World droughts from space during the 2001-2012 warmest decade

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In 2002, one of the *Eos* issues published our feature article emphasizing that the first two years of the new millennium (2000 and 2001) have started with a series of severe, large scale droughts in different parts of the globe, which strongly affected the environment, economies and human life (Kogan 2002). The concern was that due to the ongoing global warming, which was the strongest in the past 30-40 years, the process of drought intensification, expansion and penetration into the new areas has started (Solomon et al 2007). Currently, when the ten years have passed and they were even warmer than prior to 2000 (including the two warmest years of the past century), we are updating global and regional droughts records featuring on drought tendencies, area, frequency, intensity, duration and impact on the environment and socioeconomic factors. The investigation is based on satellite vegetation health (VH) technology which is a new NOAA\NESDIS tool used semi-operationally in the last few years for early drought detection and monitoring its genesis and impacts globally (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php).

Drought is a part of Earth's climate, which occurs every year without warning, recognizing administrative boarders, political and economic differences. Unlike other weather disasters, drought starts unnoticeably, develops cumulatively, produces cumulative impacts and by the time damages are visible, it is too late to mitigate the consequences. Drought affects the largest number of people on the Earth and is a very costly disaster. In the USA, drought is considered a "14 billion-dollar" annual event in terms of incurred losses (NCDC 2011). In the developing world, drought leads to food shortages, famine, mortality and population displacement. Since drought is a very complex and least understood phenomenon, there is no methods for drought prediction what would be an effective way to fight with consequences. Therefore, early detection and monitoring is currently the only way of deal with drought in assessing its impact and developing mitigation measures. Weather data have been used traditionally as a tool for drought monitoring. However, weather station network is sparse, especially in climate, ecosystem and population marginal areas. In the last 30 years, satellite technology has successfully filled this gap. Besides, satellite data and indices provide cumulative numerical approximation of drought and its impacts. In the past 10-15 years, satellite remote sensing has proven to be a perfect utility for operational drought management as a separate tool and is complementary to weather data (Kogan 2002). Finally, it is important to emphasize that drought detection and monitoring method will be considerably improved with the new generation of satellite technology that started in 2011. The new Visible Infrared Imager Radiometer Suite (VIIRS) on the NPOESS (National Polar-orbiting Operational Satellite System) Preparatory Platform (NPP) will provide observations for each 371 m of the globe with four times more spectral bands (compared to its predecessor).

Vegetation Health Method

Vegetation health method is a new tool designed to estimate the entire spectrum of vegetation health (condition) from AVHRR-based Vegetation Health (VH) indices. Remote sensing of VH is based on the 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 solar light absorption by chlorophyll) and much in the near infrared (NIR) part (due to specificity of scattering the light by leaf internal tissues and water content impact). Following these properties, the difference between NIR and VIS becomes large, indicating that vegetation is very green and vigorous. Drought normally depresses vegetation greenness and vigor (due to a reduction in chlorophyll and water content) and canopy area leading to an increase in the VIS, decrease in the NIR and a reduction in NIR-VIS. This principle is used in construction of the Normalized difference vegetation index [NDVI=(NIR-VIS)/(NIR+VIS)] which becomes the most widely used for environmental monitoring because it correlates with vegetation biomass, leaf area index and crop yield (Cracknell 1997, Kogan 2012).

However, NDVI alone is not sufficient for monitoring vegetation health and drought. Afternoon temperature of vegetation canopy is an extremely important characteristic for estimation of vegetation condition and health. Therefore, thermal characteristic of land cover was added to the NDVI tool. In addition, both NDVI and thermal indices were related to their climatology calculated from the 32-year AVHRR data. Following these principles, three indices were developed: Vegetation condition (VCI) from NDVI, Temperature condition (TCI) from 10.3-11.3 μm infrared channel measurements of brightness temperature (BT) of land surface and vegetation health index (VTI) from the combination of VCI and TCI for estimation of total vegetation health (Kogan 1997). The NDVI and BT were well calibrated and low/high frequency noise was removed from the data. The VCI, TCI and VHI were validated to be an appropriate indicators of moisture, thermal and total vegetation health conditions, respectively. The indices values change from zero, indicating extreme stress, to 100, indicating very favorable conditions. Close to normal conditions are approximated by the values around 50. VH-designed drought monitoring is based on the numerical analysis of vegetation stress from a lower greenness and above normal temperature. These conditions indicate moisture and/or thermal vegetation stress. In dry years, high temperatures at the background of insufficient water supply trigger an overheating the canopy, which intensifies the impact of moisture shortage on vegetation. Drought warning is issued if VH values decrease below 40. The details of the algorithm are presented in Kogan (1997).

Droughts during 2001-2012

This section provides global analysis of regional droughts during the 12-year of the new millennium, which was characterized by the highest global temperature in the past 100 years. All regional droughts are included in this section with special emphasis on those which were unusual and had huge economic consequences. These droughts are discussed from the point of view of their adverse features: affected area, time of initiation/end, intensity, duration and impacts. Figure 1 shows AVHRR-derived images of vegetation health focused on drought areas (red color). The most unusual droughts based on a combination of the indicated characteristics are shown on the counter map (further referred as CM). The rest, including some of the unusual, are derived by the continents and

years below the counter map (further referred as BCM). From the droughts classifying as the unusual during 2001-2012 two occurred in the most recent years. They were 2011 in southern United States and 2010 in Russia (Fig 1, CM).

The 2011 US drought covered southern states, centered on Texas, Oklahoma and New Mexico, which experienced primary hit. Drought also affected parts of Arizona, Kansas, Arkansas, Georgia, Florida, Mississippi, Alabama, South and North Carolina. However, only the areas with the strongest drought impacts are shown on the map. Considering both moisture and thermal stress, so called "exceptional" (the strongest) drought (occurs every 9-20 years) plagued 8 percent of the contiguous United States and extreme-to-exceptional drought covered nearly 15 percent of the country. Previous large-scale and intensive US droughts occurred (although centered differently) in 2002 covering western USA (especially Colorado) and in 1988 covering principal agricultural areas of the Great Plains. State level drought of exceptional intensity affected nearly 40% of Texas and Oklahoma (30% New Mexico) and severe-to-exceptional intensity hit 60% of Texas and 70% of Oklahoma; droughts of any intensity (from mild to exceptional) covered the entire states. Summer in the two hardest hit states was the hottest on record and it is estimated that the Texas drought was supposed to cost $5.2 billion in agricultural losses (AgriLife 2011). Additional losses also came from wild fires, depletion of water in lakes and reservoirs, tourism, and deterioration of human health and the ways of living.

The 2010 drought in Russia was very long, intensive, occupied a huge area and caused serious damages to the environment, economy and human health. Based on VH, this drought started in May and continued through November (Fig 1, CM). A very specific drought feature this year was intensive thermal stress, which started in April covering the entire European Russia and western part of Russian Asia. This heat stress quickly dried up soil moisture resulting in deteriorating vegetation health. The Russian drought was the worst in the last 38 years, since 1972, when a drought of similar intensity, duration and impact, covered the same spring and winter grain areas. Prior to 1972, the same scale droughts occurred 26 years earlier, in 1946, and before that, 25 years ago, in 1921 (Kogan 1985). As the result of the 2010 drought, Russian grain production dropped to 75 million metric tons (compared to 97 in 2009). The drought, which continued until November, affected not only the 2010 harvest but 2011 as well, since it triggered very dry soil conditions on a huge area of winter wheat (occupy 65% of annual grain crops) planting in August-September. Following this drought the Russian Government imposed grain embargo, which triggered sharp increase in global wheat prices (the biggest increase since 1973) since Russia is one of the main exporter of grain contributing nearly 17% of the world trade (Kramer 2010). In addition to affecting grain harvest, drought triggered hundreds of fires accompanied by a very heavy and long-lasting smoke and heat waves, which affected human health and enhanced considerably death rate in Russia.

Other two unusual cases of the past 12 years presented here are multi-year droughts in Australia and eastern (the Horn) Africa. Australian drought continued intermittently between 2002 and 2010. Southern and eastern Australia were the most affected (specifically, Queensland, New South Wales and Victoria states). However, the most dramatic event occurred during 2006 and 2007, since that drought continued for one and a half years without interruption and was severe. VH indices indicate that this long drought started in December 2005 and ended in April 2007, affecting the principal agricultural and rangeland areas during the two growing seasons. Between these seasons, the 2006 drought was the worst in the recent history because it slashed water supplies (leading to a very low

reservoir level) and crop production across large areas; it also effected energy and economy. The total VH-estimated drought area has reached 70%, including a nearly 40% area reeling from extreme and exceptional intensity. Based on FAO statistics (FAO 2012), total Australia wheat yield in 2006 dropped 46% (below 1960-2010 yield trend level). Slightly less yield reduction (37%) was observed in 2007. It is important to emphasize that four years earlier, in 2002, another drought of similar to 2006 intensity but on a larger area affected Australian agriculture reducing wheat yield by 45%. Other droughts during the 8-year period were either shorter or less intensive or covered smaller area having much less impacts on agriculture. For example, 2008-2010 droughts reduced wheat yield slightly (6-9% below trend level). Although 2003 and 2005 were also dry years in Australia, droughts have not affected the main agricultural areas resulting in good wheat crop. Compared to multi-year drought years, the 2011-12 crop pastures season was favorable in Australia, although drought in southern areas is observed in May (Fig 1).

The Horn of Africa have principally two seasons February-May (minor) and June-September (major). Although the first one is minor, it is still important for growing crops and providing food and feed until the major harvest becomes available. According to VH estimates, the past 12 years were affected by droughts almost every year, either during minor or major seasons, or both (Fig 1). Some of the droughts were severe, but not a single drought covered the entire Horn territory as it occurred in the early 1980s and late 1990s. Among the recent years, the most dreadful droughts in the Horn, which affected both major and minor seasons, occurred in 2009 and 2011 in Kenya. Available crop data for 2009 indicate that Kenya's agriculture was the most severely affected since wheat yield dropped 45% compared to 2010 good crop season (FAO 2012). We should note that 2002 and 2008 were years with intensive and long droughts as well, but they affected pastoral areas. Droughts during the minor season only occurred in 2001, 2003, 2005 and 2006. They were severe and continued for 3-4 months, although their effect on agriculture was minor since summer conditions were relatively favorable for crops. Finally, VH estimates for the first five months of 2012 again indicate drought in the Horn of Africa, which started in January in the central and southern Kenya and eastern Ethiopia. In February, this drought intensified and spread to the central Ethiopia. In mid March, the drought reached severe-to-extreme level of intensity and occupied almost 60% of Ethiopia (except northwest).

VH-based Drought Products

A few drought products have been developed based on vegetation health methodology. They include moisture index (VCI), thermal index (TCI).drought area (DA), drought intensity (DI), drought duration (DD), Fire risk (FR) and are demonstrated on Fig 2. Moisture and thermal stress are estimated from the AVHRR-derived Vegetation (VCI) and Temperature (TCI) condition indices (Kogan 1997). The worse vegetation stress is developing when both VCI and TCI have very low values indicating that compared to climatology, vegetation has minimal greenness (less chlorophyll content) and vigor (less water content) and extremely hot temperature, which stimulate excessive evaporation from the canopy and considerable depletion of water in vegetation over short period of time. Such situation developed in 2011 in southern USA, when vegetation in the major drought area experienced severe stress (both VCI and TCI are below 20), what is seen in Fig 2A. During the 2006 drought, only western part of Texas experienced both moisture and thermal stress; the eastern areas avoided moisture stress. This is supported by drought area products (Fig. 2B) indicating that the 2011 severe moisture and thermal stress in southern US affected almost 90% of the Texas state

compared to only 5-10% in 2010. In Russia situation was opposite: 2010 was extremely dry and 2011 – normal year. In Rostov province, 2010 drought affected 80% of the area, while in 2011, drought affected only a small portion of the province (10-20%).

Drought intensity is demonstrated in Fig 2C during 2007-2011 in Kenya (Horn of Africa). In the past five years, drought affected Kenya four times. Following VH estimation (both moisture and thermal stress), mild drought occurred every year, but in 2009 and 2011, droughts were moderate to severe intensity. However, thermal stress in these years was severe-to-extreme and continued for a few months. Thousands acres of vegetative land are burnt every year worldwide leaving huge scars on the land, polluting the atmosphere and affecting human health. An early assessment of fire risk can help to made preparation for fighting with fire and mitigate consequences. Drought is the principle factor creating fire risk conditions. Therefore, in drought years, the burnt area increases two fold. VH fire risk monitoring is based on assessment of severity and duration of vegetation stress (Kogan 2002). Figure 2D shows maximum fire risk area during the 2007 and 2010 seasons in Russia and Ukraine. These two droughts caused huge fires in both years. Russia was the most affected in 2010 and Ukraine was affected in both years: in 2007 in the south and in 2010 in the north. Although the fire risk area in the north was not large, it covered the region of the 1986 nuclear accident in Chernobyl. Soil and vegetation in that area are still having radioactive remnants that could be thrown into the air by wildfires.

Drought duration is one of the important parameters providing information on the possible drought impacts. For example, short and intensive drought could be detrimental for crops and pastures, in forest ecosystem mid-term drought might lead to enhanced fire risk, however, deep ground water and water in the rivers and lakes would respond mostly to very long droughts. Figure 2E shows duration of droughts of different intensity in Kenya during the two most drought-affected years, 2009 and 2011. During March-July, both minor and major growing seasons were affected by moderate and severe droughts, which continued principally for the entire period and in the same area. Some differences between the years are observed for the extreme and exceptional drought intensities. They affected southern Kenya in 2009 and central in 2011, even though their duration was much shorter – one-two months for the extreme and one month for the exceptional. Early drought detection is the most important part of drought management and developing mitigation measures. Since there is no reliable drought prediction method, drought can be detected prior to its appearance from vegetation health dynamics. As seen in Fig 2F, the first signs of the approaching 2006-07 drought in southern Australia (for both VHI and TCI) appeared in March-April 2006, two months before the time series crossed down the 40's threshold (drought start) and vegetation was still in good health (VHI>50).

Special vegetation health products

Over the years of vegetation health verification and application for drought monitoring it has been revealed that VH methodology can be successfully applied for monitoring and prediction of crop yield and a risk of malaria (Kogan et al 2012, Rahman et al 2011). Testing VH indices in 19 countries of North America, South America, Africa, Europe and Asia revealed that yield of such crops as wheat (both winter and summer), corn, sorghum, rice and soybeans has strong correlation with the VH indices during the critical period of crops' growth, development and production formation. Figure 3A demonstrates these results. As seen, there is a strong correlation of mean Kansas (USA) corn yield with VCI and TCI during the critical period (strong response to weather) of corn development in July. During drought years (the indices <40), 25-35% corn production could be

lost (depending on drought severity) compare to normal weather years. For example in 2011, Texas drought slashed corn yield by 28% compared to the average for the last 10 years and 36% relative to the highest yield received in 2010 season (http://www.nass.usda.gov/Statistics_by_State/Texas/Charts_&_Maps/zcorn_y.htm).

Malaria risk area is estimated based on a combination of VCI and TCI values. Considering that warm and wet weather stimulates development and activities of mosquitoes in biting and transferring of malaria, above 60 VCI (moist) and TCI (moderately warm) were selected to indicate an enhanced malaria risk. Inversely to malaria–stimulated criteria, below 40 VCI (dry) and TCI (hot) would indicate drought conditions unfavorable for development of malaria. These criteria were compared to malaria statistics in several countries. A strong correlation was found between the number of malaria cases and regional VCI and TCI in India, South Korea, Bangladesh, Colombia, Senegal and Namibia (Kogan 2002, Rahman et al 2011). A few models were developed for early malaria detection, monitoring malaria area, intensity, and duration and also prediction of the number of people with malaria. Figure 3B shows the results of independent model validation in Caprivi province of Namibia indicating high correlation between observed and independently simulated malaria cases. Finally, Figure 3C shows two images of VH-estimated malaria risk in southern Africa with a smaller affected area in 2012 versus larger area in 2010.

Conclusions

During the warmest decade of the current millennium, droughts have continued to dominate the world climate with huge economic consequences and the largest affected area (compared to other weather disasters). All continents are affected by drought, especially those areas where annual precipitation does not provide enough water that thermal resources can potentially evaporate (difference between precipitation and potential evapotranspiration (P-PET) is negative). Even the areas where more annual precipitation is falling compared to PET ((P-PET)>0) droughts, although less intensive and frequent, occur as well. Droughts are originated from either moisture or thermal stress, but the worst droughts are developed from the both conditions. Some of the droughts during the discussed decade were extremely intensive, long and covered large areas (2010 in Russia and 2011 in Texas, USA). However, in the past, droughts of similar intensity, area, duration and impacts have already affected the same areas (1972, 1946 and 1921 in Russia, Dust Bowl during the 1930's in southern USA). Similar to the past, multi-year drought have been recorded during the decade after 2000. They affected strongly the Horn of Africa and Australia. Sometimes these droughts move from area to other areas (the early 1980's in sub-Sahara Africa). This article demonstrates a very good space method for drought detection, monitoring and VH-based drought products for impact assessment. Since a reliable method for drought prediction is not available, one of the most important products is drought detection 4 to 8 week prior to its strike (based on the tendency of vegetation health dynamics). Other drought products are estimation of drought area, intensity, duration, origination (moisture/thermal stress), changes over time and impacts. Also, of great importance are special VH products useful for estimation of crop yield and malaria risk. The indicated information is provided weekly for every 4 by 4 km area globally to the following NOAA web site: http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php and accessed by a few thousand users every month. Finally, it is important to emphasize that, as of the end of May 2012, VH indicates that, many world areas experience vegetation stress. They include western Taxes in USA, eastern Brazil, sub-Sahara Africa (including Horn: Kenya and Ethiopia), Ukraine (major crop area), Far East of Russia, part of southern Asia and southern Australia. Drought is continuing its paces.

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