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World Droughts in the New Millennium from AVHRR-based Vegetation Health Indices

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The new millennium has started with a series of large-area droughts which have had grim consequences for the affected countries and regions. The enormous impacts of the 2000 and 2001 droughts were experienced on both physical and psychological levels, in part because no large-scale drought occurred in 1999. In some regions, severe drought continued for two years in a row.

A new remote sensing method (three-channel algorithm) for assessing vegetation stress, from the Advance Very High Resolution Radiometer (AVHRR)-based vegetation health indices, was used for the inventory of droughts in 2000 and 2001. Compared to ground-based and NDVI-based (two-channel algorithm) detection systems, this new method provides earlier drought warnings. It also makes it possible to estimate areas under droughts of different severity, and to diagnose the potential for drought development prior to the actual start of drought conditions.

Although AVHRR data and products have been used for monitoring land surface and the environment since the mid-1980s, the potential of this data has not yet been exhausted. In addition to drought-related conditions, the new method has been used successfully for assessment of fire risk, vector-borne disease outbreaks, moisture and thermal conditions, and forecasting of large-area crop and pasture productivity. Moreover, with the use of this new remote sensing method, it was proven again that reduced drought activity in one year does not indicate immunity for the next year, because drought is a re-occurring phenomenon. This was clearly demonstrated by the aforementioned two-year extreme drought cases around the world.

Unlike other remote sensing techniques, this new method for analysis of drought genesis and consequences is based on the main ecosystem's laws; that is, analysis of the health of vegetation in terms of its response to weather changes. One of the important advantages of this method is that it makes use of a combination of the normalized difference vegetation index (NDVI), normally used alone, and the 10.3–11.3-μm thermal channel. Assessment of temperature conditions permits one to identify subtle changes in vegetation health because the effect of drought is more dramatic if a shortage of moisture is accompanied by excessive temperatures. This method was validated in all major agricultural countries around the world.

Principles of a New Algorithm

Remote sensing of drought is based on properties of green vegetation to reflect and emit solar radiation. In drought-free years, green and vigorous vegetation reflects little radiation in the visible (VIS) part of solar spectrum, due to high chlorophyll absorption, and much in the near-infrared (NIR) part, due to scattering of the light by leaf internal tissues and water content. Following these properties, the difference between NIR and VIS becomes large. Drought normally depresses vegetation greenness and vigor, due to a reduction of chlorophyll and water content, and therefore, of canopy area, leading to an increase in the VIS, a decrease in the NIR, and reduction in NIR-VIS [*Gates*, 1970]. This principle is used in the construction of the normalized difference vegetation index [NDVI=(NIR-VIS)/(NIR+VIS)]. Derived from the Advance Very High Resolution Radiometer (AVHRR) flown on polar-orbiting satellites of the U.S. National Oceanic and Atmospheric Administration, NDVI has become the most widely-used for environmental monitoring because it correlates with vegetation biomass, leaf area index, and crop yield [*Cracknell*, 1997].

The new AVHRR data-based method of drought warning and surveillance is based on the estimation of green canopy stress from AVHRR-derived indices, characterizing vegetation health, moisture, and thermal conditions [*Kogan*, 1997, 2001]. Unlike the NDVI-based (two spectral channel) approach routinely applied for vegetation monitoring, the new numerical method uses both NDVI and the 10.3–11.3-μm infrared channel. The latter provides brightness temperature (BT), which indicates how hot the vegetation canopy can be. In dry years, high temperatures at the background of insufficient water supply lead to overheating of the canopy, which intensifies the impact of moisture deficit on vegetation. The data are sampled spatially, to a $(16\ \mathrm{km})^2$ latitude/longitude grid and temporally, to one-week composite.

The details of the algorithm are presented in *Kogan* [1997, 2001]. We mention in this article only the important steps of the process; these include: complete removal of high-frequency noise from NDVI and BT annual time series, approximation of seasonal cycle, and enhancement of medium-to-low frequency fluctuations associated with weather variation. The latter are used as proxies for estimation of vegetation condition and health. Three indices were developed: Vegetation Condition Index (VCI), for estimation of cumulative moisture impacts on vegetation; Temperature Condition Index (TCI), for estimation of thermal impacts; and Vegetation Health Index (VH), for estimation of combined conditions.

Droughts at a Glance from Space

A worldwide snapshot of drought-related severe vegetation stress at the end of August 2001 (red shade in Figure 1) indicates that all Northern Hemisphere continents were affected. In North America, vegetation of the southern and western states of the United States was the most severely stressed in mid-summer. Unusually dry and hot weather was the major contributor to this event. Interestingly enough, the same areas were affected in 2000. The consequences included crop losses, pasture degradation, and intensive wildfires. The second half of summer 2000 was the driest on record in Texas and Oklahoma; rainfall hardly reached 20% of normal, and the period with no rain continued for 2 to 3 months. The dryness was aggravated by widespread and excessive heat in the period of July–August, with 2–3 week temperatures exceeding the 100°F mark, and some locations reporting all- time records of 105 to 110°F [*LeComte*, 2001].

On the other side of the Atlantic Ocean, a huge area with depressed vegetation (deserts are exempted from this consideration) stretched from Africa, across southeastern Europe, and through to central Asia. The newly-created countries around the Caspian Sea reported crop and orchard losses, and in southern Mongolia, pastures were affected severely in both years. In northern Africa, widespread unfavorable surface conditions (below-normal NDVI and above-normal temperature) were observed during the entire summer of 2001. Some countries along the southern edge of

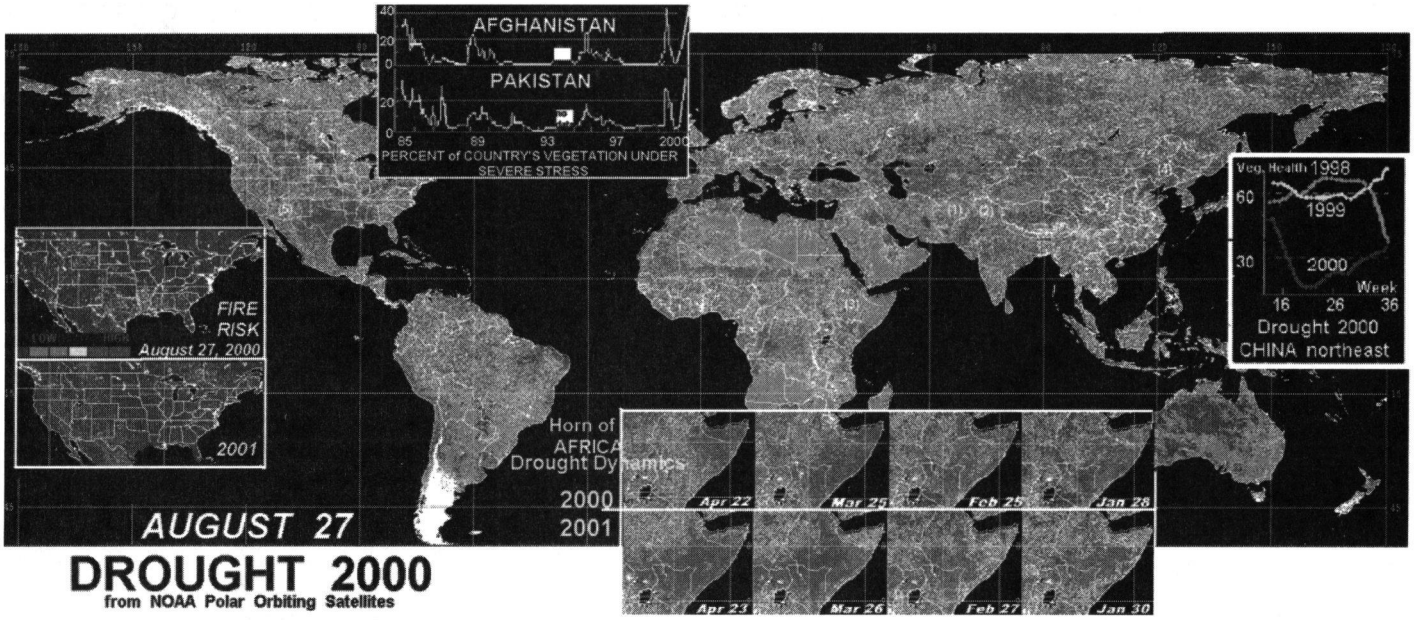

Fig. 1. Summary of vegetation health and drought-related stress (VHI index) at the end of August 2000 (inserts; top: % of areas of Afghanistan and Pakistan under severe stress; bottom: drought dynamics in the Horn of Africa; right: droughts in northeastern China; left: Fire risk assessment at the end of August in the United States). Original color image appears at the back of this volume.

the Mediterranean Sea (Morocco, Algeria, Tunisia) suffered crop losses. Similarly, vegetation stress in the Sahelian zone of subsistent agriculture (15–17°N) resulted in pasture and crop failures in Sudan, Chad, Niger, Mali, and Mauritania.

The most dramatic drought developed in the Horn of Africa two years in a row (Figure 1, bottom insert). Vegetation stress (red shading) started in January 2000, covering southern Ethiopia and Somalia, northern Kenya and adjacent regions of Tanzania, Uganda, and southern Sudan. By March of 2001, the drought had already become a natural disaster as a result of its intensification, expansion, and long duration. The consequences included failure of a minor agricultural season in Ethiopia (March–May), the outbreak of diseases in Somalia (reports on cholera), bad pasture conditions, and fire activity. Nearly twenty million people in the entire area suffered from food shortages in 2000. In early 2001, severe vegetation stress reappeared again, covering the eastern part of the Horn.

Early Drought Detection

Since AVHRR data respond cumulatively and quickly to changes in vegetation greenness, vigor, and canopy temperature, the effect of drought can be detected much earlier than it can be from weather data, traditional tools for drought detection. In the Horn of Africa (Figure 1, bottom insert), severe, drought-related vegetation stress (VH < 40) had been already observed in January 2000 and 2001, two months prior to the beginning of the minor growing season (March–May).

Moreover, vegetation stress can be diagnosed even earlier from vegetation health dynamics. As seen in Figure 2, the first signs of the approaching drought in 2000 appeared in October-November (weeks 40–48) 1999, when vegetation was still in good health (VH > 50), but a negative tendency had already appeared in VH time series. A similar situation developed during the 2000 drought in China (Figure 1, right insert). Severe drought (VH < 30) started around week 18 (early May). However, a persistent tendency toward drought was observed one month earlier when the vegetation health was still near normal (VH = 50), but was gradually deteriorating. Thus, the new tools provided considerable lead time for drought warning, which is important for pinpointing the problem, making decisions, and implementing measures to mitigate consequences.

Estimating Fire Risk

One of the vegetation health index by-products was designed to estimate fire risk. Wildfires damage huge forest and grassland areas worldwide. Several hundred million hectares of vegetative lands are burnt worldwide annually, with adverse impacts on countries' economies, the environment, safety, human health, and wildlife [*Goldammer*, 1999]. Fire suppression is an important task of fire policies, which requires timely warning about possible fire activity. Early fire indicators can help to alert the public; and help ready human and technical resources for efficient fire management well in advance of fire development, thereby assisting in the deployment of these resources in a way that is complete and more effective.

Drought is the major component, which sets conditions for fire development over large areas. Normally, fire-affected areas increase two-fold in years with long and severe droughts. Besides, drought regulates intensity and longevity of fire and the speed of its development and expansion. Therefore, early drought detection, and evaluation of its intensity, area coverage, and duration contributes to diagnosis of fire risk. The technique for monitoring potential fire danger (fire risk) on a large area is based on analysis of duration and intensity of vegetation stress. The highest fire risk is estimated when intensive vegetation stress (VH < 15) continues for at least five weeks. This technique provided timely warning of possible fire activity during fire-based vegetation clearing in the Brazilian Amazon in 1998 and 1999.

Compared to 1999, the 2000 and 2001 growing seasons in the Northern Hemisphere were characterized by elevated fire hazard. Two major areas of wildfire danger in the southern and western states of the United States were pinpointed during both years (Figure 1, left insert). The fires in the U.S. northwest in 2000 destroyed 1.6 million acres, twice exceeding the average number of fires in the last 10 years; $1.5 billion was spent to suppress the active fires [*LeComte*, 2001].

The 2001 fires hazard in the western United States was not as intensive as in 2000. Eastern Africa had above-normal fire activity, especially in March and April, which was supported by satellite-based estimates (Figure 1).

Estimation of Drought-affected Area

The new method was used for assessment of drought-affected areas. In 2000 and 2001, drought-stricken countries have had the largest area of vegetation stress over the last 15 years. In Afghanistan and Pakistan (Figure 1, upper insert), extreme drought (VH < 20) covered, respectively, around 40% and 20% in 2000, and 60% and 40% in 2001. Estimated by intensity and area coverage, Afghanistan experienced the worst drought situation in the last two years. Severe stress (VH < 30) affected vegetation on 70% and 85% of the entire country's area in 2000 and 2001, respectively; exceptional stress (VH < 10) covered 30% and

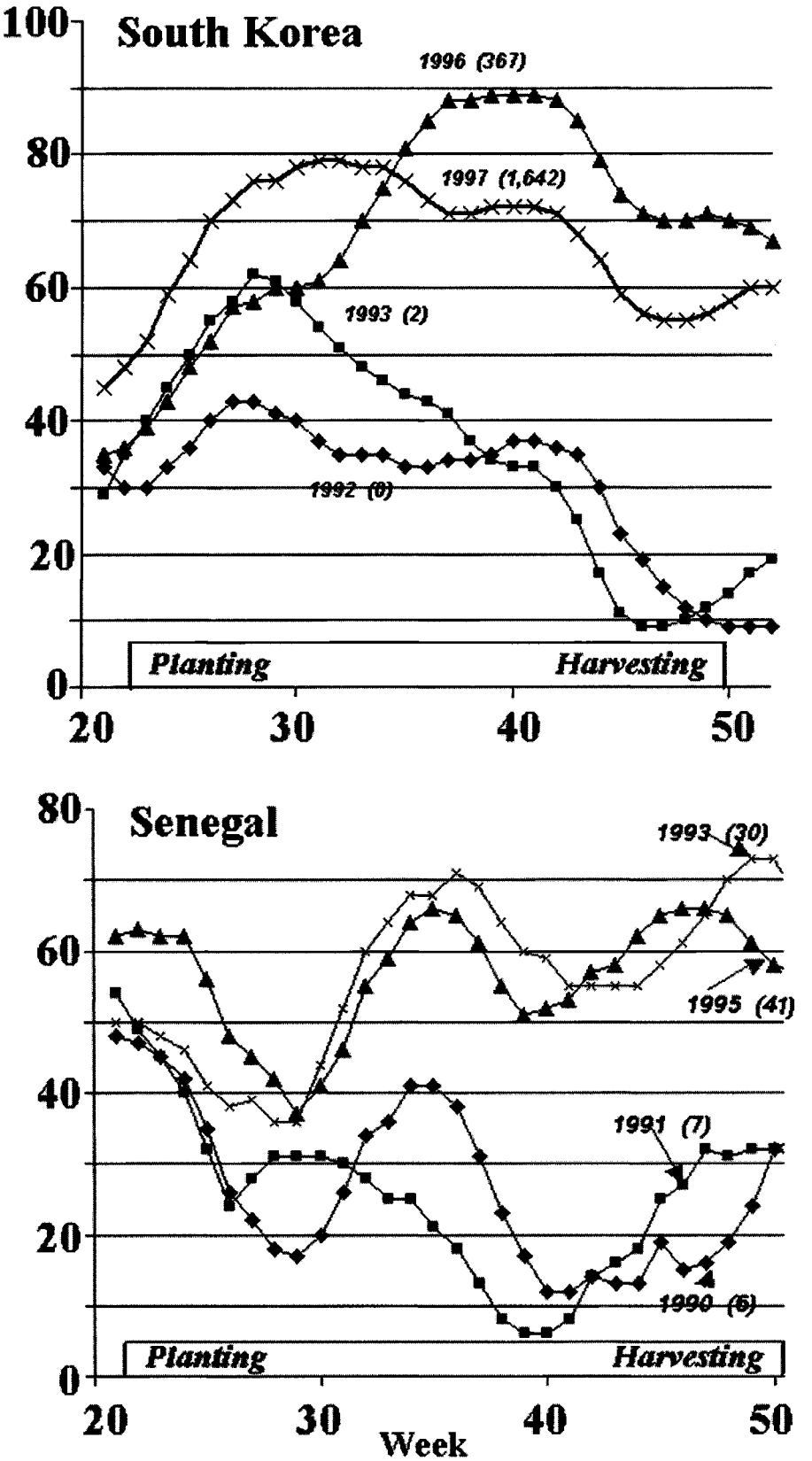

Fig. 4. Number of malaria cases (in parentheses) and AVHRR-based vegetation condition dynamics. For a province in South Korea (latitude 39–37° N, longitude 126–128° E), VCI was used. For a location in Senegal (latitude 14.5–14.3° N, longitude 16.6–16.2° E), VT was used.

the new AVHRR data-based method of drought warning and surveillance, drought can be detected 4 to 6 weeks earlier than was previously possible and outlined more accurately. Crop losses can be diagnosed long in advance of harvest in any corner of the globe. A good example is the 2000 drought in the Horn of Africa, which was detected in January-February, almost two months in advance of drought warning from other, ground-based data. Moreover, the antecedent and physiological effects discernable from satellite data can be used for diagnosis of a tendency toward deterioration of vegetation health and the potential for drought development. This provides added warning lead time, which is critically important for pinpointing the problem, making decisions, and implementing measures to mitigate drought consequences. These measures are important steps for sustainability of the developing nations.

For further information, go to the following Web site: http://orbit-net.nesdis.noaa.gov/crad/sat/surf/vci.

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Table 1. Wheat yield reduction expressed as percent from 1998 yield

Country	*1998 Yield (ton/hectare)*	*1999 Yield Reduction (%)*	*2000 Yield Reduction (%)*
Afghanistan	13.0	6	45
Eritrea	9.1	6	74
Ethiopia	13.7	18	14
Iran	19.3	5	34
Iraq	7.8	36	65
Kenya	23.3	42	44
Morocco	14.2	44	66
Pakistan	22.4	3	11*

* *Wheat yield increased*

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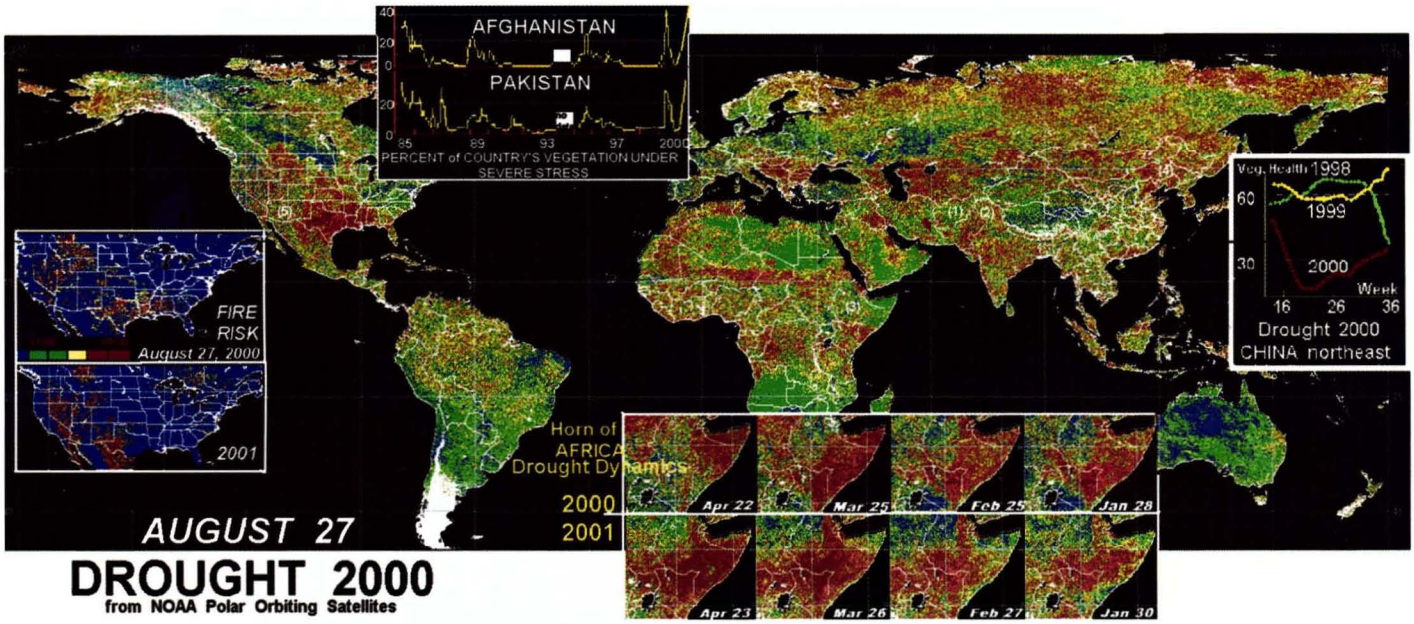
Listening to the Secret Sounds of Earth's Atmosphere

PAGES 557, 564–565

A new global network is breathing life into a dormant branch of geophysics. The study of infrasound, or long-period acoustic signals in the atmosphere was bustling in the 1950s and 1960s. Prior to 1963, almost all nuclear tests occurred in the atmosphere. After 1963, the USSR and U.S. signed the Limited Test Ban Treaty (LTBT), which eliminated all atmospheric nuclear tests. During the era of atmospheric nuclear testing, infrasound research was in demand, since the massive explosions produced strong, long-period acoustic waves that were globally observed and could be used to locate and describe the nuclear tests. Interest in this branch of geophysics waned with the end of atmospheric testing.

It has been recently rekindled by the Comprehensive Nuclear Test Ban Treaty (CTBT), which was tabled for signature at the United Nations (U.N.) in 1996. The treaty bans all nuclear tests and establishes a monitoring network of sensors that probe the Earth's solid interior, oceans, and atmosphere for unusual signals. Although the seismic network includes a large number of existing stations and adds only another network to the existing collection of global seismic networks, the infrasound network will be entirely new and will surpass smaller-scale global infrasound networks previously deployed by the U.S. military and the National Oceanic and Atmospheric Administration. The continuously monitoring stations will provide a wealth of data on human activity and on natural phenomena. The global infrasound network that is now being constructed will provide us with an unprecedented opportunity to study these phenomena on a global scale.



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