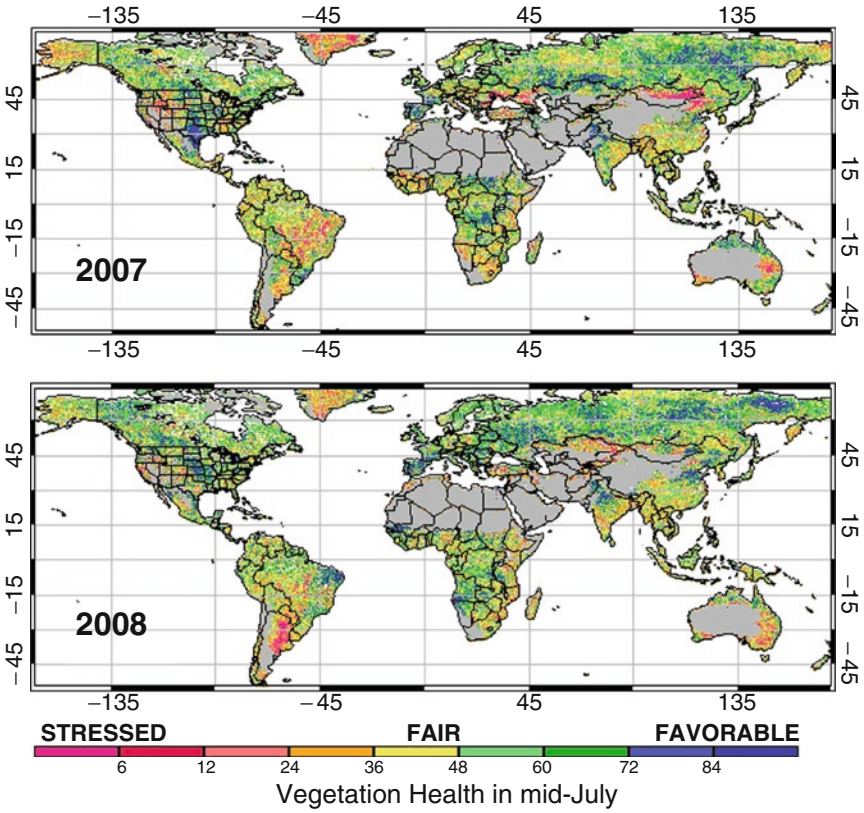

Fig. 1 Vegetation health index in mid July 2007 and 2008 (Color image is provided in Appendix 1)

It should be emphasized that satellite data in addition to drought start/end, duration and area, also estimate drought intensity. In the USA, four categories characterize drought intensity (severity): moderate (D1), severe (D2), extreme (D3) and exceptional (D4). In terms of precipitation deficit they are characterized by <70% of normal precipitation for 3 months in a row (D1), <65% for 6 months (D2), < 60% for 6 months (D3) and <65% for 12 months (D4). Satellite data show that these criteria correspond to VHI values below 35, 25, 15 and 5, respectively. Moreover, the repetition of such droughts might be, once per 2–4, 5–10, 11–20 and more than 20 years, respectively. Following these criteria it is easy to estimate area under drought of different intensity. For example, since the new millennium has started, severe-to-exceptional (D2–D4) drought area covered 7–10% of the world land, mostly in Northern Hemisphere (Fig. 2). However, in such years as 2003 and 2007 this area increased to 20%. The area of extreme-to-exceptional droughts (D3–D4) normally occupies 3–5% of global land, increasing to10% in the extreme years (2003 and 2007).

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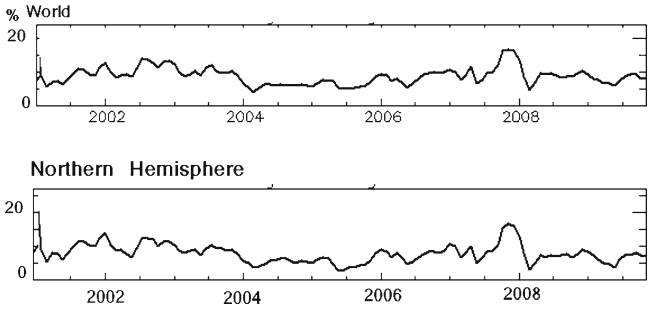

Fig. 2 Percent of the World and Northern Hemisphere areas under severe-to-exceptional drought

Regional Droughts

Ukraine was selected to investigate regional droughts. Having the best for agriculture chernozem soils, Ukraine has some misfortune to be located in a dry zone. Annual shortage of water (based on the difference between precipitation and potential evapotranspiration) is 200–400 mm. Weather data show that droughts affect Ukraine every 2–4 years. Since weather station network is limited for the Ukraine area, VH products were used to assess drought area.

Figure 3 shows percent of severe-to-exceptional (D2–D4) droughts since 1991, after Ukraine received independence. First, it should be emphasized that in some periods (1997–2000), the D2–D4 droughts missed Ukraine territory completely. However, in some periods (2001–2004 or 2006–2008), droughts followed every or every other years. Second, in drought years, 5–10% of Ukraine territory is normally affected. But this area might increase up to 20% in less favorable years which occurred 5 years out of 20. In the major crop area (southern part), drought affects 10–40% of the Ukraine territory and in extreme years such as 2007 the area might increase up to 60%. In smaller (state level) regions inside the major crop area (Odessa oblast, located in the southwestern portion of Ukraine) up to 80% of its territory was affected by 2007 drought. The damage to agriculture in such years is enormous, especially if drought is preceded by winter wheat damage by extremely cold weather in winter.

Very useful information for planners and decision makers is drought intensity in order to estimate the consequences, especially from the extremely severe droughts. VH data provide such information (Fig. 4). As seen, less intensive droughts occurred in Ukraine every year and even several times during the growing season. When the intensity of drought increases the probability of such drought becomes smaller as well as the affected area. Droughts in the range between moderate (D1) and exceptional (D4) occurred every year covering principally 20–40% of the entire Ukraine; although in very unfavorable years the area might be 50–80%. In the last 20 years, Ukraine experienced such droughts six times (probability 30%). Similar probability with 40% coverage of the entire Ukraine is estimated for the droughts in the

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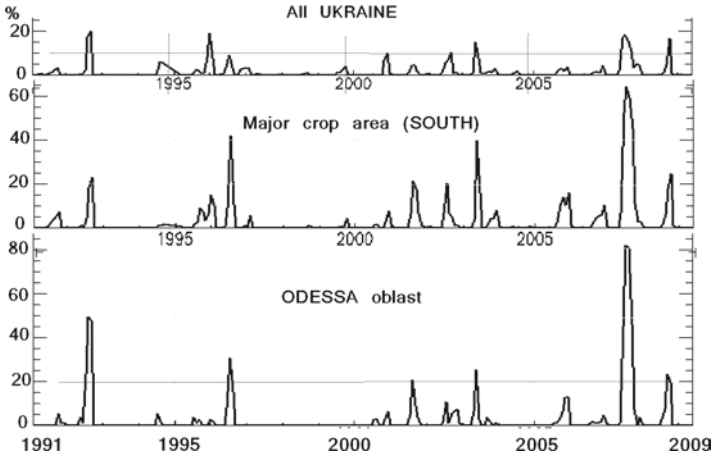

Fig. 3 Percent of Ukraine affected by severe, extreme and exceptional droughts

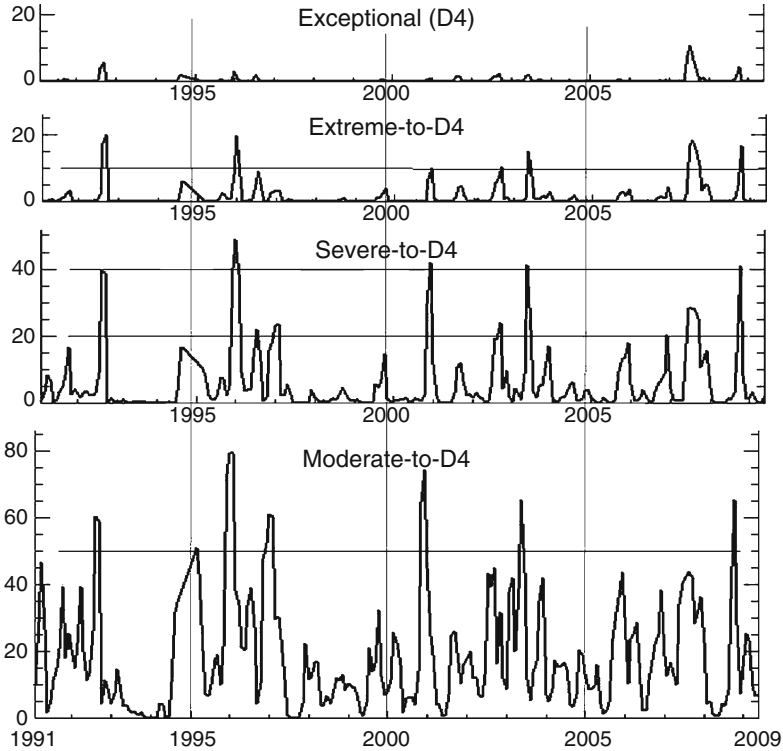

Fig. 4 Percent of Ukraine affected by droughts of different intensity

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category severe and stronger (D2–D4). Finally, exceptional droughts (D4) might cover 5–10% of Ukraine; from the last 20 years such droughts occurred twice in 2003 and 2007.

The VH system was also applied for analysis of drought origin and for early detection of drought start, duration and end. These results are shown in Fig. 5 for an area of 64 km^2 in the southwestern part of Ukraine. As seen from the combined NDVI and BT estimates, that area experienced drought-related vegetation stress between May and August, including 2-month period (June–July) with the highest drought severity (VHI was at the level of 5–6 corresponding to D4 category). This drought was triggered by the extreme temperatures, since TCI = 0–10 indicating severe thermal stress (TCI = 0 represent the highest temperature). Following thermal stress, VCI reduced drastically from favorable moisture conditions (80–100) during January–April to unfavorable (below 40) conditions at the end of May.

The beginning of drought in Fig. 5 is identified in the late April when VHI crossed down the 40 threshold. However, since VH system reflects cumulative weather impact on vegetation, the drought approach can be observed 4–6 weeks prior to the threshold crossing, specifically, when stable deterioration of the conditions have started (dashed arrows in Fig. 5). Therefore, the 2007 drought-related vegetation stress could be predicted in early March, when VHI (health) indicated normal (41–50) and VCI (moisture) even favorable (80–100) conditions. Considering the early stress detection and the size of affected area, VH data provide considerable lead time warning important for pinpointing the problem, making decisions and implementing measures to mitigate drought consequences.

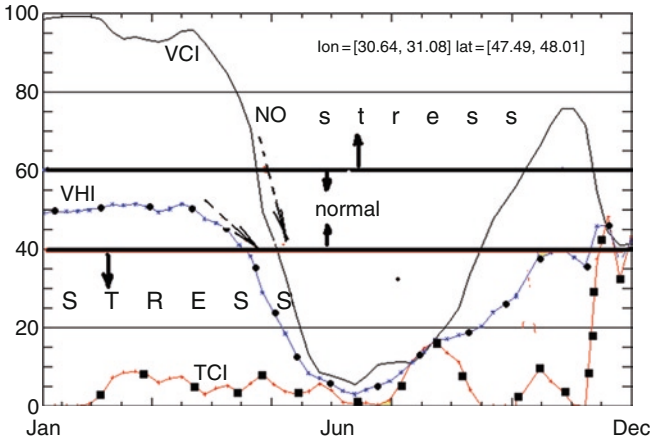

Fig. 5 Dynamics of vegetation health indices, 2007, Ukraine

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Conclusions

The new vegetation health indices, which characterize moisture and thermal conditions and the entire vegetation health, have been used successfully for early drought detection and estimation of crop and pasture production losses in 20 countries around the globe. Unlike other NDVI-applied remote sensing techniques, the new method is based on both NDVI and BT, the three ecosystem's laws and 22-year climatology. Using the combination of NDVI and 10.3–11.3 μm BT provide additional and more accurate information about drought. This method was tested and validated against ground data in all major agricultural countries of the world and in different climatic zones. With the introduction of the new method, drought can be detected 4–8 weeks earlier than before in any corner of the globe, outlined more accurately and the impact on grain reduction can be diagnosed long in advance of harvest. The drought estimates provide new information such as drought area, intensity and dynamics useful for planners, policy and decision makers. The VHI data set and products are provided operationally to NOAA/NESDIS web site every week (http://www.orbit.nesdis.noaa.gov/smcd/emb/vci/VH).

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