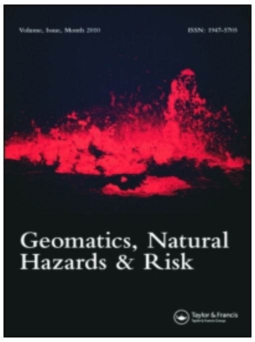

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Early twenty-first-century droughts during the warmest climate

FELIX KOGAN*† and WEI GUO‡
†Center for Satellite Applications and Research (STAR), National Environmental Satellite Data and Information Services (NESDIS), National Oceanic and Atmospheric Administration (NOAA), College Park, MD, USA
‡IM Systems Group, Inc., College Park, MD, USA

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The first 13 years of the twenty-first century have begun with a series of widespread, long and intensive droughts around the world. Extreme and severe-to-extreme intensity droughts covered 2%–6% and 7%–16% of the world land, respectively, affecting environment, economies and humans. These droughts reduced agricultural production, leading to food shortages, human health deterioration, poverty, regional disturbances, population migration and death. This feature article is a travelogue of the twenty-first-century global and regional droughts during the warmest years of the past 100 years. These droughts were identified and monitored with the National Oceanic and Atmospheric Administration operational space technology, called vegetation health (VH), which has the longest period of observation and provides good data quality. The VH method was used for assessment of vegetation condition or health, including drought early detection and monitoring. The VH method is based on operational satellites data estimating both land surface greenness (NDVI) and thermal conditions. The twenty-first-century droughts in the USA, Russia, Australia and Horn of Africa were intensive, long, covered large areas and caused huge losses in agricultural production, which affected food security and led to food riots in some countries. This research also investigates drought dynamics presenting no definite conclusion about drought intensification or/and expansion during the time of the warmest globe.

1. Introduction

The twenty-first century began with a series of widespread, long and intensive droughts around the world. Droughts of severe-to-exceptional (SE) intensity covered 7%–16% and extreme intensity – 2%–6% of the world land (Kogan et al. 2013). A wide range of economic and societal activities have been affected, especially agriculture, forestry, water, energy, ecosystems, transportation and recreation in multifaceted ways. These droughts had adverse consequences for societal sustainability since they reduced agricultural production, caused a misbalance between grain supply and demand, shortages of food, malnutrition, human health deterioration, poverty, regional disturbances, population migration and death. Global food security (GFS) was the twenty-first century's issue 8 years out of 13 when drought reduced global grain production (the main source of food and feeds for the world's population)

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*Corresponding author. Email: Felix.Kogan@noaa.gov below steadily grown consumption (PotashCorp 2012). Additional GFS concern arises from anticipated drought intensification, expansion and penetration to the new areas due to the current and future climate warming (Solomon et al. 2007). Since drought prediction is a challenging task, comprehensive global and regional drought watch is an important measure to detect drought-related crop and pasture losses early enough in order to offset drought consequences.

This feature article presents a travelogue of the twenty-first-century global and regional droughts during the warmest global and regional climate. The droughts were identified and monitored with the National Oceanic and Atmospheric Administration (NOAA) operational space technology, called vegetation health (VH). The VH is a comprehensive and accurate measure of vegetation conditions with a specific emphasis on drought watch and assessment of drought start/end, area, intensity, duration, origination and impact on the environment and socio-economic activities. The VH method has been developed from observations by the advanced very high resolution radiometer flown on NOAA operational afternoon polar-orbiting satellites since the late 1970s (Kogan 1997). Unlike many other satellite-based methods, the VH algorithm combines normalized difference vegetation index (NDVI) and brightness temperature (BT), and was validated by the users in 29 countries and applied real time globally in the recent 5 years (Kogan et al. 2011, 2012). These drought assessments are delivered every week to the NOAA website (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php). In 2012, this site was visited by nearly 45,000 users including policy- and decision-makers, commodity traders, farmers, relief organizations, scientists and others. The information in the form of digital data, colour-coded maps and 1981 to present time series characterize numerically drought features for each 4 km^2 of the global land, including continents, 192 countries and almost 4000 of the first-order administrative divisions. Besides drought, the Web contains weekly assessments of global VH, moisture and thermal conditions, no noise NDVI and BT, malaria risk, fire risk and excessive soil wetness. In writing this paper we pursue three goals (1) review global drought features and impacts during the warmest climate period, (2) investigate the past 33-year drought trend and (3) inform the users about the satellite-based products available for real-time drought detection and monitoring land cover and atmosphere near the ground.

2. Drought versus other natural disasters

Among natural disasters, drought is the most complex and least understood phenomenon because it is a multidisciplinary event which is affected by climate, weather, soil, ecosystem, surface/ground water, socio-economic and others. Drought prediction, an effective way to fight its consequences, is a very challenging task. Meanwhile, we have to deal with drought since it is a part of Earth's climate which occurs every year without warning, ignoring countries' borders, political and economic differences. Unlike other natural disasters, drought has many specific features: it begins unnoticeably, develops cumulatively, might continue for weeks, months and even years, 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 US, a high-technology country, drought is a “14-billion-dollar” annual event in terms of incurred losses (NCDC 2011). One of the worst droughts, in 1988, cost US taxpayers nearly 60 billion (Heim 2002). In the developing world, drought leads to food shortages, famine, malnutrition, population movement, mortality and unrests (1982–1984 droughts in sub-Saharan Africa). The characteristics of drought include start/end, area, intensity, duration, origination and impacts. Four general drought categories are recognized: meteorological, agricultural, hydrological and socio-economic, with metrics for their estimation (Wilhite & Glantz 1985).

3. Role of satellites for drought monitoring

There are a few methods of drought detection and monitoring. Weather, climate and hydrological data have been used traditionally as a drought tool. Precipitation, temperature, snow pack, reservoir level, ground water, soil moisture and crop yield are the most popular parameters for drought detection, monitoring and impacts estimation. Another instrument is weather/climate indices, such as Palmer drought severity index (PDSI, based on water balance), standardized precipitation index (based on probability of precipitations), US drought monitor (USDM, percentile metrics of five composite weather parameters), agricultural index (yield anomaly) and others (Heim 2002). There are a few important reasons for satellite data to be used. First, the weather station network is sparse, especially in climate, ecosystem and population marginal areas. For example, in Africa, the total number of 4 km^2 satellite observation pixels is 1800 times larger than the number of weather observing stations (from the World Meteorological Organization's [WMO] global telecommunication system). Currently, satellite technology has successfully filled in weather station gaps. Second, satellite data and indices provide cumulative (a very important property) numerical approximation of drought and its impacts. Third, in the past few years, advanced remote sensing techniques have proven their perfect utility for operational drought management and impact estimation as a separate and additional tool to weather data (Kogan et al. 2013). Finally, satellite drought monitoring was validated in many countries against *in situ* data (Kogan et al. 2012).

4. Vegetation health method

VH is a satellite-based three-channel numerical method for assessment of vegetation health (condition) including drought-related stress (Kogan 1997). The method stems from the properties of green vegetation to reflect and emit incoming sunlight. In drought-free years, green and vigorous vegetation reflects little light in the visible (VIS) part of solar spectrum (due to high light absorption by chlorophyll) and much in the near infrared (NIR) part (due to specificity of light scattering by leaf internal tissues and water content). As a result, the difference between NIR and VIS becomes large, indicating that vegetation is very green, vigorous and healthy. Drought normally depresses vegetation greenness and vigour (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 the construction of the normalized difference vegetation index [NDVI = (NIR − VIS)/(NIR + VIS)], which becomes widely used for environmental monitoring because it matches well with vegetation biomass, leaf area index and crop yield (Cracknell 1997, Kogan et al. 2012).

However, NDVI alone is not sufficient for monitoring VH and drought. Daytime temperature of vegetation canopy is an extremely important characteristic of changing conditions. Therefore, afternoon BT, calculated from the canopy emission in the 10.3–11.3 μm IR channel of solar spectrum, was added to the NDVI tool. But more importantly, high-frequency noise was removed from NDVI and BT and their values were expressed as a deviation from 32-year (1981–1993, 1995–2012) climatology. Climatology of NDVI and BT is a very essential part of the VH algorithm because the original parameters characterize two groups of environmental variables: long-term (climate, ecosystems, soils, etc.) and short-term (weather), where drought belongs to. Since the first group is a much stronger contributor to NDVI and BT values than the second, the long-term group signal was removed from these indices by normalizing them to their climatology, which was calculated based on the principles of the law of minimum, law of tolerance and carrying capacity (Kogan 1997). Processing of NDVI and BT data included producing weekly composite from daily observations for each 4-km^2 pixel, pre- and post-launch calibration of visible channels, non-linear correction of IR observations and converting them to BT, and complete removal of high-frequency noise (clouds, aerosols, viewing geometry, random, etc.) by statistical smoothing of their time series. Finally, following equations (1)–(3), climatology signal was removed from NDVI and BT, which were transformed to the vegetation condition index (VCI – a proxy for moisture conditions), temperature condition index (TCI – thermal proxy) and their combination – vegetation health index (VHI).

$$\mathrm{VCI} = 100 \times (\mathrm{NDVI} - \mathrm{NDVI}_{\mathrm{min}}) \times (\mathrm{NDVI}_{\mathrm{max}} - \mathrm{NDVI}_{\mathrm{min}})^{-1} \tag{1}$$

$$\mathrm{TCI} = 100 \times (\mathrm{BT}_{\mathrm{max}} - \mathrm{BT}) \times (\mathrm{BT}_{\mathrm{max}} - \mathrm{BT}_{\mathrm{min}})^{-1} \tag{2}$$

$$\mathrm{VHI} = \alpha \times \mathrm{VCI} + (1 - \alpha) \times \mathrm{TCI}, \tag{3}$$

where NDVI, $\mathrm{NDVI}_{\mathrm{max}}$, $\mathrm{NDVI}_{\mathrm{min}}$, BT, $\mathrm{BT}_{\mathrm{max}}$ and $\mathrm{BT}_{\mathrm{min}}$ are no noise weekly NDVI or BT and their 1981–1993, 1995–2012 absolute maximum (AMax) and absolute minimum (AMin). Since the AMax and AMin reflect the lowest and the highest values of NDVI and BT for each week during the 32-year observation period, they characterize the extreme thresholds of weekly NDVI and BT fluctuations due to weather variation. The Max–Min envelops, outlining these thresholds in the annual cycle, permit one to estimate if a particular year NDVI and BT are closer to AMin (the lowest greenness (equation (1)) and the highest BT (equation (2))) indicating vegetation stress or closer to Amax (highest greenness and lowest BT) indicating healthy conditions. Similar to climatic thresholds (average, minimum, maximum, etc.), the Amax–Amin envelop was named “climatology” relative to which each year’s week NDVI and BT are normalized for each pixel.

Each index was approximated from zero, characterizing extreme vegetation stress, to 100 – optimal conditions and was calculated on a weekly basis for each 4 km^2 land surface between 75° N and 55° S (Kogan 1997). Drought criterion was set when indices drop below 45, which is the level when crops and pasture yield start to decline either below the multi-year mean or long-term technological trend (Kogan 1997; Kogan et al. 2012). Finally, it is important to mention that VCI and TCI approximate weather variations compared to NDVI and BT, which represent more ecosystem spatial variation rather than weather temporal variations (Kogan et al. 2012, 2013). Regarding drought monitoring, VH indices identify drought start ($\mathrm{VH} < 45$), intensity (following USDM classification (Svoboda et al. 2002)), duration (number of days when $\mathrm{VH} < 45$), area (per cent of a region or an administrative division with

VH < 45 or lower thresholds for more intensive droughts), origination (from either moisture stress (VCI), or thermal stress (TCI), or both (VHI), which is the worst drought) and impacts (estimation of crop losses, water depletion, etc. based on models).

5. Droughts during the warmest years and impacts

During 2000–2012, many droughts (some unusual) affected very important agricultural regions of the northern hemisphere, especially in the last 3 years: the USA (2011, 2012), Kazakhstan (2012), Ukraine (2010, 2012) and Russia (2010). In some years these droughts were strong, long, covered large area and affected the environment, economies (especially agriculture) and human livelihood severely. The 2012 global drought area and intensity in the middle and at the end of the year are shown in figures 1 and 2. The impact of this drought on the central US environment and economy was enormous since it stimulated wildfires, water level reduction and yield losses (corn, soybeans, hay and pasture). The latter resulted in price increase for food and farmland (U.S. Drought 2012). The 32-year VH records show that such drought re-appears every 9–20 years (2002 in the western US, 1988 in the Great Plains) plaguing nearly 10% of the contiguous United States. In the opposite part of the world (Kazakhstan, Ukraine and southern Russia), the 2012 drought continued for 5–7 months, considerably reducing crop production when grain losses (compared

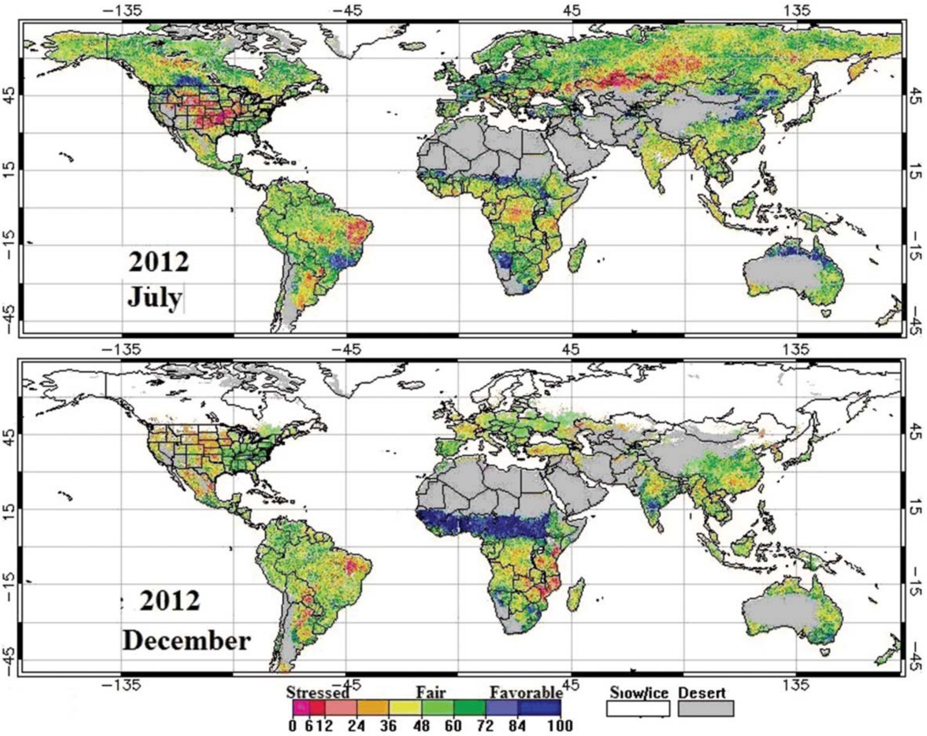

Figure 1. Drought-related vegetation stress in 2012 summers of northern (July) and southern (December) hemispheres.

to 2011) reached 20% in Russia and 50% in Kazakhstan (UNDP 2012). This drought has still continued in the USA at the end of 2012 (figure 1, December) and was observed during the growing season in the southern hemisphere (eastern Brazil, northern Argentina and a short time in southern Australia).

The 2011 US drought centred in Texas, Oklahoma and New Mexico affected also the neighbouring states (figure 2). In the two hardest hit states (Texas and Oklahoma), VH-estimated drought of exceptional (the strongest), severe-to-exceptional (SE) and moderate-to-exceptional (ME) intensity (USDM classification (Svoboda et al. 2002)) covered nearly 40%, 60%–70% and up to 100% of these states, respectively. Summer was the hottest on record and it is estimated that Texas would experience $5.2 billion in agricultural losses (AgriLife 2011). In addition, losses came from wildfires, depletion of water in lakes and reservoirs, a decrease in tourism, and deterioration of human health and way of living (Texas 2011).

The 2010 drought in Russia, Ukraine and Kazakhstan (figure 2) was very long, intense, covered a huge area and caused serious damages to the environment, economy and human health. The VH estimated that this drought began in early May, from intensive heat, which quickly depleted soil moisture and deteriorated VH

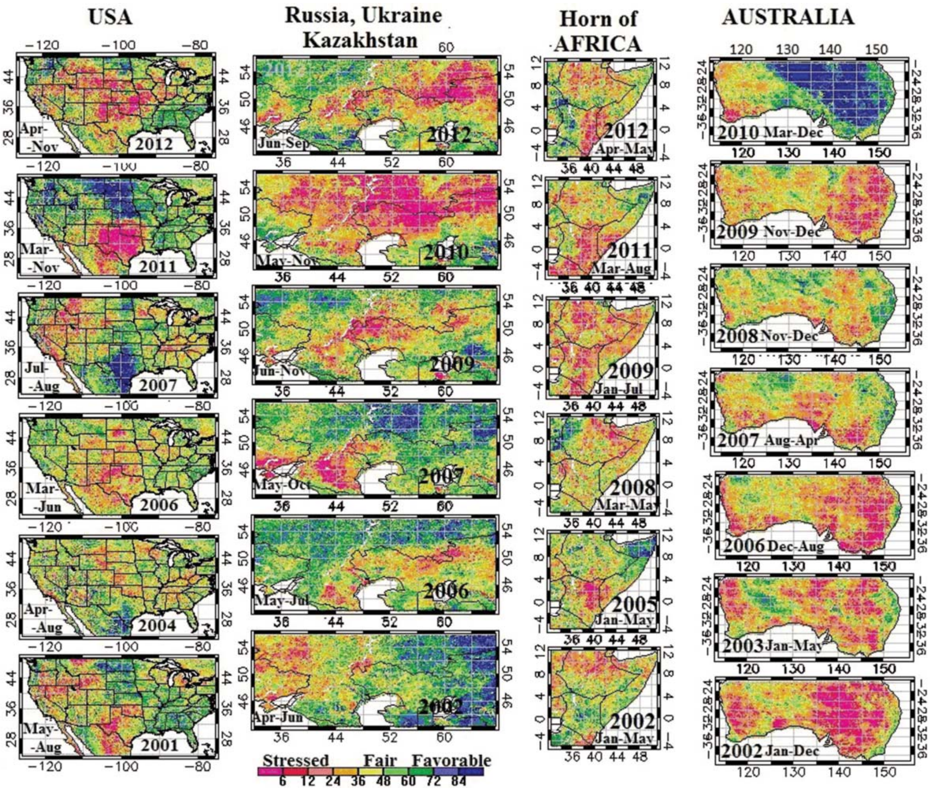

Figure 2. Regional vegetation stress during droughts of the twenty-first century. Each image shows drought area and intensity in a week of the peak drought development, monthly period indicates drought duration. Following USDM drought classification (Svoboda et al. 2002), moderate-to-exceptional (ME) and extreme-to-exceptional (EE) droughts were defined when VH was below 30 and below 10, respectively.

considerably. Russian grain production in 2010 dropped 23% to 75 million metric tons (compared to 97 in 2009, FAO 2011–2012) forcing the Russian Government to impose a grain embargo. This triggered a sharp increase in global wheat prices, which were the largest since 1973, when the former Soviet Union (FSU) purchased unexpectedly huge amount of grain from the international market (Kramer 2010). The 2010 drought triggered hundreds of fires and heavy smoke, deteriorating human health and increasing the death rate in Russia. This drought also affected the 2011 harvest, since winter wheat (occupy 65% of annual grain crops area) was planted in dry soil. Drought of such scale and impacts in Russia occurs every 25–40 years (1972, 1946, 1921 and earlier).

Other two unusual cases in the past 13 years are multi-year droughts in Australia and eastern (the Horn) Africa (figure 2). The Australian drought continued intermittently between 2002 and 2010. Southern and eastern Australia was the most affected (Queensland, New South Wales and Victoria). Very dramatic events occurred during a 17-month period (December 2005 to April 2007), when severe drought slashed water supplies, crops and rangeland production severely. The total VH-estimated drought area reached 70%, including a nearly 40% of the area reeling from extreme-to-exceptional (EE) intensity category. Following FAO (2011–2012), Australian wheat yield dropped 46% in 2006 and 37% in 2007 (below the 1960–2010 yield's trend). Another strong event was the 2002 drought, which reduced wheat yield by 45%. Other droughts in Australia produced smaller impact on agriculture because they were either shorter, or less intensive, or covered smaller areas.

The Horn of Africa is a very important area from the point of food security for a huge population. This area has two agricultural seasons March–May (minor) and June–September (major). Although the first one is the minor, it is still important for growing crops and providing food and feed until the major harvest becomes available. VHI estimated that during the current millennium, the Horn was affected by droughts almost every year (figure 2). The most dreadful droughts, affecting both seasons, occurred in 2009 (January–July) and 2011 (March–August) in Kenya. The drought of 2009 reduced wheat yield by 45%, as compared to 2010 (FAO 2011–2012). The 2002 and 2008 droughts were intensive and long and covered pastoral areas. Droughts of 2001, 2003, 2005, 2006 and 2012 affected the minor seasons and their impacts on food supply was limited since the major season's crop harvest was satisfactory.

Among other areas in the northern hemisphere, VH (not shown) indicated five summer droughts in Alaska (2004, 2005, 2007, 2009, 2011) and western USA (2002, 2004, 2006, 2007, 2011), which are accompanied by forest fires (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php). VH-derived vegetation stress was observed in India 3 years in a row (2001–2003) and in Mongolia 4 years in a row (2004–2007). In general, every 1–4 years, droughts cover eastern China and Mongolia (2009, 2010 and 2012). In the southern hemisphere, starting from 2004, crop areas in Argentina have been affected by drought every other year (2004, 2006, 2008, 2010 and 2012), which sometimes spreads to Paraguay and southern Brazil (2011–2012 and 2012–2013 summer), causing a reduction in soybeans production and wildfires (Terra Daily 2012).

Although the consequences of the 2013 world droughts have not been quantified yet, VH estimated that during the northern hemisphere growing season, ME and SE intensity droughts were observed on nearly 22% and 11% of the USA, respectively. Figure 3 shows July 2013 world areas which experienced moisture (VCI) and thermal

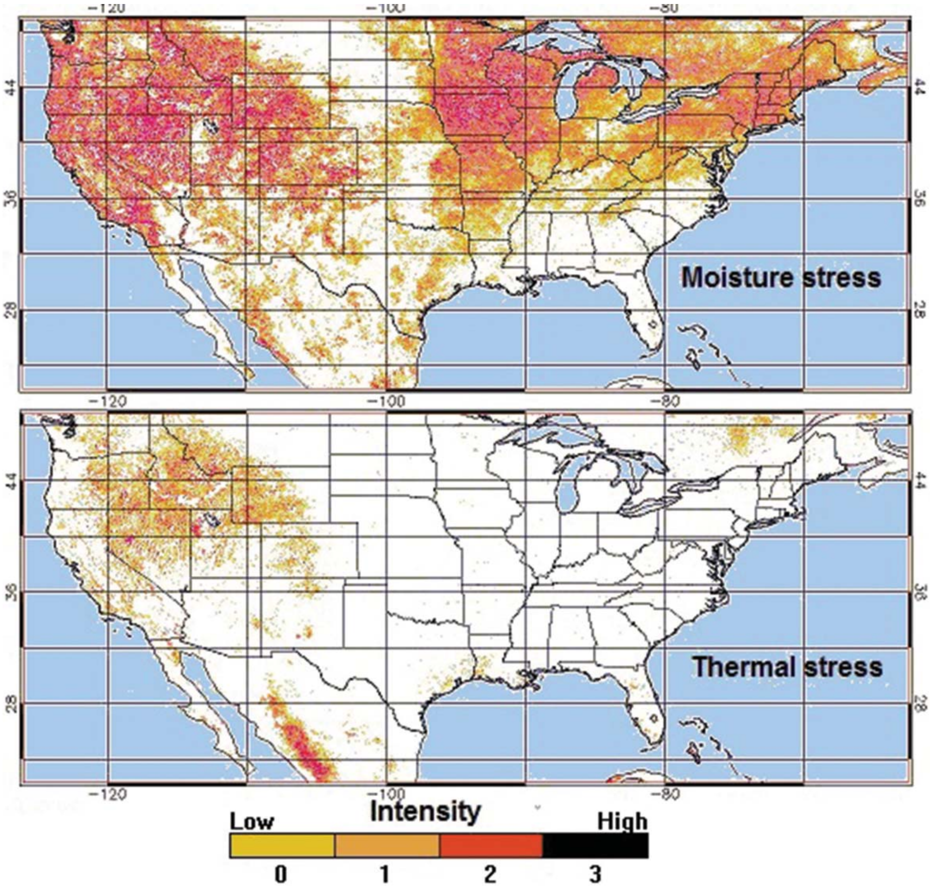

Figure 3. Drought-related moisture (VCI) and thermal (TCI) vegetation stress in July 2013.

(TCI) vegetation stress in these two categories. Again, the USA was the most severely affected during May–October when moisture deficit conditions were accompanied by stressful temperatures. Almost one-half of the USA was under ME and up to 20% under SE drought at some periods of the growing season. The 2013 US drought was different from the two previous years since it affected mostly western states depleting water resources and triggering wildfires. However, in some areas of Midwestern states this drought affected crop farmers and ranchers (C2ES 2013; Huffington Post 2013). The July 2013 moisture and thermal vegetation stresses were also observed in south-western Australia, southern Russia and western Kazakhstan. Some specific of the July 2013 weather is extreme thermal stress in the north (above 55° N) and south (below 30° S).

6. Drought dynamics during the warmest world

Figure 4 shows regional drought dynamics (expressed as a per cent of drought-affected area to the area of the entire region shown in figure 2) during the 32-year (1981–2012) period of the warmest globe, including the current millennium. The

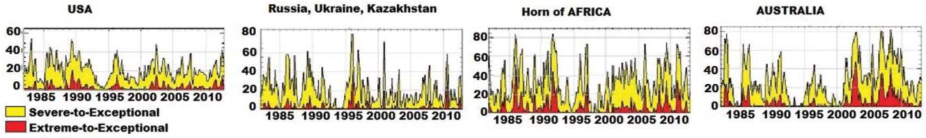

Figure 4. 1982–2013 dynamics of drought area and intensity (% from the area shown in figure 2).

upper line indicates all droughts from moderate-to-exceptional (ME) intensity and the lower line corresponds to the most severe droughts (EE). Following the analysis, no definite conclusion could be made about drought intensification or/and expansion in the two selected (ME and EE) categories in the discussed regions during the time of the warmest globe. And it is important to emphasize that the world in the last 100 years became 0.85° warmer and that one-third of this warmth occurred in the past 30 years (Solomon et al. 2007; IPCC 2012). It is noticeable that only in Australia the drought area increased from the early 2000 in both categories: for ME to 30% (from 20% during 1982–2002) and for EE to 10% (from 5%). For the combined area of major grain crops of southern Russia, Ukraine and northern Kazakhstan drought area shrunk slightly in both categories from the late 1990s. In the other two regions, drought area has not experienced any trend. No long-term-drought-area-change conclusion is also supported by the widely used PDSI dynamics over the past 60 years (Sheffield et al. 2013) and analysis of the 30-year VH data in Ukraine, although the mean Ukrainian temperature increased 1.5 °C over the last 50 years (Kogan et al. 2013). This discussion allows us to conclude that although the global temperature has increased almost 1 °C in the last 100 years, especially in the last 30 years (IPCC 2012) and regional temperature almost doubled the global temperature increase, changes in drought area and intensity are currently controlled by regional climate dynamics and human activities. In addition to drought dynamics discussion, we should also emphasize that the investigated regions showed some specifics in the covered drought area and intensity: ME drought rarely exceeded 50% of the contiguous USA, while it might exceed 50% in the Horn and 60% in southern Australia, especially during the current millennium; in the EE drought category, in the USA and the main grain area of the FSU (southern parts of European Russia, Ukraine and northern Kazakhstan) drought area was less than 10%, although the EE drought in 2010 occupied 38% of the FSU and 22% of the USA in 2012.

7. Conclusions

The advanced satellite-based VH technology indicates that during the current warmest period of the past 100 years, droughts have continued to dominate the world climate with huge agricultural losses and other economic consequences. Droughts of ME, SE and EE intensities covered 17%–35%, 7%–16% and 2%–6% of the total world area, respectively (Kogan et al. 2013). Only in the last 2 years drought occupied 33% of the world land in 2012 and 22% in 2013. Some of the twenty-first-century droughts in the US, FSU, Australia and Horn of Africa were extremely intensive, long, covered large areas and resulted in huge agricultural production losses, which affected food security and led to food riots in some countries. Besides agricultural losses, these droughts led to wildfires, depletion of water resources and others calamities. It is important to emphasize that prior to 2000, extremely intensive and large-area droughts have already affected the investigated areas (1988, 1996 in the USA; 1995 in Russia and Kazakhstan; 1986, 1993, 1997 in the Horn; 1982, 1986, 1992 in Australia). Regarding drought dynamics, satellite data indicate that in spite of the global temperature increase, especially in the last 30 years, changes in drought area and intensity are currently controlled by regional climate dynamics and human activities.

VH drought assessments and data-sets are provided every week to NOAA website (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php), covering the world, continents, 192 countries and nearly 4000 the-first order administrative divisions. The indicated website contains colour-coded maps and digital data of global VH, moisture and thermal conditions, no noise NDVI, BT and such products as drought and its change (including start/end, intensity, duration and origination), moisture and thermal conditions, malaria risk, fire risk and areas of excessive soil moisture. Following a popularity of VH Web, which is visited by 3000–4000 users every month and the results of VH data validation in many countries on all continents, we can conclude that this space method for drought detection, monitoring and impact assessment is reliable. Finally, this method will be considerably improved with observations from the new generation of operational satellite, called Suomi NPP (National Polar-orbiting Partnership) with many advanced sensors on board. The new visible infrared imager radiometer suite (VIIRS) has started to provide radiance measurements with much higher spatial (375 m) resolution and four times more spectral bands (compared to its predecessor). Besides, VIIRS is currently providing exceptional data quality due to on-board calibration of visible channels, narrow response function, sharper view and consequently, better quality NDVI, new vegetation indices (from mid-IR channels) and other products (net primary production, leaf area, vegetation fraction and others).

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