Contribution of Remote Sensing to Drought Early Warning

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Abstract

The main goal of global agriculture is to feed 6 billion people, a number likely to double by 2050. Frequent droughts causing food shortages, economic disturbances, famine, and losses of life limit ability to fulfill this goal. NOAA/NESDIS has recently developed a new numerical method of drought detection and impact assessment from NOAA operational environmental satellites. This is the first globally universal technique to deal with such a complex phenomenon as drought. The method was tested and adjusted based on users' response; validated against conventional data in 25 countries, including all major agricultural producers; and accepted as a tool for monitoring grain production potential. Now, drought can be detected 4-6 weeks earlier than before and delineated more accurately, and its impact on grain production can be diagnosed far in advance of harvest, which is the most vital need for global food security and trade.

Introduction

The main goal of global agriculture is to feed 6 billion people, a number likely to double by 2050. Although the Green Revolution of the last 50 years led to an intensive increase in agricultural production, frequent droughts offset the gains from enormous technological efforts and spending in satisfying the growing world demand for food and feed. In just the last ten years of the 20th century (declared by the United Nations as the International Decade for Natural Disaster Reduction), widespread intensive droughts claimed 50-150 million tons of grain (the main source of food for world population) (Figure 1, FAO 2000). In developing countries, the economic, physical, and social effects of drought could be detrimental, resulting in famine, human suffering, death, and abandonment of whole geographic regions (Riebsame et al. 1990; Changnon 1999).

Drought early warning and monitoring are crucial components of drought preparedness and mitigation plans (Wilhite and Glantz 1993). Recent advances in operational space technology have improved our ability to address many issues of early drought warning and efficient monitoring. With help from environmental satellites, drought can be detected 4-6 weeks earlier than before and delineated more accurately, and its impact on agriculture can be diagnosed far in advance of harvest, which is the most vital need for global food security and trade. This chapter describes how the new operational space technology can help agriculture detect drought early enough to assess and mitigate its impacts on grain production.

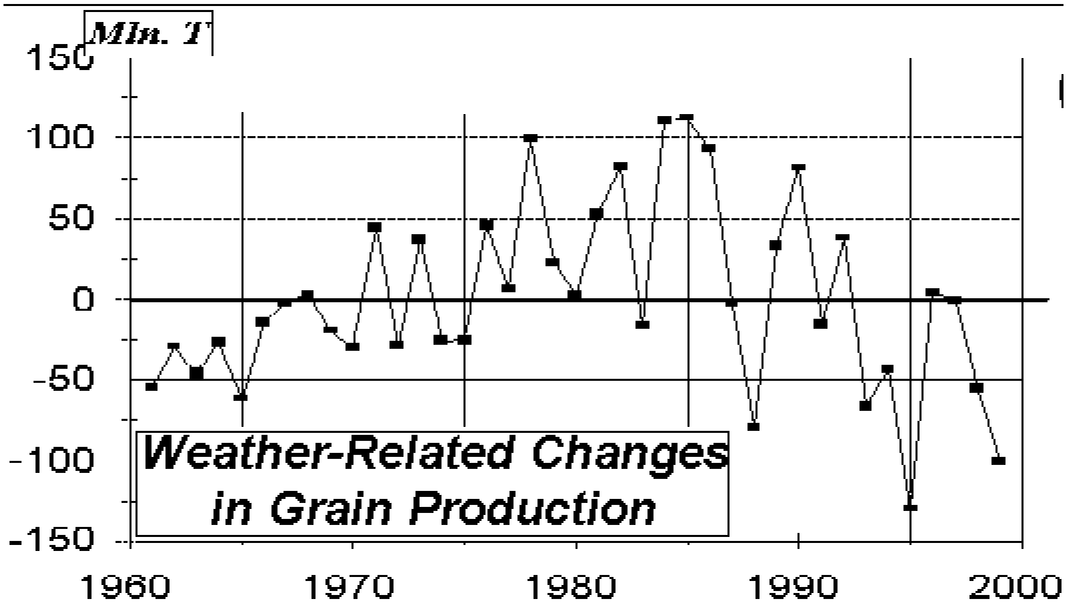


Figure 1. Weather-related variation in world grain production.

Drought as a Natural Disaster

Drought is a part of the earth’s climate. It occurs every year with no warning, without recognizing borders or economic and political differences. Of all natural disasters, drought affects the largest number of people. During 1967–91, drought affected 51% of the 2.8 billion people who were affected by natural disasters (Obassi 1994). During the same period, 3.5 million people perished, 45% of them from drought. It has been said that “drought follows the plough” (Glantz 1994), a statement which has proved true. Very productive land is extremely vulnerable to drought. In addition, drought has unique features. Unlike other natural disasters, it starts unnoticed and develops cumulatively. Furthermore, its impact is cumulative and not immediately observable by eye or ground data. By the time the results are evident, it is too late.

Operational Weather Satellites

Operational weather satellite measurements help us cope with these problems. Weather satellites, first launched 40 years ago, were designed to help weather forecasters, but were found to be useful for addressing vegetation issues. Since the late 1980s, they have also been used for drought detection, monitoring, and impact assessment in agriculture (Kogan 1995, 1997, 2000; Hayas and Decker 1996; Unganai and Kogan 1998; Liu and Kogan 1996).

Radiances measured by the space sensors, especially by the Advanced Very High Resolution Radiometer (AVHRR) on NOAA polar-orbiting satellites, respond closely to changes in leaf chlorophyll, moisture content, and thermal conditions (Gates 1970; Myers 1970). Over the last 20 years, the AVHRR data has been used extensively, continuously monitoring earth surface changes, and it is widely recognized around the world. AVHRR-based spectral radiances have been combined into indices and used as proxies for estimation of the entire spectrum of vegetation health (condition) from excellent to stressed (Kogan 1997, 2000).

Moreover, AVHRR-based multiyear daily observations from space provide cost effectiveness, free access, and a repetitive view of nearly all of the earth's surfaces. They are indispensable sources of information versus in situ data, whose measurements and delivery are affected by telecommunication problems and difficult access to environmentally marginal areas, places of economic disturbances, and areas of political and military conflicts. Furthermore, they are preferable to in situ data in spatial and temporal coverage and in quick data availability. Finally, they characterize an area rather than a point location, which is typical for agricultural and weather observations.

New Method and Data

A new method for early drought detection, monitoring, and impact assessment is based on estimation of vegetation stress from AVHRR-derived indices designed to monitor vegetation health, moisture, and thermal conditions (Kogan 1997). Unlike the two spectral channel approach routinely applied to vegetation monitoring, the new numerical method, introduced in the late 1980s, is based on a three spectral channel combination: visible (VIS, ch1), near infrared (NIR, ch2), and 10.3-11.3 μm infrared (IR, ch4). The new method is built on three basic environmental laws: law-of-minimum (LOM), law of tolerance (LOT), and the principal of carrying capacity (CC).

LOM postulates that primary production is proportional to the amount of the most limiting growth resource and becomes the lowest when one of the factors is at the extreme minimum. LOT states that each environmental factor that an organism or ecosystem depends on has maximum and minimum limiting effects, wherein lies a range that is called the limits of tolerance. With regard to these laws, the CC is defined as the maximal population size of a given species that resources of a habitat can support (Reinign 1974; Ehrlich et al. 1977; Orians 1990).

The new method was applied to the NOAA Global Vegetation Index (GVI) data set issued routinely since 1985 (Kidwell 1995). The GVI is produced by sampling the AVHRR-based 4-km (global area coverage format, GAC) daily radiances in the VIS (0.58-0.68 μm), NIR (0.72-1.1 μm), and IR (10.3-11.3 and 11.5-12.5 μm), which were truncated to 8-bit precision and mapped to a $(16\ \text{km})^2$ latitude/longitude grid. To minimize cloud effects, these maps were composited over a 7-day period by saving radiances for the day that had the largest difference between NIR and VIS.

Since AVHRR-based radiances have both inter-annual and intra-annual noise (variable illumination and viewing, sensor degradation, satellite navigation and orbital drift, atmospheric and surface conditions, methods of data sampling and processing, communication and random errors), its removal is crucial for the new method. The initial processing included post-launch calibration of VIS and NIR, calculation of the Normalized Difference Vegetation Index (NDVI=[NIR-VIS]/[NIR+VIS]), and converting IR radiance to brightness temperature (BT), which was corrected for nonlinear behavior of the sensor (Rao and Chen 1995, 1999; Winereb et al. 1990).

The three-channel algorithm routines also included complete removal of temporal high frequency noise from NDVI and BT values, stratification of world ecosystems, and detection of medium-to-low frequency fluctuations in vegetation condition associated with weather variations (Kogan 1997). These steps are crucial in order to use AVHRR-based indices as a proxy for temporal and spatial analysis and interpretation of weather-related vegetation condition and health.

Finally, three indices characterizing moisture (VCI), thermal (TCI), and vegetation health (VT) conditions were constructed following the principle of comparing a particular year's NDVI and BT with the entire range of their variation during the extreme (favorable/unfavorable) conditions. Based on the LOM, LOT, and CC, the extreme conditions were derived by calculating the maximum and minimum (MAX--MIN) NDVI and BT values from 14-year satellite data. The (MAX--MIN) criteria were used to classify "carrying capacity" of ecosystems in response to climate and weather variations. The VCI, TCI, and VT were formalized as:

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

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

$$VT = a*VCI + b*TCI$$

where NDVI, $NDVI_{max}$, and $NDVI_{min}$ are the smoothed weekly NDVI and its multiyear absolute maximum and minimum, respectively; BT, BT_{max}, and BT_{min} are similar values for brightness temperature; and a and b are coefficients quantifying a share of VCI and TCI contribution in the combined condition. For example, if other conditions are near normal, vegetation is more sensitive to moisture during canopy formation (leaf appearance) and to temperature during flowering. Therefore, the share of moisture contribution into the total vegetation condition (health) is higher than temperature during leaf canopy formation and lower during flowering. Since moisture and temperature contribution during a vegetation cycle is currently not known, we assume that the share of weekly VCI and TCI is equal.

Major Droughts

United States. The United States is the world's largest producer and leading exporter of agricultural products. Drought is a very common phenomenon in the North American climate. It occurs almost every year somewhere in the nation, and agriculture is often seriously affected. A classic example of devastation occurred in 1988, when drought caused around $40 billion in damage to the U.S. economy in terms of human health, environment, and wildlife (compared to $15 billion in damages for the 1989 San Francisco earthquake). Grain production fell below domestic consumption probably for the first time in the last half century (Reibsame et al. 1990; Kogan 1995).

The AVHRR-based estimate in Figure 2 shows that by the end of June 1988, vegetation experienced stress in the most productive areas of the Great Plains, the breadbasket of the United States. The effect of the drought was exacerbated by the time of its occurrence (during a critical period of crop growth) and the worst combination of moisture (VCI) and thermal (TCI) stress.

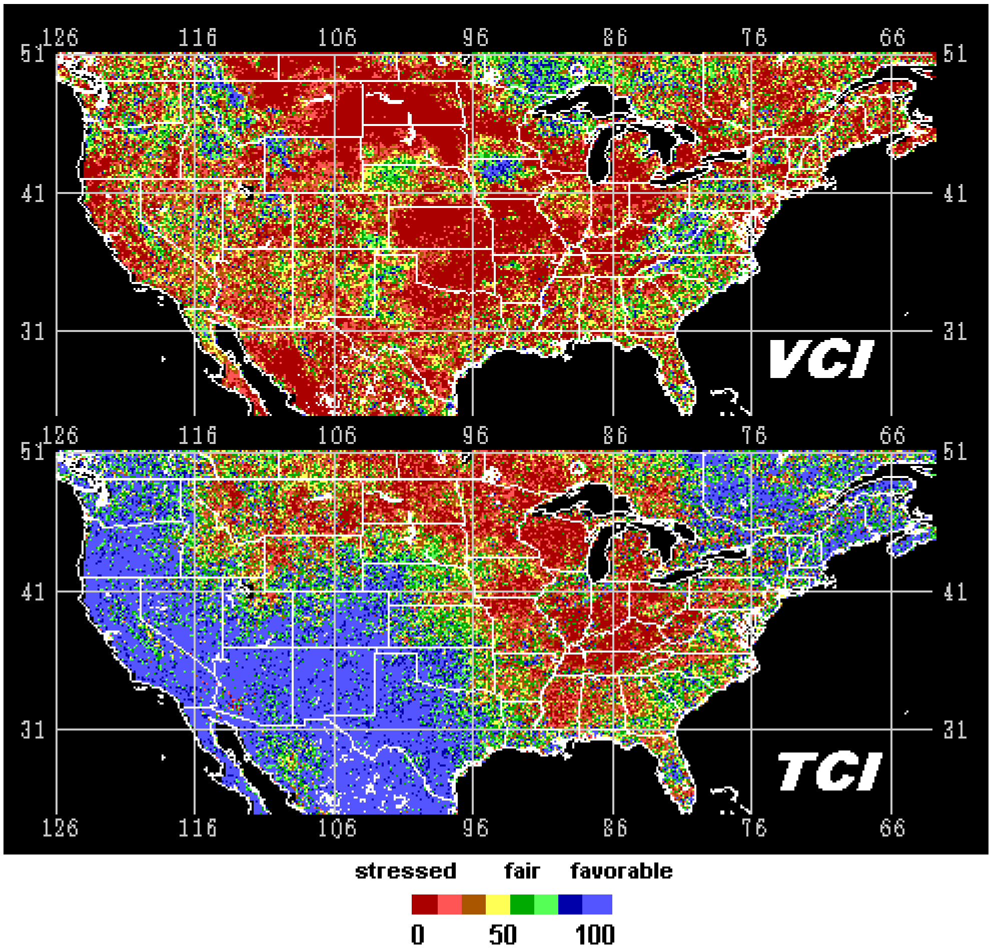


Figure 2. Moisture (VCI) and thermal (TCI) stress (black), end of June 1988, USA, NOAA-9.

Total U.S. corn production dropped by nearly 30% (other grain crops also had considerable losses), and the most affected states were in a zone that was experiencing a three-month shortage of rains (Kogan 1995). The economic effect of this drought was felt globally because the 1988 total world corn production was 50 million tons less than in 1987 and 75 million tons less than in 1989. Total world grain production in 1988 dropped 3% (FAO 2000).

Other major U.S. droughts of the last 15 years occurred in 1989 and 1996. These droughts were quite similar. Both started very early and affected the primary winter wheat areas by the end of April (Figure 3, left). Compared to them, the 1988 vegetation stress (shown in black) did not

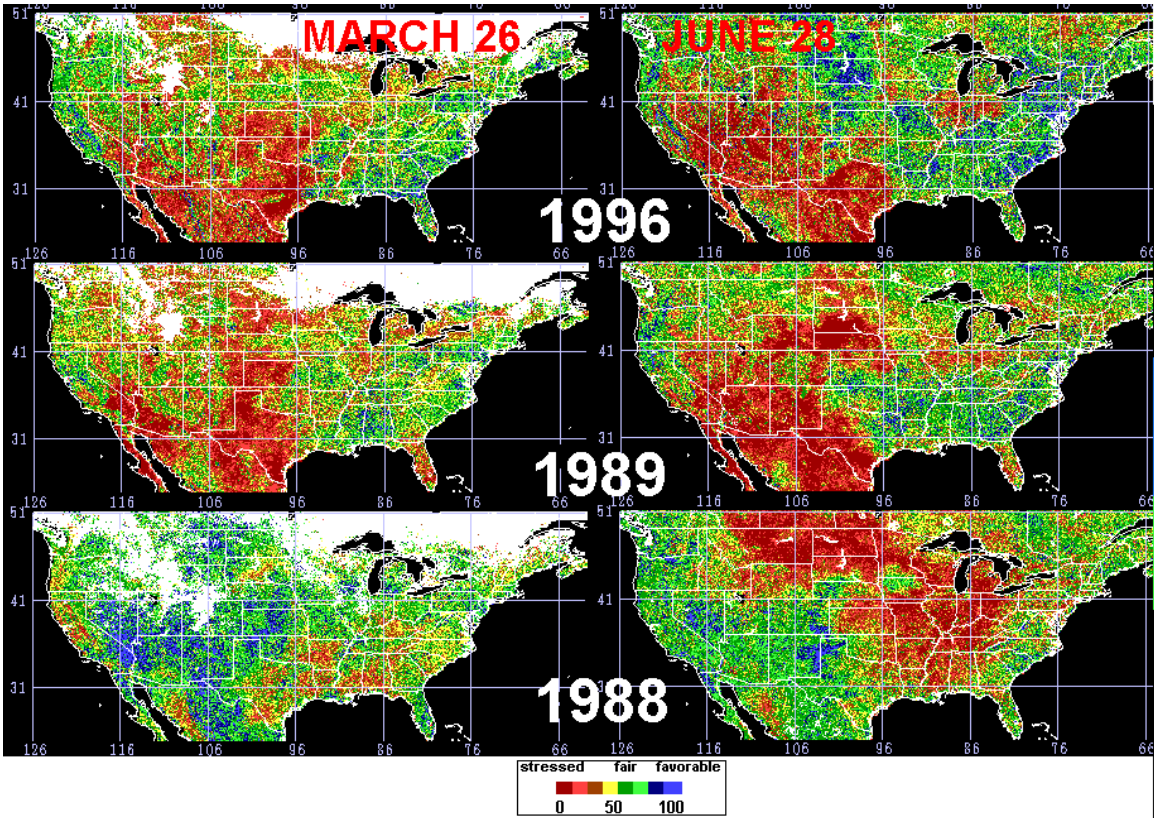


Figure 3. Vegetation stress (black), USA, NOAA-9, -11, and –14 polar-orbiting satellites data.

appear as early. Three months later, the 1988 drought turned into a national disaster, affecting vegetation during the most critical mid-season period (Figure 3, right). The 1989 and 1996 vegetation stress persisted into the summer, although in 1989, only spring crops were affected. Luckily, crop production was reduced in only a few states of the central and northern Great Plains and the total 1989 U.S. spring crop production did not shrink much (Kogan 1995).

Former Soviet Union (FSU). If the United States is the largest seller of grain, the FSU has been and will likely be the largest buyer of U.S. grain. Climate and weather are key factors constraining agriculture and grain production. Since the breakup of the Soviet Union in 1991, grain yields have stagnated because of limited introduction of new technology. This factor, in combination with frequent droughts, led to serious grain shortages. Therefore, monitoring FSU grain production and possible purchases is very important for U.S. grain growers and traders.

Since 1991, four major (every other year) and two minor droughts have been identified by the AVHRR-based indices (Figure 4). Some of them occur two years in a row (e.g., 1995 and 1996). The major droughts of the last decade covered 100-150 million acres of crops and rangeland and reduced the total FSU grain production 10-15% (20-30 million metric tons). The individual countries incurred grain losses up to 30%. The worst economic problems occur when major drought affects both winter (mostly Ukraine and southern Russia) and spring grain crops (eastern regions in 1991, 1996, 1998).

Argentina. Argentina is the world's second largest exporter (after the United States) of corn and coarse grains, and the third largest exporter of wheat (FOA 2000). Droughts do not bypass Argentina since the climate provides considerably less precipitation than thermal resources can potentially evaporate; droughts and dry spells are frequent and devastating. In the last 15 years, Argentina experienced two major and several minor droughts. By all standards, the most damaging droughts occurred during the 1988/89 and 1989/90 crop seasons (Figure 5), when the country lost 15-20% of the total volume of grain. The minor droughts were less intensive and affected smaller areas and/or only a part of the growing season, leading to a 5-10% reduction in crop yields.

China. China is the world's leading agricultural country, producing the largest portion of global grain and cotton, most of which is consumed domestically. From time to time, China also imports small amounts of agricultural commodities. However, in 1994, China unexpectedly purchased a huge volume of cotton, almost double the amount of their previous largest purchase. These imports were preceded by a cotton yield reduction three years in a row: 22% in 1992/93, 11% in 1993/94, and 7% in 1994/95 (the estimates were relative to the average yield in the very productive 1990/91 and 1991/92 seasons [Kogan 1997; USDA 1994]). Our investigation indicates that this reduction can be attributed to unfavorable growing conditions, which caused vegetation stress in the main cotton-growing areas (Figure 6). The most severe vegetation stress (both moisture and thermal) occurred in 1992, which also showed the largest yield reduction. Some deterioration of vegetation conditions was also observed in 1994, but the drought-related stress was partially offset by near-normal summer rainfall. Unlike the other two drought years, 1993 AVHRR-derived vegetation stress in the cotton-growing area was due to excessive moisture.

Technology Transfer

The objective of NESDIS is to interact with the global community and provide early drought (and related environmental calamities) warnings and impacts on agriculture; validate and calibrate satellite-based products; and develop new applications. These goals are reached in several ways: distributing the products through NOAA's web site, scientific cooperation, training, and public outreach.

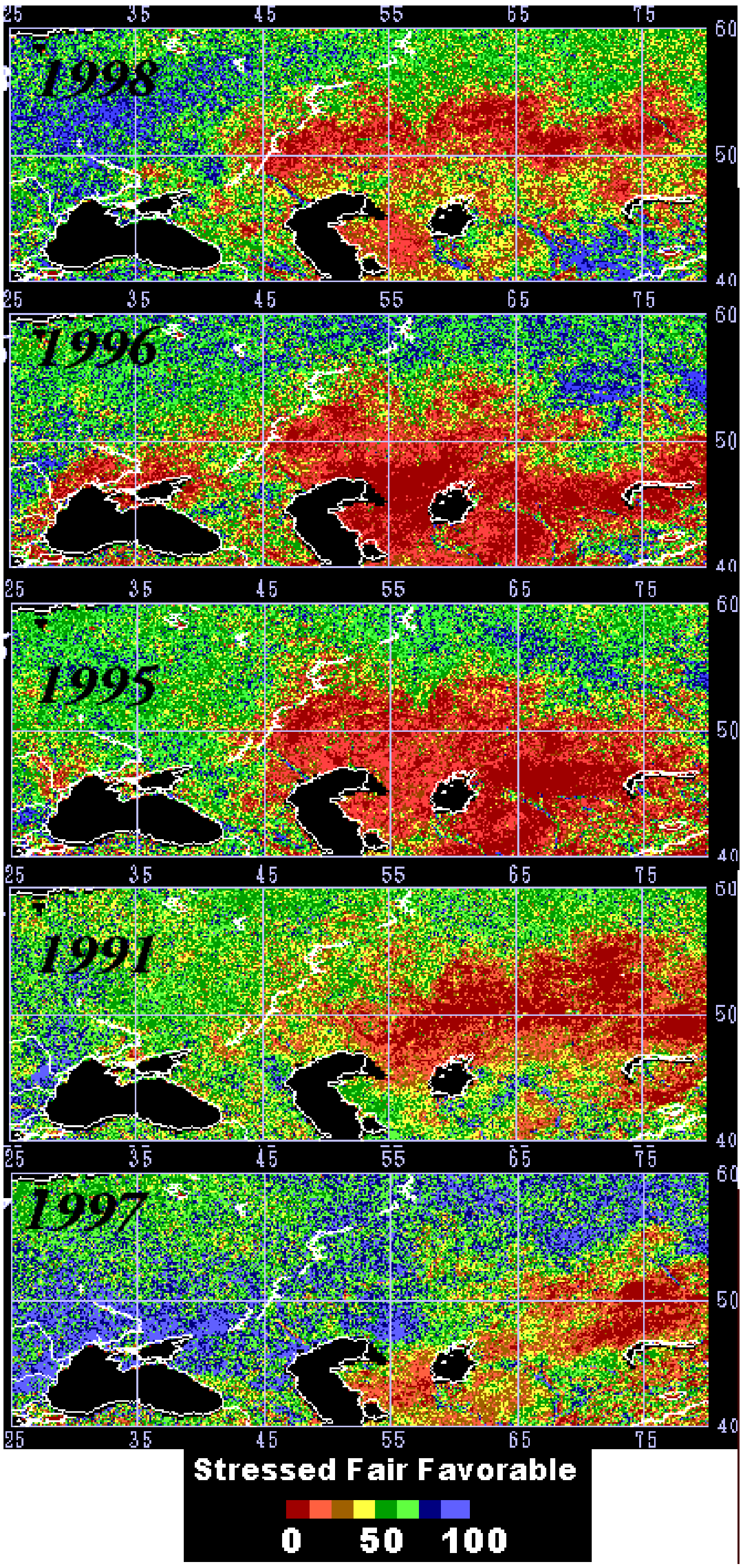


Figure 4. Vegetation stress (black), FSU, NOAA-11, and –14 polar-orbiting satellites data.

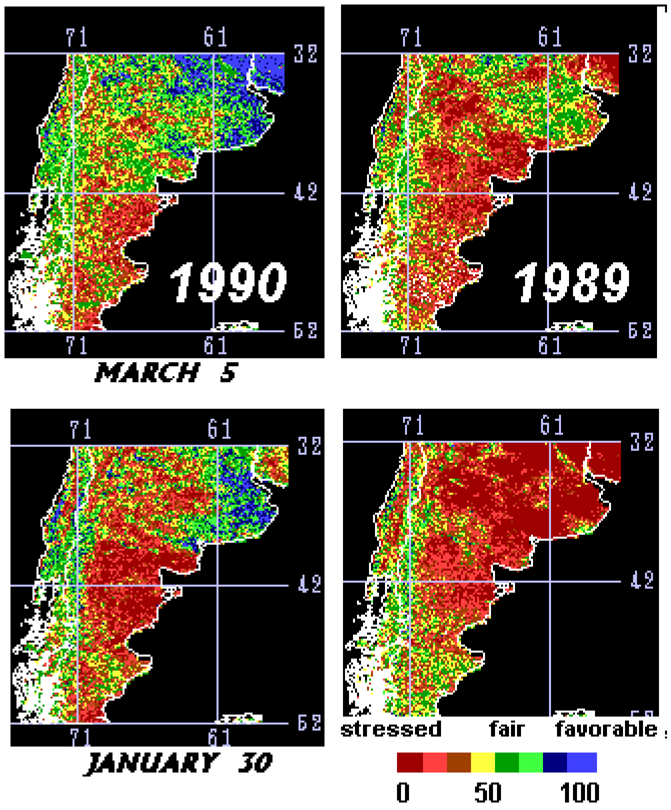


Figure 5. Vegetation stress (black), Argentina, NOAA-11 and –14 polar-orbiting satellites data.

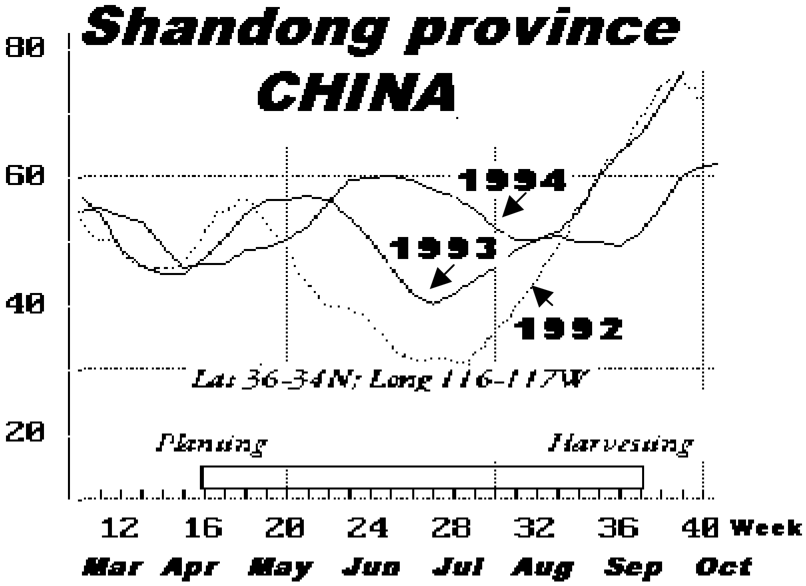


Figure 6. Vegetation health dynamics in Shandong province (25% of China's total cotton production, USDA 1994); the strongest and longest vegetation stress (VT below 40) was in 1992.

The products and data discussed in this paper are delivered in real time (every Monday) to the following web site address: http://orbit-net.nesdi.noaa.gov/crad/sat/vci. They show global and regional vegetation health, moisture and thermal conditions, and fire risk potential. An important part of this process is close cooperation with users, taking into account their suggestions and comments on how the products perform versus available ground data. Some of the comments are quite inspiring. For example: “I am using your images of USA, China and Argentina for the world grain stock analysis” (Dr. Seiler, University of Rio Quarto, Argentina, 1999); “your information on drought is going to Mexico’s Minister of Agriculture to make important decisions on implementing the Alternative Crop Program to the farmers of Central Mexico; in November 1998 the Minister met with the President and showed the images to explain how drought affected rural areas” (Mr. Cuevas, adviser to the Minister of Agriculture, Mexico, 1999); “I use your images as a background for my 10-day agricultural and climate conditions assessments” (Mr. Themaat, Disaster Management Center, Republic of South Africa, 1999); “I look at your fire monitoring web site and find it useful for us in Brazil” (Dr. de Silveira, National Meteorological Institute, Brazil, 2000).

We also provide 2-4 month one-on-one (on-site) training for users of the new technology. This includes access to satellite data, hardware, and software. The users are required to match their country’s conventional data with satellite-based products to validate existing products and to develop new applications based on joint interests. Another way of interacting with users is a long-term cooperation program. Among recent projects, the most successful (which led to the development of a new PC-based data processing system and AVHRR-based crop yield models) were with China, Kazakhstan/Israel (supported by the U.S. Agency for International Development), and Poland (U.S.–Poland bi-national fund).

AVHRR-based Crop Yield Prediction

Crop yield modeling has been a very successful program, specifically in the area of limiting ground data. The background for this task was done in the mid 1990s and was confirmed in the U.S. Midwest and in Zimbabwe (Hayas and Decker 1996; Kogan 1997; Unganai and Kogan 1998). It has been shown that vegetation health indices highly correlate with yield during the critical period of crop development and might be used for modeling and diagnosis of crop yield. Currently, satellite-based crop yield models have been developed for Argentina, Brazil, the Republic of South Africa, Morocco, Poland, Hungary, Kazakhstan, India, and China. In Poland, this program was so successful that the AVHRR-based drought detection and watch method and its models were accepted by the government as an official tool for cereal yield diagnostics. An example of independent evaluation in Morocco (Figure 7) shows that regional wheat yield estimates (line) follow closely the official statistics (bar), especially in the main regions of wheat production.

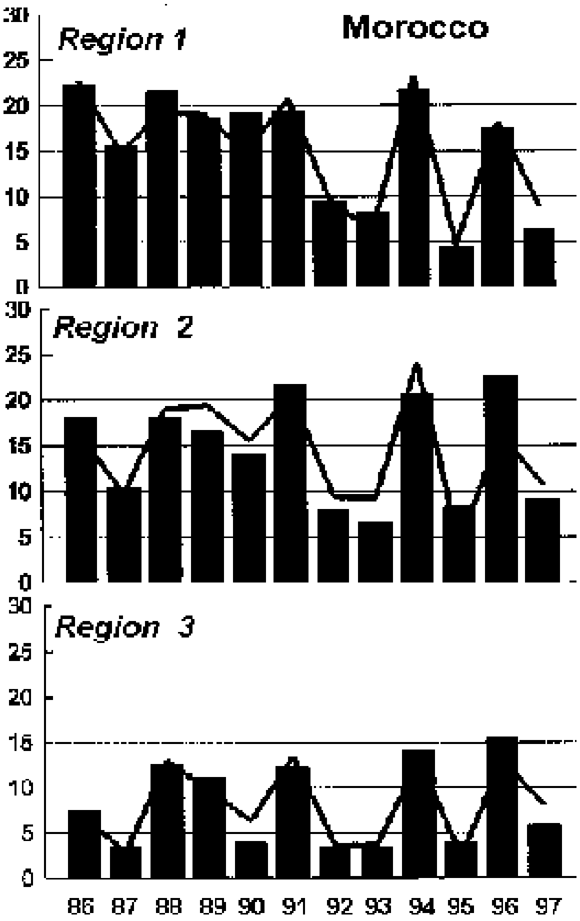


Figure 7. Independent evaluation of wheat yield estimated from satellite (line) and ground (bars) data, Morocco, major regions, 1985-1998.

Vegetation Health 2000

Although the 21st century has just started, drought has already claimed its toll. Huge areas in central Africa, the Middle East, Southeast Asia, central South America, and the central United States had vegetation stress (Figure 8). Compared to fair and favorable vegetation conditions in 1999, a quarter of the world is suffering from dryness in 2000. The most severely affected areas are in the Horn of Africa, where vegetation stress started in January (Figure 9). In a four-month period, the stress intensified and expanded to new areas. By the end of April, this drought turned into natural disaster, affecting 90% of Kenya, Somalia, and Uganda and almost all agricultural lands of Ethiopia. The minor ("belg") crop season in Ethiopia (March–May), which normally provides food and feed before the start of the main growing season, almost completely failed. Moreover, a huge area of the entire Horn of Africa region is under the threat of fire. It is estimated that nearly 15 million people in the Horn of Africa are affected. Agriculture was also affected in Afghanistan, Pakistan, India, Mongolia, and China (Figure 8). The new space-based

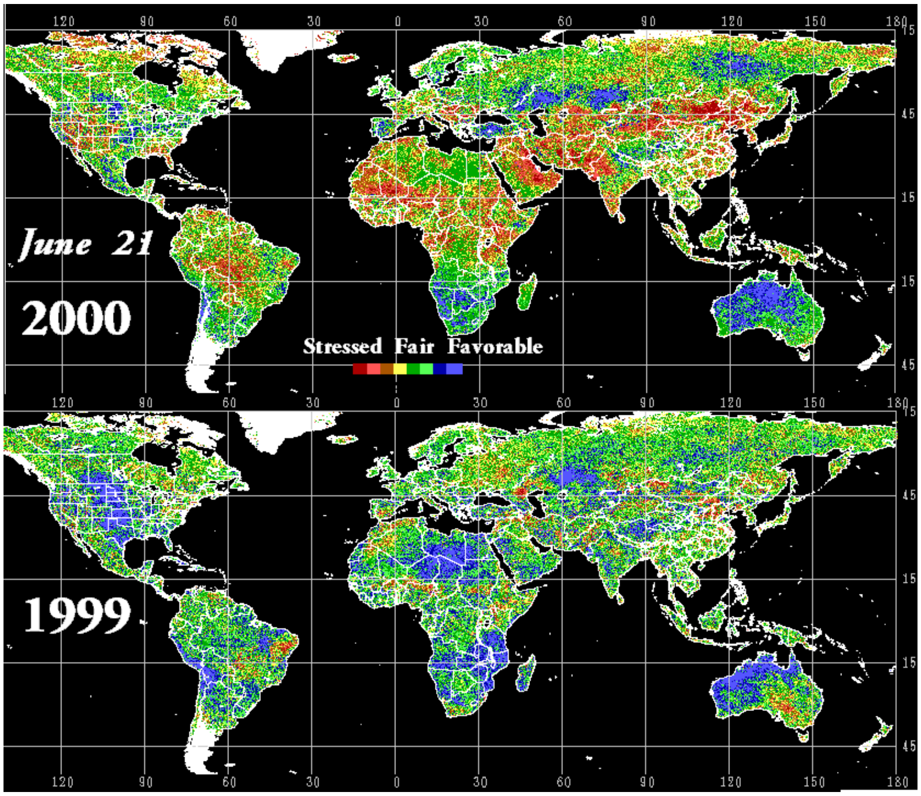


Figure 8. World vegetation health (stressed=black, fair=grey, favorable=white).

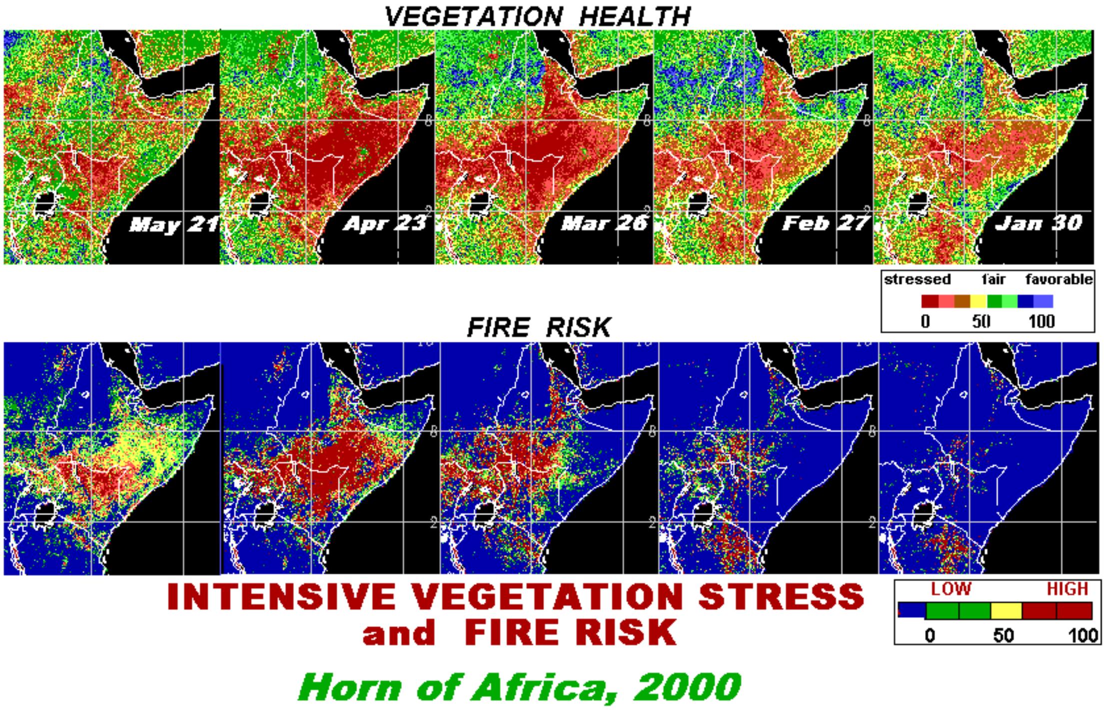
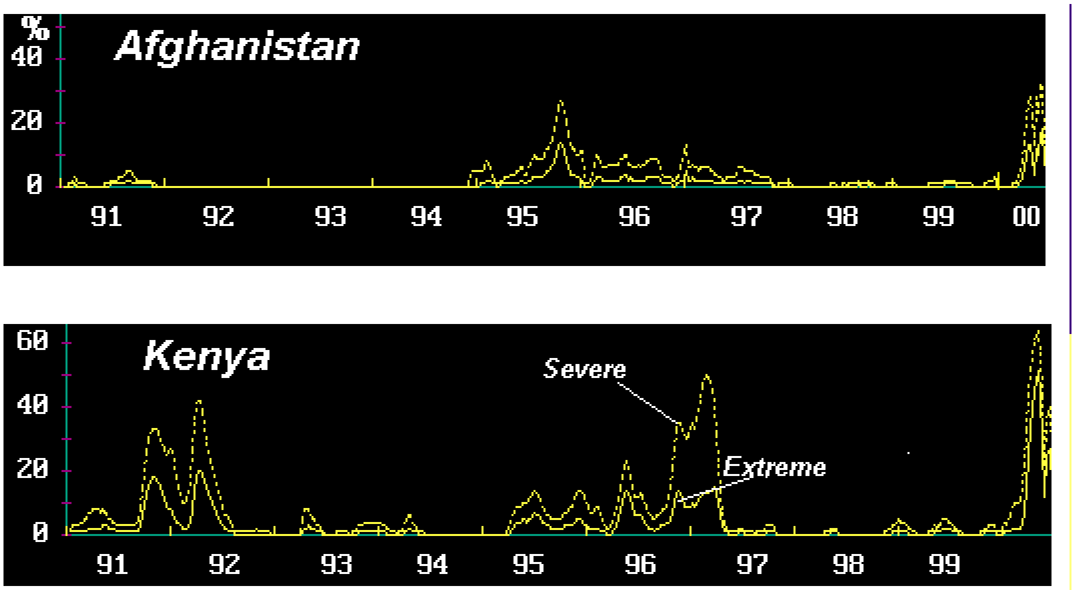


Figure 9. Dynamics of vegetation stress in the Horn of Africa, 2000, NOAA-14.

technique is useful not only for early drought detection and diagnosis of impacts, but also for assessment of the size of the affected area. As seen in Figure 10, in Afghanistan and Kenya, the area of vegetation stress in 2000 is the largest since 1991 in both categories (severe and extreme).



NOAA-11 and 14

Figure 10. Percent area in Kenya with severe and extreme droughts.

Conclusions

The results of this chapter show that we begin the 21st century with exciting prospects for the application of operational meteorological satellites in agriculture. With the introduction of the new method, which was tested around the world, including all principal agricultural producers, drought can be detected 4-6 weeks earlier than before in any corner of the globe and delineated more accurately, and its impact on grain production can be diagnosed long before harvest. This is the most vital step for global food security and trade.

The current developments in satellite technology and sensor design, along with great achievements in numerical methods, speed and capacity of computers, and available hardware and software, will bring more progress in the application of operational and research satellites. With the accumulation of satellite data we will continue to enhance the accuracy of hazard detection, monitor the environment, increase the lead time of estimates, and better diagnose impacts. New products geared to diagnose epidemics, human health problems, and insect development will be more aggressively pursued. New sensors will widen our abilities to detect problems earlier and with higher spatial accuracy. New high-resolution capabilities of satellite sensors will help with precision agriculture and the ability to move from problem detection to mitigation. A new era of satellites will provide the ability to estimate economic effectiveness of applied technologies in order to optimize profit.

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