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Since 1990, the role of satellite observations for climate and land services increased considerably, especially with the introduction in 2011 of the new generation of NOAA operational satellites, called Suomi NPOSS Polar-Orbiting Partnership (S-NPP). S-NPP will continue as the Joint Polar Satellite System (JPSS) for the next two decades. The Visible Infrared Imaging Radiometer Suite (VIIRS) on the S-NPP spacecraft is accommodating the best technical and scientific features of its predecessors and has several new important features. S-NPP and JPSS, in addition to data collection, will address the impacts of climate and weather on industries, water, energy, population health, and other resources and activities. This article discusses how these operational satellites improve early drought detection, monitoring its features (intensity, duration, area, etc.) and prediction of agricultural losses; how fast the Earth's natural resources deteriorate; and whether the current warm climate intensifies droughts and increases its area and duration. These climate services have already become available to the global community (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php). The S-NPP/VIIRS data permits its users to enhance long-term environmental data records, thereby improving the ability to estimate global warming, land-cover changes, and better monitoring of environmental resources.

1. Introduction

Global warming, declining stock of natural resources, intensification of weather extremes, and land-cover changes in combination with a rapid population growth have recently raised the global community's concerns about future food supply/demand and global food security (GFS). In 8 years out of the first 15 years of the twenty-first century, GFS was decision-makers' concern, when global grain production (the main source of food and feeds for the Earth's population) dropped below a steadily grown consumption (PotashCorpo 2013). During these 8 years, droughts in the main grain-producing countries were the major cause of a negative balance between grain supply and demand (Kogan and Guo 2014). Currently, additional GFS concern arises from anticipated drought intensification, expansion, and penetration to new areas following global warming (Gillins 2014; Solomon et al. 2007).

Unfortunately drought occurs every year, occupies large areas, affects many people, and is the most costly disaster (NCDC 2011). To address drought monitoring, prediction, and impact assessments, the world community needs a reliable, accurate, and real-time climate and weather monitoring system, which is based on observations from operational satellites (having served global communities for the past 35 years). In 2011, a new era of

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operational satellites started with the launch of the Suomi (last name of Verner Suomi to honour his contribution to environmental satellites) Polar-Orbiting Partnership (SNPP) satellite. The SNPP is the first risk-reduction mission of operational environmental spacecrafts, which will continue as Joint Polar Satellite System (JPSS) for the next two decades. The scientific objectives of the JPSS are to improve weather forecasts, climate, and water services (especially severe events); to provide better the Earth's ocean, atmosphere, and land observations and monitoring capabilities; to develop new products and applications; and to continue enhancing long-term environmental data records. New JPSS benefits will also include the improvement of public health and safety, better monitoring of crucial resources (energy, agriculture, health, water, etc.), homeland security, environment (land and climate change, diversity, tourism, etc.), military support, weather disasters watch, and others (JPSS 2014).

This article discusses how the new operational satellites and sensors will enhance observations from the previous generation of operational and scientific satellites and improve climate, land cover, and food security services, specifically early drought detection and monitoring of its unique features, such as intensity, duration, area, and impacts. One of the important topics of this discussion will focus on the prediction of drought-related agricultural losses in advance of harvest and the estimation of food shortages in order to avoid regional disturbances and political instability. The discussion will also focus on the continuity of space observations and the development of several decades of data records.

2. SNPP/VIIRS

SNPP has five sensors: Visible-Infrared Imaging Radiometer Suite (VIIRS) to observe ocean atmosphere and land; Cross-track Infrared Sounder (CrIS) for three-dimensional measurements of temperature, pressure, and moisture profiles; Advanced Technology Microwave Sounder (ATMS); 22-channel cross-track scanner, to retrieve sounding observations; Ozone Mapper Profiler Suite (OMPS), to measure total-ozone and ozone-profile; and Clouds and Earth's Radiant Energy System (CERES) to measure solar-reflected and Earth-emitted radiation from the top of the atmosphere to the Earth's surface. The next plan is to launch JPSS-1 in 2017 with VIIRS, CrIS, ATMS, OMPS, CERES, and JPSS-2 during 2023–2025 with VIIRS, CrIS, ATMS, and OMPS (JPSS 2014).

The VIIRS is one of the principle S-NPP instruments used for the estimation of the impacts of the Earth's environment on socioeconomics. One of the primary components of this service is drought detection, monitoring, prediction of drought-related agricultural losses, and the assessment of food security. The VIIRS accommodated the best technical and scientific features of its USA's predecessors: the three and a half decades of the Advanced Very High Resolution Radiometer (AVHRR) on NOAA polar-orbiting operational satellites (POES) and the nearly 15 years of Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's TERRA and AQUA scientific satellites.

Similar to its predecessors, VIIRS flies in a polar, Sun-synchronous orbit, collecting afternoon data to measure the highest daily temperature, which is very important for drought monitoring. It will provide multi-year services vital for land-cover and climate change detection (Table 1). Significant VIIRS observation improvements (Table 1) include a 1.3 times wider swath, a sharper view of the swath edge, multiple spectral channels, higher spatial resolution, excellent radiometric features, faster data processing,

Table 1. SNPP/VIIRS compared with predecessors (POES/AVHRR and AQUA/MODIS).

Similarity	Improvement
Operational	Higher resolution
Multi-year services	Narrow response function
Polar-orbiting	Swath wider
Afternoon	Swath edge sharper
Sun-synchronous orbit	More channels
Land channels	Immediate data availability
	Higher data accuracy
	Data continuity

and the availability of new products and services (JPSS 2014; Kuciauskas et al. 2013; Solbrig and Lee 2013). Among the numerous VIIRS improved and new products (daytime and night-time low clouds, light emission, sea surface temperature, aerosols, elevated dust, land cover, ocean colour, chlorophyll concentration, moonlight, volcanic activities and ash dispersion, wildfires, snow–cloud discrimination, etc.), enhanced high-resolution drought detection and monitoring will improve the prediction of its detrimental consequences for agriculture, economics, ecosystems, energy, human health, recreation, transportation, and water resources management.

VIIRS provides observations in 22 reflective and emissive bands, with five of them, called imagery bands, having the highest 375 m spatial resolution, and the rest, moderate bands, with 750 m resolution. The moderate bands are used for such products as aerosol, cloud, ocean colour, snow, sea surface temperature, fire detection, etc. Imagery bands are used for land-surface reflectance/emission, cloud, snow/ice, Normalized difference vegetation index (NDVI), vegetation health (VH) indices, etc. (JPSS 2014). VIIRS observes the entire world's land, between 180° W and 180° E and between 55° S to 75° N, every day. Since the data volume is massive, it is collected and processed by subregions (granules, total 64 for the world) 45° W–E by 16° 30′ N–S each. VIIRS acquires 330 Mb/min data and 2.3×10^9 grids day^{-1}. The total number of optimally processed world grid cells is approximately 36×10^6 at 500 m spatial resolution.

For the purposes of high-resolution drought and land-cover and climate changes monitoring, the VIIRS land and climate products were developed from three emissive bands, I1 (visible), I2 (near-infrared (NIR)), and I5 (infrared (IR)), whose characteristics are shown in Table 2. A brief algorithm from data reading to product development consists of a few important steps such as the retrieval of orbital granule data, projecting each granule's pixels data to a 500 m grid's (set up as an optimal standard) orbit map, selecting pixels close to the centre of the grid and close to nadir, filling gaps, producing daily maps for I1,

Table 2. Characteristics of VIIRS imagery bands.

Type	Band	Wavelength (μm)	Spatial resolution at nadir (m)	Spatial resolution at edge (m)
Reflective	I1	0.600–0.680	375	800
Reflective	I2	0.846–0.885	375	800
Reflective	I3	1.580–1.640	375	800
Emissive	I4	3.550–3.930	375	800
Emissive	I5	10.500–12.400	375	800

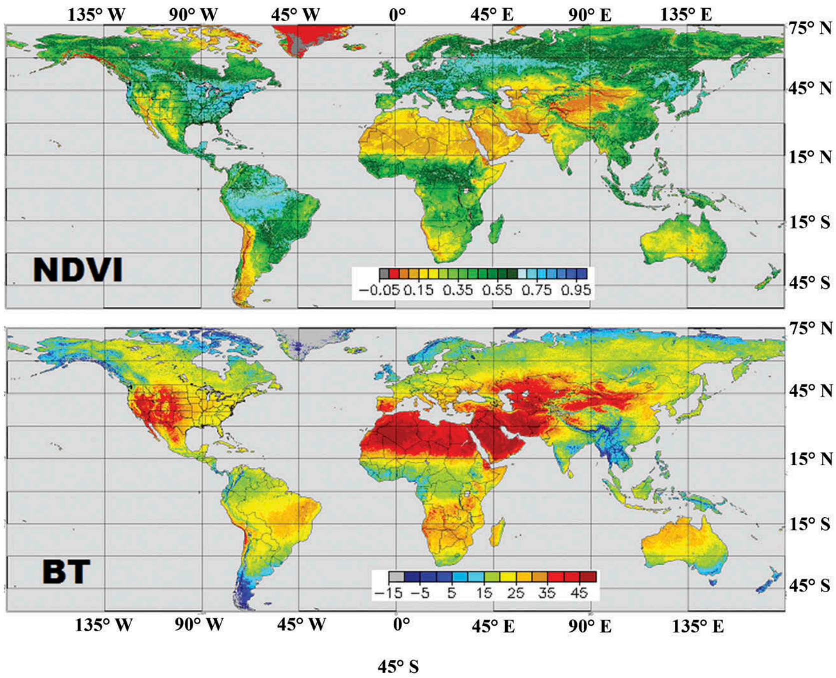

Figure 1. SNPP/VIIRS weekly composite normalized difference vegetation index and brightness temperature (°C) for 8–14 July 2013.

I2, and I5, radiance calibration, calculation of daily NDVI ((NDVI) = (I2 – I1)/(I2 + I1)), conversion of I5 emission to brightness temperature (BT), production of weekly NDVI and BT maps (based on NDVI's maximum value composite technique), and suppression of high-frequency noise. Figure 1 shows no noise weekly composite SNPP/VIIRS NDVI and BT sampled data.

3. Continuity of data records

As was mentioned above, the longest (35 years) high spatial (4 km) and temporal (7-day composite) resolution data records were developed from NOAA/POES. From the current POES in space, the NOAA-19 is still providing excellent observations of reflectance/emission, which has been converted to climate products (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php), and has been used successfully by thousands of world users. However, NOAA-19, launched in 2009, has reached its life expectancy and its AVHRR data might deteriorate soon, requiring a complete switch to SNPP/VIIRS currently and later to JPSS/VIIRS. One of the principle questions for this switch (considering the sensors' differences) is whether POES/(AVHRR)'s 35-year data records can be continued using VIIRS observations.

Our investigation, comparing simultaneous records from the POES/AVHRR and SNPP/VIIRS, showed that in order to keep continuity of these data, some adjustments are needed. As seen in Figure 2(*b*), the differences between AVHRR and VIIRS NDVI are considerable (global correlation line shifted up from the 1-by-1 line), because of the differences in the NIR spectral response function (SRF). The VIIRS collects reflectance

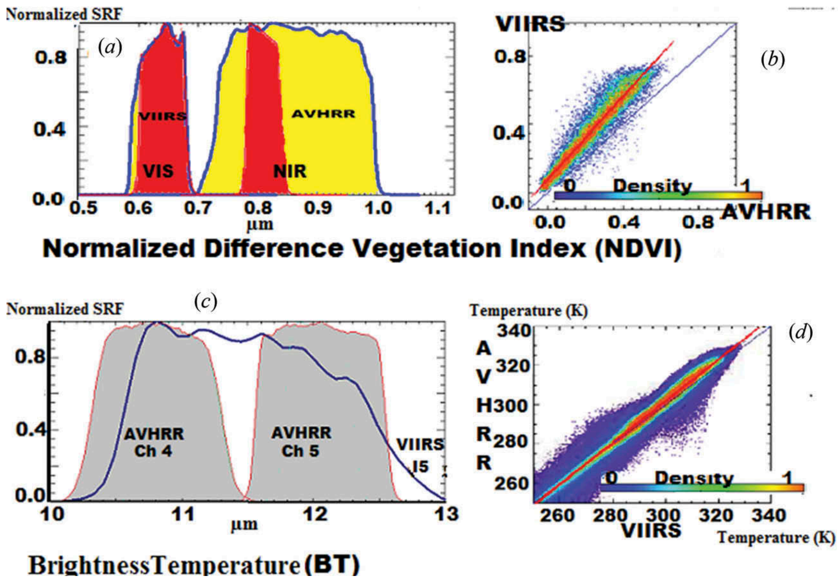

Figure 2. VIIRS and AVHRR spectral response function for visible (VIS), near-infrared (NIR), and infrared (IR) channels (*a* and *c*) and correlation between VIIRS and AVHRR NDVI (*b*) and BT (*d*).

data from narrower NIR bandwidths (Figure 2(*a*)) producing much higher reflectance values. Although the VIS data for both sensors are collected from almost the same bandwidths, resulting in almost equal reflectance values, VIIRS NDVI is nearly 30% higher than AVHRR. Similar results were obtained for the other narrow bandwidth sensors (Gonsamo and Chen 2013; Trishchenko, Cihlar, and Li 2002). Following these considerations, VIIRS NDVI should be adjusted to AVHRR NDVI to keep the continuity of a 35-year time series.

In contrast to NDVI, global AVHRR's versus VIIRS's BT correlation line almost coincides with the 1-by-1 line, although for the 310–340 K interval, the line is slightly shifted to the higher AVHRR-measured BT values (Figure 2(*d*)). These differences are also related to the dissimilarity in IR's SRF (Figure 2(*c*)). The AVHRR sensor has been collecting data from two IR bandwidths: 10–11 µm (Ch 4) and 11–12 µm (Ch 5), from which only Ch 4 was used for modelling the vegetation canopy's BT, as being less contaminated by atmospheric moisture. VIIRS collects high-resolution IR data from the entire 10–12 µm spectral range, providing slightly smaller BT values because atmospheric moisture in the 11–12 µm diapason slightly attenuates NIR and BT. To answer the question of whether VIIRS BT should be adjusted to AVHRR BT for maintaining continuity of data records, additional investigation indicated (Figure 3) that for many ecosystems the difference between these values could be considerable (1.5–4 K), except for deciduous forests (0–1.5 K) during summer in both hemispheres.

NDVI and BT adjustments are also warranted by the facts that during the entire period of simultaneous two-sensor observations (September 2012–September 2013), the correlation between NDVIs and BTs in the principal global vegetation area (between longitude 180° W and 180° E and latitude 40° S and 40° N, containing nearly 1,000,000 4 km pixels) was very high and stable over time (Figure 4, Pearson correlation coefficient is 0.96 for NDVI and 0.95 for BT at the end of the indicated period). The slope of linear

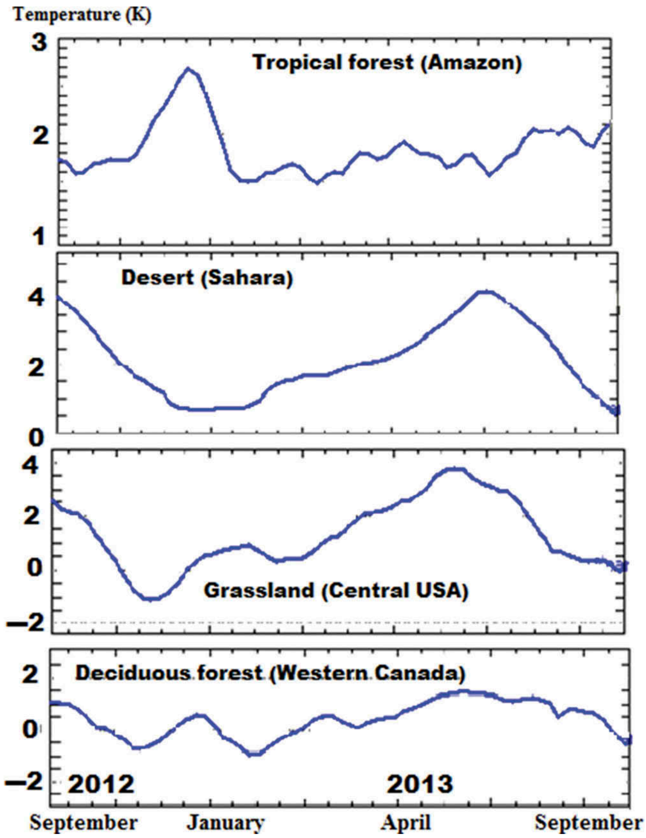

Figure 3. Difference between AVHRR BT and VIIRS BT (in kelvin) for different ecosystems during September 2012 and 2013. (Amazon Basin: lat [−7.743, 0.78], lon [−71.34, −57.77]; Sahara: lat [20.04, 29.51], lon [−6.95, 33.46]; western Canada: lat [53.8132, 59.4951], lon [−125.950, −113.007]; central USA: lat [37.083, 40.2397], lon [−101.644, −94.6989]).

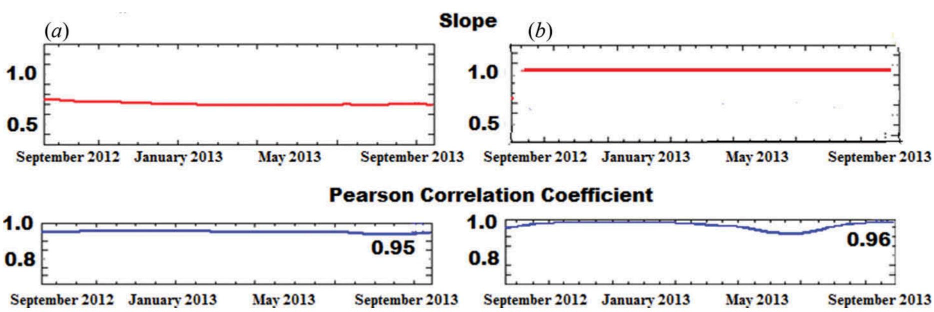

Figure 4. Dynamics of slopes and Pearson correlation coefficients during the period September (week 35) 2012 to November (week 47) 2013 for linear regression of (*a*) weekly AVHRR-NDVI versus VIIRS-NDVI and (*b*) AVHRR-BT versus VIIRS-BT.

regression is stable as well, with a mean value of 0.702 for NDVI and 1.047 for BT (the intercept for BT fluctuates depending on the season). The VIIRS to AVHRR adjustments would require the reduction of VIIRS NDVI by around 30% and an increase of VIIRS BT

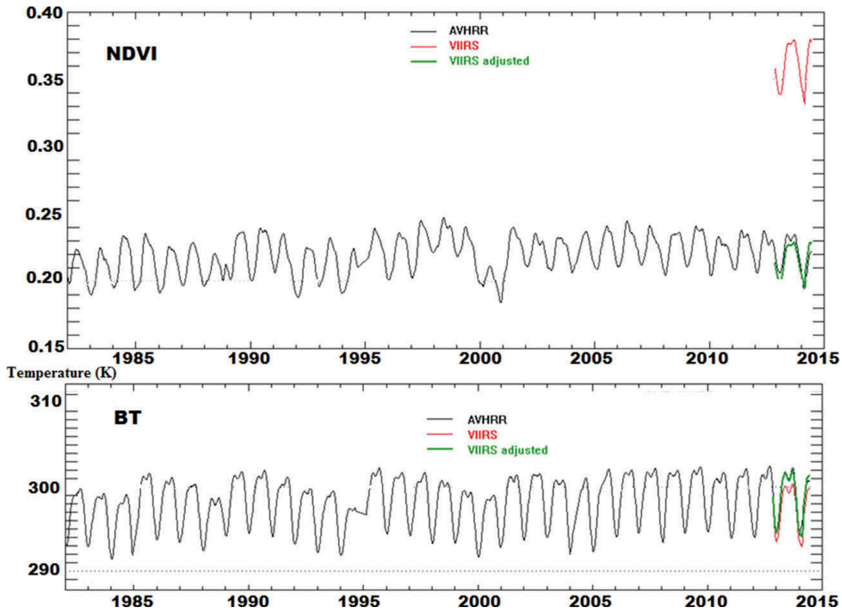

Figure 5. Global (180° W – 180° E and 45° S – 45° N) mean weekly NDVI and BT time series during 1981–2014 from AVHRR overlaid with 1.8 years (week 23 2013 to week 20 2014) of VIIRS indices original and adjusted to AVHRR values.

by approximately 1–4 K. Figure 5 demonstrates 34-year global (180° W – 180° E and 45° S – 45° N) mean NDVI and BT time series combining AVHRR 1981–2014 weekly records with the 1.8-year (week 23, 2013 to week 20, 2014) VIIRS records for original and adjusted values.

4. Improvements in drought monitoring

Drought is one of the most important environmental disasters affecting GFS. During the twenty-first century, eight out of 15 years, large-scale droughts were responsible for GFS deterioration, resulting in huge losses of grain and its global production fell below steadily growing consumption (PotashCorpo 2013). Currently available VIIRS data can considerably improve drought detection and monitoring, helping to provide advanced warnings on potential crop losses, especially if drought affects the major producing countries, as was the case in 2012, when drought covered the major USA corn area and considerably reduced its production. Advanced predictions of drought-related crop losses in the developing world might lead to forward metrics on the needed food assistance to avoid humanitarian crises.

The VH methodology is currently used at NOAA and will be applied to SNPP/VIIRS data, which will gradually replace AVHRR-based NOAA-19 observations. The VH method has been successfully used since 2005 with the old generation of NOAA operational satellites (Kogan and Guo 2014; Kogan, Adamenko, and Guo 2013; Kogan et al. 2013), providing real-time and historical data and products (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php) through the NOAA web. The 2012 and 2013 tests of the SNPP/VIIRS data showed advantages in more accurate drought detection and assessment of its spatial distribution, intensity, impacts on crops, and prediction of their losses.

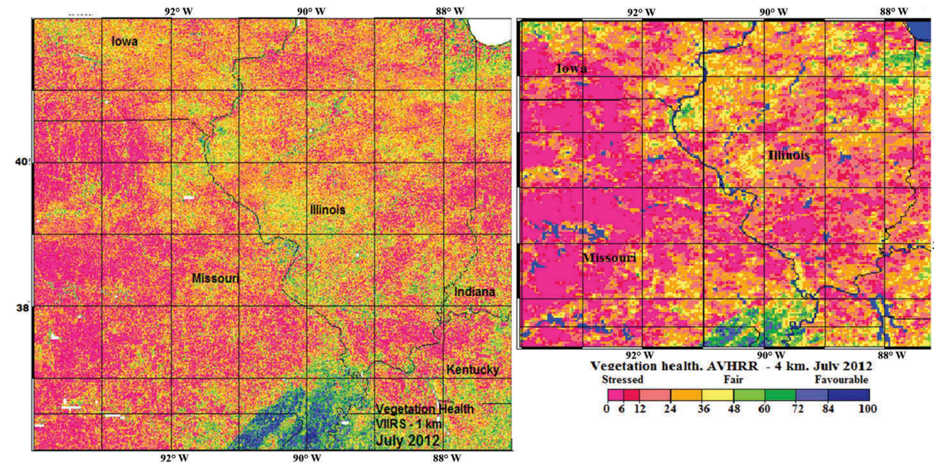

Figure 6. Vegetation health SNPP/VIIRS 1 km versus NOAA/AVHRR 4 km, 22 July 2012, northeastern part of Great Plains, USA.

One of the examples for spatial drought improvement is shown in Figure 4. The VH method is currently going through improvements that will be applied to SNPP/VIIRS, considering the difference between the old and new generations of operational satellites mentioned earlier (Tables 1 and 2).

Although the VH-based SNPP/VIIRS system is still going through testing (data calibration, adjustment, and validation), some advantages of the new system have already been observed and are discussed further. Figure 6 demonstrates one of the most important improvements in SNPP/VIIRS operational capabilities in spatial drought monitoring. Following much higher data resolution and better data quality due to the wider swath and sharper view of the swath edge (obtained by constraining the pixel dimensions to within a factor of two from nadir to scan edge compared to the six-fold factor of pixel growth for old systems), more pixels become available for filling the gaps and improving the accuracy of data sampling and mapping. As a result, VIIRS VH and drought products currently provide more accurate assessments of vegetation stress compared to the old sensor. Although drought and vegetation stress pattern areas for the new and old sensors are similar, the SNPP/VIIRS 1 km image shows that at the background of a very intensive vegetation stress in 2012 over southern Iowa, northern Missouri, and Illinois, this stress was weaker along rivers (yellow and green areas on the image). This improvement can provide a more accurate assessment of drought impacts on crop losses on a limited area, including small farms, which is important for regional food security.

The VH methodology will also provide advanced warnings on drought start, area, intensity, and duration, which is important for making the best decisions on drought impact in advance of its start and developing measures to mitigate the negative consequences. Figure 7 demonstrates these features: following (7*a*), moisture conditions in May 2012 were favourable (VCI > 60), whereas intensive thermal stress (thermal conditions from TCI < 20) during May–July evaporated much spring water, thereby deteriorating moisture conditions considerably. This resulted in a stable decline of VCI from 80 (indicated by #1) to 40 (#2 indicates the beginning of moisture stress and drought). The period of stable deterioration from favourable conditions to drought beginning and beyond (red error) continued for approximately 5 weeks, providing a 5-week advance

(*a*)

(*b*)

(*c*)

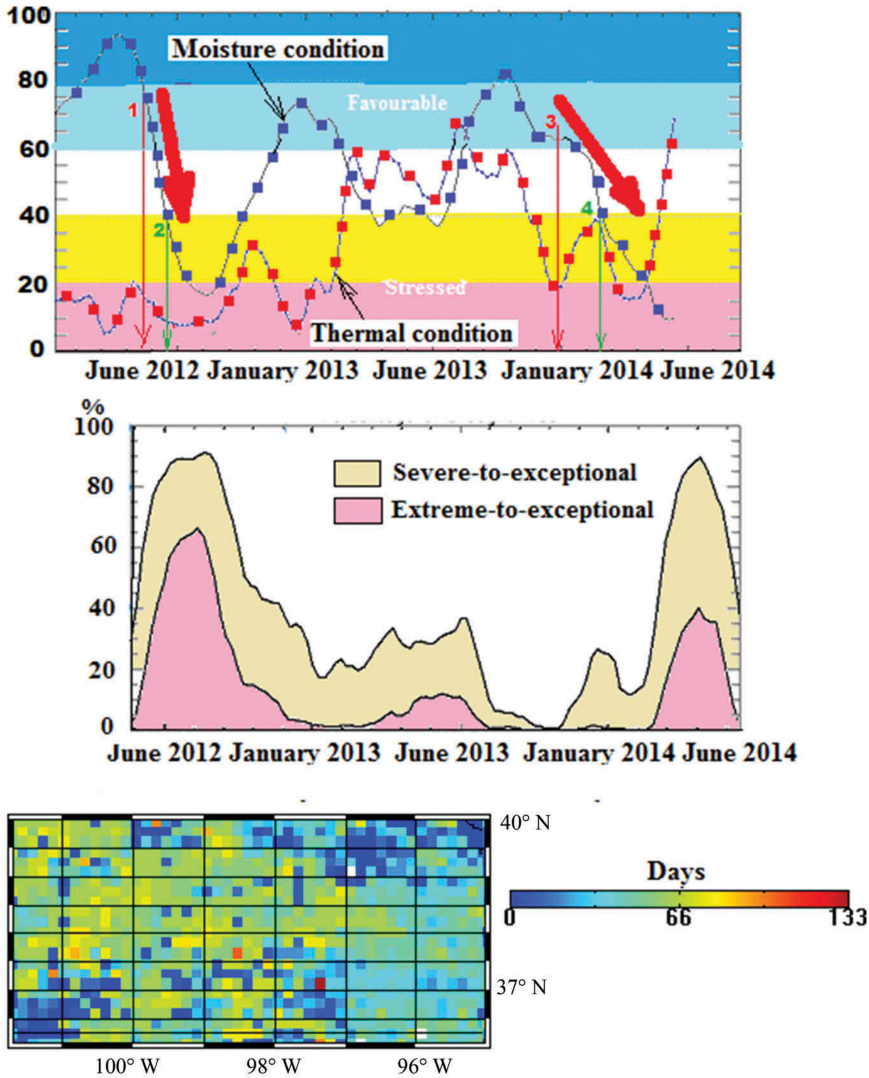

Figure 7. Dynamics of (*a*) moisture (VCI) and thermal (TCI) conditions; (*b*) percentage drought area of two intensities during June 2012 to June 2014; and (*c*) number of days with moisture-based severe-to-exceptional drought during March–July 2012, Kansas, USA. Explanation of notations in Figure (*a*): thin red arrows and red numbers of 1 (June 2012) and 3 (January 2014) indicate the beginning of moisture condition deterioration; thin green arrows and green numbers of 2 (July 2012) and 4 (early March 2014) indicate the beginning of moisture stress (VCI <40); thick red arrow indicates the direction of moisture deterioration starting from the period of favourable moisture conditions (VCI above 60) and continuing to the beginning of moisture-based vegetation stress (VCI below 40). Data were sampled from 375 m to 4 km resolution for better display.

warning of drought start. A similar situation with drought prediction was observed between January and April 2014 (#3, 4, and red arrow), although in May and early June, thermal conditions improved and some recovery from moisture stress will be expected. Figure 7(*b*) indicates that in 2012, 65 and 95% of Kansas area was under severe-to-exceptional and extreme-to-exceptional vegetation stress (drought), respectively,

which continued in some areas 60–80 days between March and July 2012 (Figure 7(*c*)). Such severe, long, and large-area drought resulted in 68% losses of corn yield (estimated relative to the 1975–2011 yield time series trend (Hoerling et al. 2014; FDD 2013)).

5. Conclusion

In 2011, the new era of operational environmental spacecrafts started with the launch of the SNPP NOAA operational satellite, which will be continued for the next two decades as the JPSS system. The VIIRS, one of the major new sensors on board these satellites, is showcasing the best technical and scientific features compared with its predecessors, both operational and scientific. Meanwhile, VIIRS has new features such as wider swath, sharper view at the swath edge, multiple spectral channels, higher spatial resolution, excellent radiometric features, faster data processing and availability, better data quality, and faster data delivery, which will improve climate, weather, land, water, and socio-economic services.

One of the many advantages of VIIRS is the improvement in drought detection and monitoring of its area, intensity, duration, origination, and impacts. The VH methodology has been applied to VIIRS data from May 2012, showing considerable improvement in monitoring vegetation condition and drought. It has been found that the new system provides more precise drought spatial resolution, leading to a more accurate assessment of crop losses. These features are very important since large-scale drought reduces global agricultural production every 3–5 years, causing a misbalance between crop production supply and demand, which leads to shortages of food, human health deterioration, poverty, regional disturbances, population migration, and death (Hoerling et al. 2014; PotashCorpo 2013; FDD 2013). The new generation of operational satellites permits its users to enhance long-term environmental data records, thereby improving the ability to estimate global warming, land-cover changes, and better monitoring of environmental resources.

Although the SNPP/VIIRS system is still going through testing (data calibration, adjustment, and validation), it is already clear that the new data will be used for the development of new products, which will considerably improve climate, weather, water, and socio-economic services. Among them, there will be an enhanced drought watch, including up to 2 months advanced drought detection in the area of 500 m, with the shortest temporal interval. Moreover, data will be calibrated to provide modelling agricultural production and assessment of crop losses up to 3 months ahead of harvest. Forestry will benefit from the prediction of fire danger or risk and the crop ecosystems will benefit in the estimation of areas saturated with water from excessive rainfall and expected crop losses. An enhanced quality of VIIRS data will be used for monitoring climate forcing (e.g. ENSO) impacts on land cover and productivity and also for regional and global assessments of climate and land-cover changes, which is important for the prediction of degraded environmental resource. Improvements are expected in the area of mosquitoes-borne diseases, specifically their early detection, assessment of risk, intensity, area under threat, and the number of affected people. Such important parameters in plant process modelling as the fraction of photosynthetic active radiation (FPAR) and leaf area index (LAI) will be measured with greater accuracy. VIIRS data of moderate resolution will also be used to improve such traditional land parameters as NDVI and BT. SNPP/VIIRS vegetation health data (VHP) will be available for download for the entire globe by the end of 2015 from the NOAA's CLASS and pub ftp server (ftp://satepsanone.nesdis.noaa.gov/VHP/VVHP/ and http://www.class.ngdc.noaa.gov/saa/products/welcome).

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