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Source: Environmental Health Insights, 9(s2)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/EHI.S19590

Monitoring the Impacts of Wildfires on Forest Ecosystems and Public Health in the Exo-Urban Environment Using High-Resolution Satellite Aerosol Products from the Visible Infrared Imaging Radiometer Suite (VIIRS)

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Supplementary Issue: Ecosystem Services and Environmental Health

ABSTRACT: Increasing development of exo-urban environments and the spread of urbanization into forested areas is making humans and forest ecosystems more susceptible to the risks associated with wildfires. Larger and more damaging wildfires are having a negative impact on forest ecosystem services, and smoke from wildfires adversely affects the public health of people living in exo-urban environments. Satellite aerosol measurements are valuable tools that can track the evolution of wildfires and monitor the transport of smoke plumes. Operational users, such as air quality forecasters and fire management officials, can use satellite observations to complement ground-based and aircraft measurements of wildfire activity. To date, wildfire applications of satellite aerosol products, such as aerosol optical depth (AOD), have been limited by the relatively coarse resolution of available AOD data. However, the new Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on the Suomi National Polar-orbiting Partnership (S-NPP) satellite has high-resolution AOD that is ideally suited to monitoring wildfire impacts on the exo-urban scale. Two AOD products are available from VIIRS: the 750-m × 750-m nadir resolution Intermediate Product (IP) and the 6-km × 6-km resolution Environmental Data Record product, which is aggregated from IP measurements. True color (red, green, and blue [RGB]) imagery and a smoke mask at 750-m × 750-m resolution are also available from VIIRS as decision aids for wildfire applications; they serve as counterparts to AOD measurements by providing visible information about areas of smoke in the atmosphere. To meet the needs of operational users, who do not have time to process raw data files and need access to VIIRS products in near-real time (NRT), VIIRS AOD and RGB NRT imagery are available from the Infusing satellite Data into Environmental Applications (IDEA) web site. A key feature of IDEA is an interactive visualization tool that allows users to display tailored combinations of AOD and RGB imagery, as well as overlay the VIIRS smoke mask and fire hotspots at pixel resolution (~750-m × 750-m), and zoom into the county level. Two case studies of recent wildfires in the Western US are presented to show how operational users can access and display VIIRS aerosol products to monitor the transport of smoke plumes and evolution of fires in the exo-urban environment on the regional and county scales. The new National Oceanic and Atmospheric Administration (NOAA) Western Region Fire and Smoke Initiative is also discussed, which will enhance IDEA to allow visualization of VIIRS aerosol products down to the neighborhood scale. The new high-resolution VIIRS aerosol products can be used for NRT monitoring of human exposure to smoke, and they can be used to gauge the spread of fires and, thus, provide advanced warning for evacuations and fire suppression efforts, thereby reducing risks to human populations and forest ecosystems in the exo-urban environment.

KEYWORDS: remote sensing, aerosols, atmosphere, urbanization, wildfires, air quality

SUPPLEMENT: Ecosystem Services and Environmental Health

CITATION: Huff et al. Monitoring the Impacts of Wildfires on Forest Ecosystems and Public Health in the Exo-Urban Environment Using High-Resolution Satellite Aerosol Products from the Visible Infrared Imaging Radiometer Suite (VIIRS). *Environmental Health Insights* 2015:9(S2) 9–18 doi: 10.4137/EHI.S19590.

RECEIVED: February 04, 2015. **RESUBMITTED:** March 29, 2015. **ACCEPTED FOR PUBLICATION:** March 30, 2015.

ACADEMIC EDITOR: Timothy Kelley, Editor in Chief

TYPE: Technical Advance

FUNDING: This work was funded in part by National Oceanic and Atmospheric Administration (NOAA) grants NA11NES4400009 and NA11NES4400005. The authors confirm that the funder had no influence over the study design, content of the article, or selection of this journal.

COMPETING INTERESTS: Authors disclose no potential conflicts of interest.

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Introduction

The spread of urbanization into exo-urban environments is bringing increasing numbers of people into contact with natural hazards, such as wildfires. For example, in 2000, 37 million (approximately one-third) of homes in the US were located in what has been termed the Wildland-Urban Interface (WUI).[1,2] The WUI is land that is situated in and near forests and other wildlands and that is susceptible to wildfires.[3] As the exo-urban environment has spread into the WUI, where homes and property are vulnerable to wildfires, the costs of wildfire suppression have steadily risen.[4] Figure 1 shows that while federal costs of wildfire suppression were limited

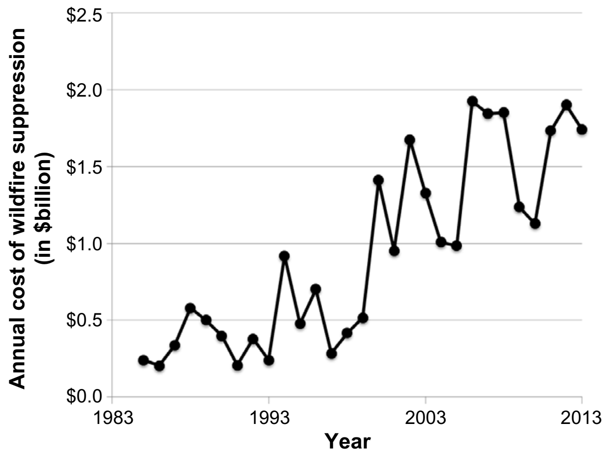

Figure 1. Annual cost of wildfire suppression in the US by the federal government in billions of dollars.[4]

AQI value	AQI category	AQI color
0–50	Good	Green
51–100	Moderate	Yellow
101–150	Unhealthy for Sensitive Groups	Orange
151–200	Unhealthy	Red
201–300	Very unhealthy	Purple
301–500	Hazardous	Maroon

Figure 2. US EPA's air quality index (AQI). The AQI is a dimensionless, color-coded scale that communicates the relative hazards of ambient air pollutants, including O_3 and $PM_{2.5}$.[9]

to <$1 billion per year in the 1980s and 1990s, they have fluctuated between $1 and $2 billion per year since 2000.[4] The costs of damage from wildfires is often >$1 billion per fire in property loss and damage and can easily be 10% of the national total for a given year.[5] The rising costs of wildfire suppression and property damage are indicative of the spread of human populations into areas at risk from wildfires.

As development expands into exo-urban environments, forest ecosystem services are also affected. Over the past 15 years, wildfires have become larger and more damaging,[3] which has direct effects on all aspects of forest ecosystem services. Ecosystem services include provisioning services (eg, food, water, fiber, and fuel), regulating services (eg, climate regulation, water and disease regulation), cultural services (eg, spiritual, esthetic, recreational, and educational), and supporting services (eg, primary production and soil formation).[6] Forests and woodlands supply essential ecosystem services on a global scale, but forest fires have become a global threat to the function and condition of forest ecosystems, exacerbated by population growth.[6] The US Forest Service indicates that forest health and biodiversity are declining in the US, particularly on private lands.[7]

Smoke from wildfires poses a risk to the public health of people living in exo-urban environments as well. Smoke contains fine particulate matter ($PM_{2.5}$), often in high concentrations. The US Environmental Protection Agency (EPA) has designated $PM_{2.5}$ as one of six criteria pollutants, for which National Ambient Air Quality Standards (NAAQS) have been established.[8] The NAAQS are tied to EPA's air quality index (AQI), a unitless measure that is color coded to promote effective communication of ambient air quality conditions to the public (Fig. 2).[9] Smoke from wildfires can deteriorate air quality to the Code Orange range and higher, both in the vicinity of the wildfire and downwind via transport of smoke. Consequently, people living in exo-urban environments can be at higher risk for health effects due to exposure to $PM_{2.5}$, such as asthma, heart attacks, strokes, and early death; members of "sensitive groups" are most at risk, including children, the elderly, and people with existing respiratory and cardiovascular diseases.[9] Globally, exposure to ambient $PM_{2.5}$ is responsible for >35 million premature deaths every year.[10]

Given the increasing risks to humans and forests in the exo-urban environment from wildfires, new tools are necessary to provide early warning of fire hazards and to help mitigate threats to public health and forest ecosystem services. Observations of atmospheric aerosols from earth-observing satellite sensors, such as the MODerate resolution Imaging Spectroradiometer (MODIS) instrument on the National Aeronautics and Space Administration's (NASA's) Terra and Aqua satellites, have been used in the past decade to track the evolution of fires and monitor transport of smoke plumes.[11–13] One key satellite product, aerosol optical depth (AOD), is particularly useful for wildfire applications because numerous studies have shown that ground-level $PM_{2.5}$ concentrations can be estimated from satellite AOD.[14] Applications of MODIS AOD for near-real time (NRT) monitoring of exo-urban wildfire impacts have been limited, however, by the relatively coarse 10-km × 10-km spatial resolution (at nadir) of the Collection 5 MODIS AOD product, which decreases in resolution to 40-km × 40-km at pixel edges.[15,16] MODIS Collection 6 has a new higher-resolution 3-km × 3-km AOD product, which decreases in resolution to 12-km × 12-km at pixel edges.[17,18] Although the 3-km × 3-km MODIS AOD product is useful for tracking large fires, it has limited usefulness for smaller fires or for fire monitoring on the city scale.

The new Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on the Suomi National Polar-orbiting Partnership (S-NPP) satellite has high-resolution AOD that is ideally suited to monitoring wildfire impacts on the exo-urban scale. S-NPP, launched in October 2011, is the first in the next generation of NASA's and National Oceanic and Atmospheric Administration's (NOAA's) Joint Polar-orbiting

Satellite System series. VIIRS wavelength bands are similar to those of MODIS, so VIIRS AOD is based on the MODIS heritage.[19] As a result, VIIRS AOD is similar to MODIS AOD, but with higher spatial resolution. VIIRS aerosol observations can be used for NRT monitoring of human exposure to smoke, and they can be used to gauge the spread of fires and thus, provide advanced warning for evacuations and fire suppression efforts.

VIIRS Aerosol Data Products

VIIRS AOD (officially termed aerosol optical thickness, AOT) is retrieved using separate algorithms for land and ocean, which utilize different sets of wavelengths.[19] AOD is a measure of the scattering and absorption of visible light by particles in a vertical column of the atmosphere. It is unitless and is typically displayed on a color-coded scale, where reds, oranges, and yellows indicate areas of relatively high AOD, and blues and greens indicate areas of relatively low AOD. The current version of the VIIRS AOD algorithm does not retrieve aerosol properties over bright surfaces, in cloud-affected pixels, over inland water (such as the Great Lakes), or at night. AOD is calculated separately for land and ocean using a look-up table of precomputed values for several atmospheric parameters, to simplify radiative transfer calculations. The VIIRS AOD algorithm over land involves the selection of an aerosol model from among five prescribed models (eg, dust, high-absorbing smoke, low-absorbing smoke, clean urban, and polluted urban aerosols). The look-up tables for the selected aerosol model are used to invert the satellite-measured radiances, in order to obtain surface reflectance and AOD simultaneously. Because optical properties are different for different aerosols, the accuracy of retrieved AOD depends on the correct choice of aerosol model. One of the five models is selected based on the minimal residual approach, ie, by comparing the derived spectral surface reflectance ratios with expected/prescribed values.[19]

Recent analyses of the new Collection 6 MODIS 3-km × 3-km AOD product have found that it is less accurate over urban areas compared to darker surfaces, such as vegetation and large water bodies.[18] The limitations of AOD algorithms for bright surfaces are well known and are related to the fact that assumptions in the algorithms regarding spectral surface reflectance, which are valid for dark vegetated surfaces, are not valid for bright surfaces, such as deserts and (to a lesser extent) urban areas. Because the VIIRS AOD algorithm is based on the MODIS heritage, the VIIRS Intermediate Product (IP) and Environmental Data Record (EDR) AOD have shortcomings that are similar to those of the Collection 6 MODIS 3-km × 3-km AOD product over urban areas. NOAA is in the process of developing alternate algorithms to address this issue, similar to the MODIS deep blue algorithm.[20] Regardless, VIIRS AOD retrievals are expected to be very accurate over dark surfaces, such as forested areas (where most wildfires occur), and also at the WUI, which is not as bright as urban areas because it is a transition zone between forests and suburban regions.

The VIIRS 750-m resolution IP AOD was originally intended for internal use only, but NOAA has released it to the public, given its potential for a variety of air quality and wildfire-related applications. The VIIRS 6-km resolution EDR product is the official VIIRS AOD product for public use. It is aggregated from IP retrievals in an 8 × 8 pixel box.[19]

To illustrate the advantages of the higher spatial resolution of VIIRS AOD products compared to MODIS AOD products for wildfire applications, Figure 3 shows coincident observations of Collection 5 MODIS AOD and VIIRS EDR AOD for a smoke plume in the Midwestern US on September 25, 2012. The smoke plume was captured at the edge of the scan for both MODIS and VIIRS. Pixel sizes grow in size at the edge of the scan by a factor of four for MODIS (to 40-km × 40-km) and by a factor of two for VIIRS (to 12-km × 12-km). The higher-resolution VIIRS EDR AOD captures the smoke plume's structure and variations that are not resolved by MODIS AOD, particularly at the edge of its scan. A similar comparison, not shown here, can be made between the Collection 6 MODIS 3-km × 3-km AOD and VIIRS IP AOD. In all cases, VIIRS AOD products have higher spatial resolution than their MODIS counterparts. Thus, VIIRS aerosol observations have the potential to be essential tools for operational fire managers and public health officials in ways that previous, lower-resolution satellite aerosol products were not.

Another unique aspect of VIIRS AOD compared to MODIS AOD is the number of quality flags associated with the AOD data. The IP product has four quality flags: High, Degraded, Excluded, and Not Produced. The EDR product has three quality flags: High, Medium, and Low. EDR AOD quality flags are based on the number of IP AOD pixels with a particular quality flag falling inside or outside of a threshold. For example, an EDR High quality pixel is composed of at least 16 (out of a possible 64) IP High quality pixels. Data users have access to these quality flags, which can be very useful when analyzing a wildfire event with thick smoke plumes that the VIIRS AOD algorithm can mistake for clouds, as explained in the "Case Study" section.

The VIIRS smoke mask identifies areas of thick and thin smoke, and it is another useful aerosol product for monitoring the impacts of wildfires in the exo-urban environment. The VIIRS aerosol algorithm identifies smoke using spectral variability tests that are based on aerosol indexes computed using reflectances from the M1 (412 nm), M2 (445 nm), and M11 (2.25 μm) bands of the VIIRS instrument.[21] The VIIRS aerosol algorithm discriminates clouds from aerosols using spatial variability tests. Despite careful pixel screening for nonretrievable conditions, false smoke detections occur near cloud edges and turbid water; thus, users should proceed with caution when interpreting VIIRS aerosol retrievals in these areas.

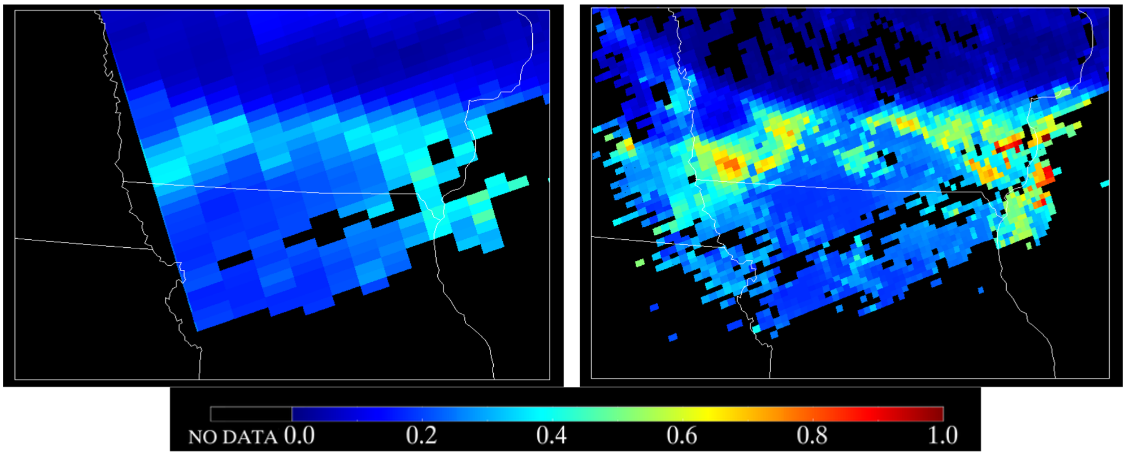

Figure 3. Comparison of Collection 5 MODIS AOD (left) and VIIRS EDR AOD (right), showing areas of high AOD associated with a smoke plume across southern Iowa and northern Missouri on September 25, 2012. For this event, the smoke plume was captured at the edge of the scan for both MODIS and VIIRS. Pixel sizes grow in size at the edge of the scan by a factor of four for MODIS (to 40-km × 40-km) and by a factor of two for VIIRS (to 12-km × 12-km). The higher-resolution VIIRS EDR AOD product captures the variations in the density of the smoke plume (red, orange, and yellow colors), which are not resolved by the MODIS AOD product.

True color imagery (abbreviated RGB for red-green-blue) is also available from VIIRS at 750-m × 750-m resolution as a complement to the aerosol products. It is generated from a combination of the M5 (red, 672 nm), M4 (green, 555 nm), and M3 (blue, 488 nm) bands of the VIIRS instrument. True color imagery is useful for monitoring wildfires because it provides a visible observation, and smoke plumes are evident as gray features.

VIIRS EDR AOD data are archived through NOAA's Comprehensive Large Array-data Stewardship System (CLASS; http://www.nsof.class.noaa.gov). The VIIRS data on CLASS are in native hierarchical data format (HDF), not image files, and they are not available in NRT. As a result, the usefulness of VIIRS data from CLASS is limited for operational users, such as air quality forecasters or fire management officials, who do not have time to process raw data files and need access to satellite products as soon as possible after observation.

To meet the needs of operational users, NOAA has developed the Infusing satellite Data into Environmental Applications (IDEA) web site (http://www.star.nesdis.noaa.gov/smcd/spb/aq/), which provides imagery of VIIRS aerosol products in NRT for the continental US (CONUS) and Alaska. VIIRS aerosol products on IDEA are generated from Direct Broadcast data downloaded from receiving stations at the University of Wisconsin–Madison and the University of Alaska–Fairbanks; the aerosol products are available on IDEA <2 hours after data capture. VIIRS aerosol products on IDEA include true color imagery, IP and EDR AOD imagery, a smoke mask overlay, fire hotspots at pixel resolution (~750-m × 750-m), and 48-hour forward trajectories initialized for locations with high aerosol loading (AOD >0.4). These images can be downloaded in graphic and Keyhole Markup Language (KML) formats for maximum ease of use for operational users. In addition, the images are archived online so users can generate their own time series of historical imagery for post-event analysis.

A key feature of IDEA is the interactive, Google Maps-based visualization tool that allows users to zoom in to the county level and display VIIRS aerosol products in tailored combinations to meet specific needs. An example of the tool is shown in Figure 4. It allows the user to specify the type of VIIRS AOD product (IP or EDR) and select the desired quality flag. There are slider bars that allow the user to adjust the opacity of the RGB and AOD imagery (to display, for example, only RGB or AOD). Toggle buttons allow the user to overlay VIIRS fire hotspots, the VIIRS smoke mask, and county boundaries. Users can save any combination of imageries and overlays for later reference.

Results and Discussion

To illustrate the usefulness of high-resolution VIIRS aerosol products for monitoring wildfires in the exo-urban environment, two case studies are presented using NRT data from the IDEA web site. The case studies focus on recent fires in the Western US that affected the exo-urban environment on different spatial scales: the Carlton Complex fire, which was part of a regional outbreak of wildfires in Central Washington State in mid-July to mid-August 2014, and a series of wildfires on the city/county scale in northern San Diego County in May 2014.

Carlton Complex fire, mid-July to mid-August 2014 (state/regional scale). The Carlton Complex fire began as four small fires in North–Central Washington State on July 14, 2014 and merged into one large fire on July 20. It continued to burn through mid-August.[22] It was one of the five major fires burning in Central Washington in the period July 2014 to August 2014, including the Chiwaukum Creek fire, Mills

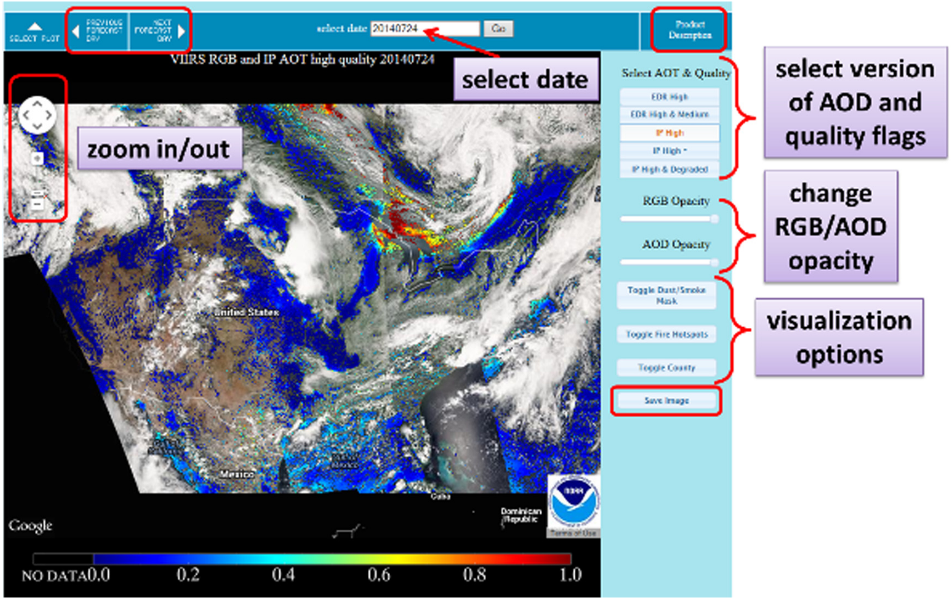

Figure 4. Example of VIIRS interactive visualization tool on the IDEA web site for July 24, 2014, showing IP AOD and RGB imagery.

Canyon fire, R Road fire, and Saddle Mountain fire.[23] The Carlton Complex fire was the largest wildfire in Washington State's history; it burned 256,108 acres and destroyed approximately 300 homes, resulting in widespread power outages and evacuations.[22,23]

Air quality in the vicinity of the Carlton Complex fire was periodically degraded throughout mid-July to mid-August due to widespread smoke plumes. Figure 5 shows a representative example of $PM_{2.5}$ air quality, indicated by small colored dots that reflect the AQI scale, for northeastern Washington State on August 10, 2014; 24-hour average $PM_{2.5}$ concentrations (in μg/m^3) are also listed next to the colored dots. Fire hotspots are designated by red flame symbols and smoke plumes are represented by gray shaded areas, as identified by NOAA's Hazard Mapping System (HMS) Fire and Smoke Product. The HMS Fire and Smoke Product is a multisatellite-based analysis that is quality controlled by a trained analyst; it is not available in NRT.[24] The approximate location of the Carlton Complex fire is indicated by a black circle. On August 10, $PM_{2.5}$ air quality at locations just east of the Carlton Complex fire was in the Code Orange range, which represents an exceedance of the daily NAAQS for $PM_{2.5}$ (ie, 35 μg/m^3). Under Code Orange conditions, members of "sensitive groups" are advised to reduce prolonged or heavy exertion outdoors.[9] Across much of the remainder of the region affected by smoke from the multiple wildfires burning in Central Washington, $PM_{2.5}$ was in the upper Code Yellow (Moderate) to Code Orange range, while in the areas to the west of the fires, $PM_{2.5}$ was in the Code Green (Good) range. This gradient in air quality reflects transport of smoke across the region, upwind from the fires, and underscores the need for a tool to track smoke plumes in NRT to protect public health.

Smoke plumes and AOD from the Central Washington fires, including the Carlton Complex fire, are readily evident using VIIRS products. Figure 6A is the VIIRS RGB NRT image from the IDEA web site, zoomed in to the regional scale, showing northeastern Washington State and southern British Columbia on August 10, 2014. Smoke plumes from the many fires across the state appear as gray features covering much of North–Central Washington and extending across the US–Canada border into southern British Columbia. Fire hotspots identified by VIIRS are overlaid on the RGB image as red dots. The approximate location of the Carlton Complex fire is indicated by a white circle. Figure 6B shows the corresponding VIIRS EDR AOD NRT image from the IDEA web site. The extent of the smoke plumes is indicated by areas of high AOD, colored in red, orange, and yellow in Figure 6B. The 6-km × 6-km resolution EDR AOD product is particularly useful for large, regional wildfires, such as the fires burning across Washington State in July–August 2014, when monitoring transport of smoke plumes is a priority. The 750-m × 750-m resolution IP AOD product provides too high a level of detail on the regional scale, which can be distracting.

For dense smoke plumes, such as the ones associated with the Central Washington fires, users can take advantage of the VIIRS AOD quality flag options and view the Medium or Degraded quality products. High quality IP and EDR AOD are recommended for most applications, but in the case of thick smoke plumes, the VIIRS AOD algorithm can misidentify smoke as a cloud and exclude the smoke pixels from the High quality AOD product. As a result, there can be gaps in High quality VIIRS AOD retrievals over thick smoke plumes. In these types of situations, users can elect to view Medium or Degraded VIIRS AOD to get a more complete picture of

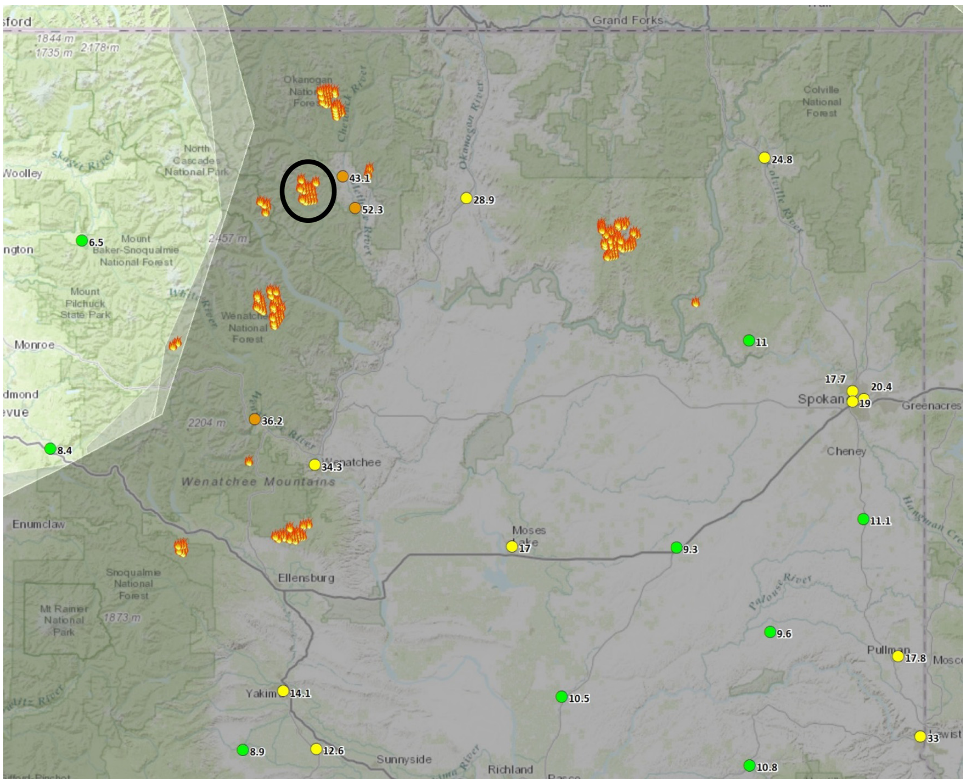

Figure 5. Map of northeastern Washington State showing locations of fire hotspots (red flames) and smoke plumes (gray shaded areas) associated with wildfires burning on August 10, 2014. Darker gray colors indicate thicker smoke plumes. The black circle indicates the location of the Carlton Complex fire. Small colored circles reflect the AQI scale and indicate 24-hour average $PM_{2.5}$ concentrations in µg/m^3; note the Code Orange concentrations adjacent to the Carlton Complex fire. [Hotspots and smoke plume data courtesy of NOAA Hazard Mapping System Fire and Smoke Product; $PM_{2.5}$ concentration data courtesy of EPA AIRNow-Tech.]

AOD distribution. In Figure 6B, for example, the High and Medium quality EDR AOD pixels capture almost all of the thick smoke associated with the Central Washington fires on August 10.

For wildfires affecting a multicounty or cross-border region, such as the Central Washington wildfires, the NRT VIIRS aerosol products can provide information on the spread of the fires and the extent of smoke plumes. Tracking smoke plumes is especially critical for air quality forecasting applications, while fire managers need to know how quickly a fire is spreading to plan for evacuations. The combination of high-resolution VIIRS AOD and RGB imagery can illustrate the areal extent and influence of smoke from fires on human populations and provide a complement to ground-based and aircraft monitoring.

San Diego County fires, May 13–16, 2014 (city/county scale). Multiple relatively small wildfires broke out across northern San Diego County in Southern California in the period May 13–16, 2014. These fires affected the municipalities of Carlsbad, Escondido, Harmony Grove, Lakeside, Oceanside, Rancho Santa Fe, and San Marcos, as well as Marine Corps Base Camp Pendleton. As many as 125,000 people were evacuated as a result of the fires, which burned nearly 20,000 acres of land.[25] Costs for destruction or damage to private property from the fires were estimated at $29.8 million, with an additional $27.9 million for firefighting, support, and environmental restoration costs.[26] The most significant fires included the Bernardo Fire (Rancho Santa Fe, 1,548 acres), the Cocos Fire (San Marcos, 1,995 acres), the Freeway Fire (Fallbrook, 56 acres), the Highway Fire (Deer Springs, 380 acres), the Poinsettia Fire (Carlsbad, 600 acres), the Pulgas Fire (Oceanside, 14,416 acres), the River Fire (Oceanside, 105 acres), the San Mateo Fire (Camp Pendleton, 1,457 acres), and the Tomahawk Fire (Camp Pendleton, 5,367 acres).[27]

Similar to the Central Washington fires, the San Diego County fires affected air quality at nearby locations. Figure 7 is a map of Southern California showing $PM_{2.5}$ air quality, indicated by small colored dots that reflect the AQI scale, on May 16, 2014; 24-hour average $PM_{2.5}$ concentrations (in µg/m^3) are also listed next to the colored dots. As in Figure 5, fire hotspots identified by the NOAA HMS Fire and Smoke Product are designated by red flame symbols, and smoke plumes are represented by gray shading. In the case of the San Diego County fires, there were no $PM_{2.5}$ observations in the vicinity of the fires, so the immediate impacts on air quality were not known with certainty. However, at upwind locations in interior California, near Wildomar and Banning, $PM_{2.5}$ reached the Code Orange range, which is an exceedance of the daily NAAQS for $PM_{2.5}$ and represents air quality that is unhealthy for "sensitive groups." This is an

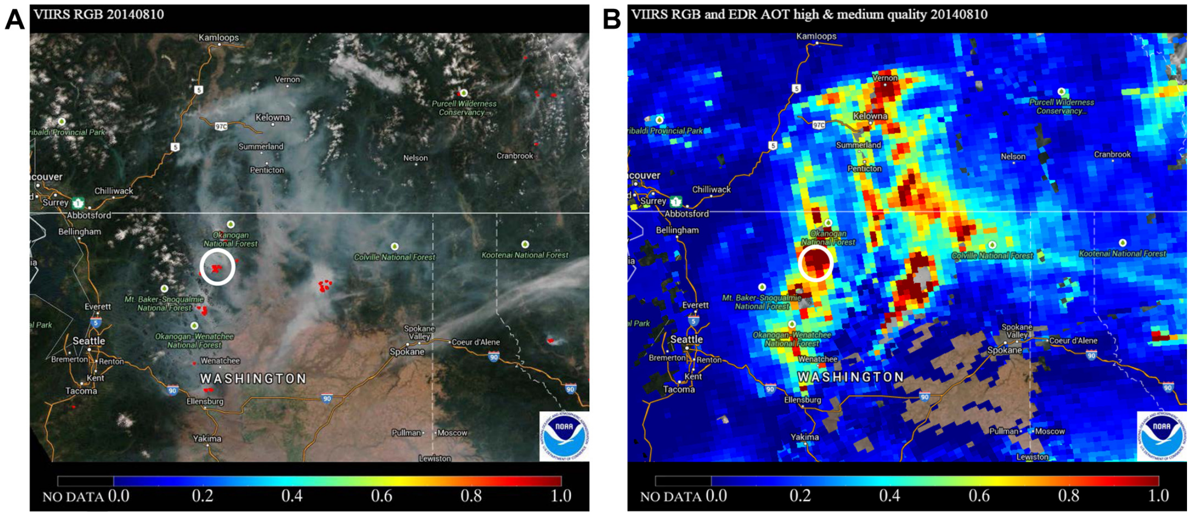

Figure 6. (**A**) The left panel shows VIIRS true color (RGB) NRT imagery from the IDEA web site for northeastern Washington State and southern British Columbia on August 10, 2014. Fire hotspots identified by VIIRS are overlaid as small red dots. The approximate location of the Carlton Complex fire is indicated by a white circle. Smoke plumes from the many fires burning across North–Central Washington State are evident as gray features covering much of northeastern Washington and southern British Columbia. (**B**) The right panel shows VIIRS 6-km × 6-km resolution Environmental Data Record (EDR) aerosol optical depth (AOD) NRT imagery overlaid on VIIRS RGB imagery from the IDEA Web site for northeastern Washington State and southern British Columbia on August 10, 2014. The approximate location of the Carlton Complex fire is indicated by a white circle. Areas of high AOD, shown by the red, orange, and yellow colors, correspond to smoke from the wildfires burning across North–Central Washington and southern British Columbia.

example of how smoke can be transported away from wildfire source regions and can affect public health at upwind locations that may not experience the direct fire impacts of property destruction or evacuations. The more indirect effects of smoke transport on air quality underscore the need for NRT monitoring and tracking of smoke plumes by satellite observations, which complement ground-based and aircraft measurements.

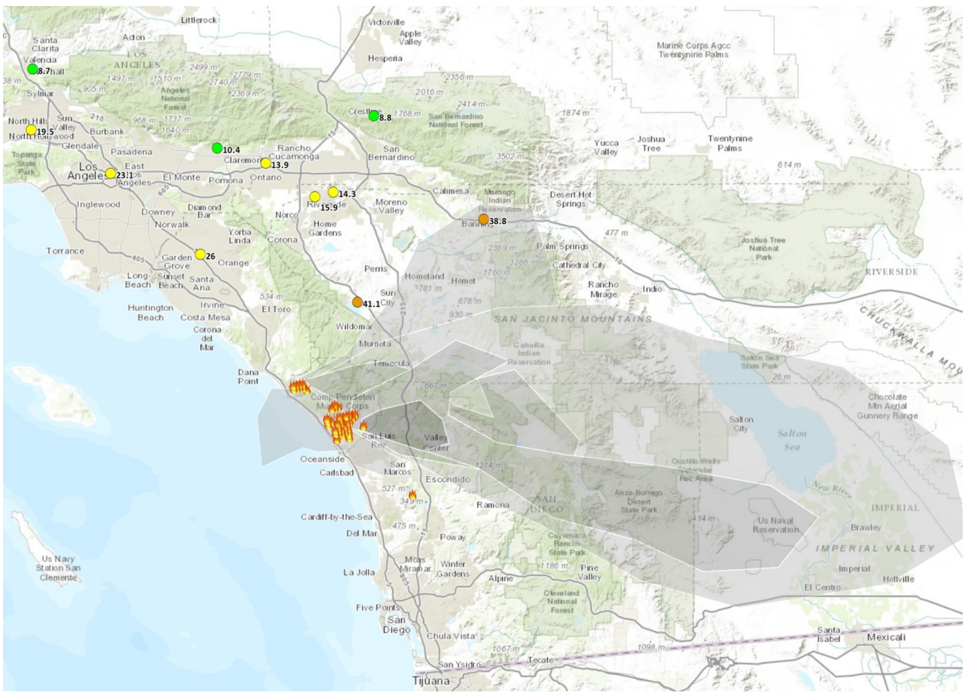

Figure 7. Map of Southern California showing locations of fire hotspots (red flames) and smoke plumes (gray shaded areas) associated with wildfires burning in northern San Diego County on May 16, 2014. Darker gray colors indicate thicker smoke plumes. Small colored circles reflect the AQI scale and indicate 24-hour average $PM_{2.5}$ concentrations in $\mu g/m^3$; note the Code Orange concentrations downwind (northeast) of the fires. [Hotspots and smoke plume data courtesy of NOAA Hazard Mapping System Fire and Smoke Product; $PM_{2.5}$ concentration data courtesy of EPA AIRNow-Tech.]

For wildfires on the county or city scale, such as the San Diego County wildfires, the 750-m × 750-m resolution VIIRS IP AOD product is most useful for monitoring smoke transport. Figure 8A shows High quality NRT IP AOD imagery from IDEA for Southern California on May 16, 2014. Smoke plumes associated with the San Diego County wildfires are indicated by the red, orange, and yellow colors north of San Diego, near Temecula, Oceanside, and Fallbrook, which correspond to areas of high AOD. The IP AOD product provides more detail than the EDR product and resolves variations in AOD on the urban scale, making it ideal for analyzing smaller-scale fires.

In situations when smoke is diffuse or less evident in true color imagery, as is often the case with county- or city-scale fires, the VIIRS smoke mask can provide a complementary means of identifying smoke plumes. Figure 8B shows the VIIRS RGB NRT image from IDEA for May 16, overlaid with VIIRS fire hotpots (red circles) and the VIIRS smoke mask (pink shading). The smoke plumes from the San Diego County wildfires are difficult to discern in the RGB image, but the smoke mask captures the thickest plumes, aiding in identification and tracking. In addition, the VIIRS hotspots give NRT information on fire location, without having to wait for postanalysis products such as the NOAA HMS fire and smoke products.

Although the NRT VIIRS aerosol products available through the IDEA web site have the potential to provide unparalleled detail for operational monitoring of fires and smoke, the current version of the VIIRS NRT interactive visualization tool on IDEA does not have the ability to zoom in to neighborhood-level resolution, thereby limiting its usefulness for the smallest-scale fires. VIIRS aerosol data do have sufficient resolution to resolve fires and smoke on the neighborhood scale, however, as shown in Figure 9 for a neighborhood west of Temecula. Trade-offs between data processing time and storage space limit the highest zoom level on the current version of IDEA to approximately 325 km. To address the shortcomings of the web display system and meet the needs of operational users, the IDEA web site will be enhanced and expanded to include additional products, as described in the next section.

Western Region Fire and Smoke Initiative. The Western Region Fire and Smoke Initiative is a new project that will enhance VIIRS fire, smoke, and aerosol products for the National Weather Service's Western Region and quantify key socioeconomic impacts of wildfires. The interactive VIIRS visualization tool on IDEA will be updated to allow zoom-in capability to the street level for targeted regions in the Western US. Incident meteorologists and fire managers will be able to access this enhanced system while on the ground, utilizing smart phones or other mobile devices. VIIRS aerosol products that will be displayed on the enhanced version of IDEA include fire hotspots, fire radiative power (FRP), proxy burned area, and areal extent of smoke plumes. The dissemination of FRP will be valuable for planning and field coordination as the product can be used to instantaneously categorize fires based on their intensity.[28] Being able to access VIIRS aerosol products in NRT on the neighborhood scale will allow operational users to take full advantage of the 750-m × 750-m resolution VIIRS IP AOD product, for maximum effectiveness in tracking smoke plumes and fire extent.

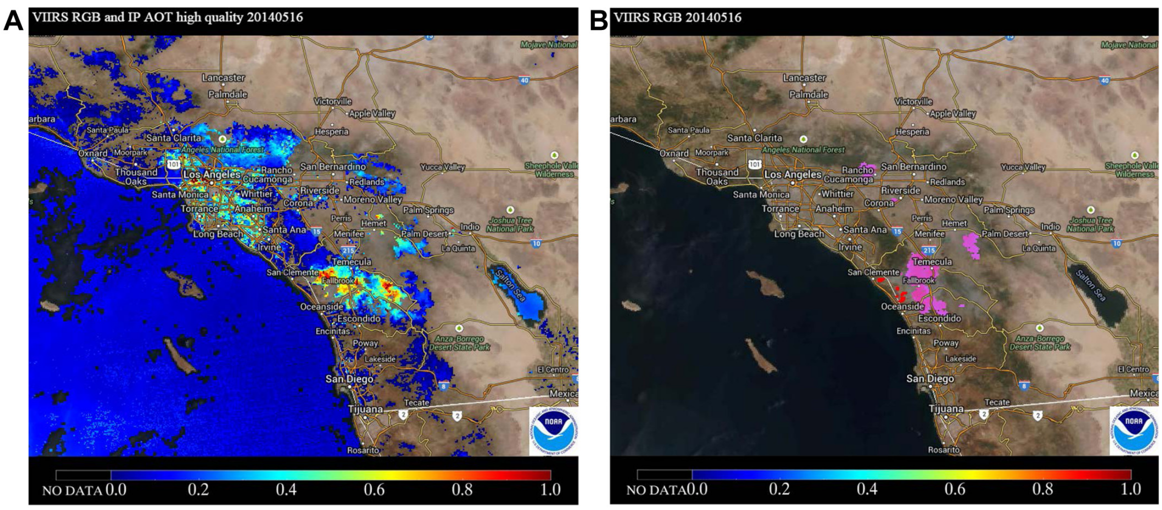

Figure 8. (**A**) The left panel shows VIIRS 750-m × 750-m resolution Intermediate Product (IP) aerosol optical depth (AOD) NRT imagery from the IDEA web site for Southern California on May 16, 2014. Areas of high AOD, shown by the red, orange, and yellow colors, north of San Diego, near Temecula, Oceanside, and Fallbrook correspond to smoke from the wildfires burning in northern San Diego County. Areas of high AOD over Los Angles are due to urban haze. (**B**) The right panel shows VIIRS true color (RGB) NRT imagery from the IDEA web site for Southern California on May 16, 2014. Fire hotspots identified by VIIRS are overlaid as small red dots. The pink shaded areas correspond to the VIIRS smoke mask. Smoke from the San Diego County wildfires is evident as a light gray feature in the RGB image, but it is difficult to discern. The pink VIIRS smoke dust mask captures the thickest parts of the smoke plume, aiding in identification and tracking.

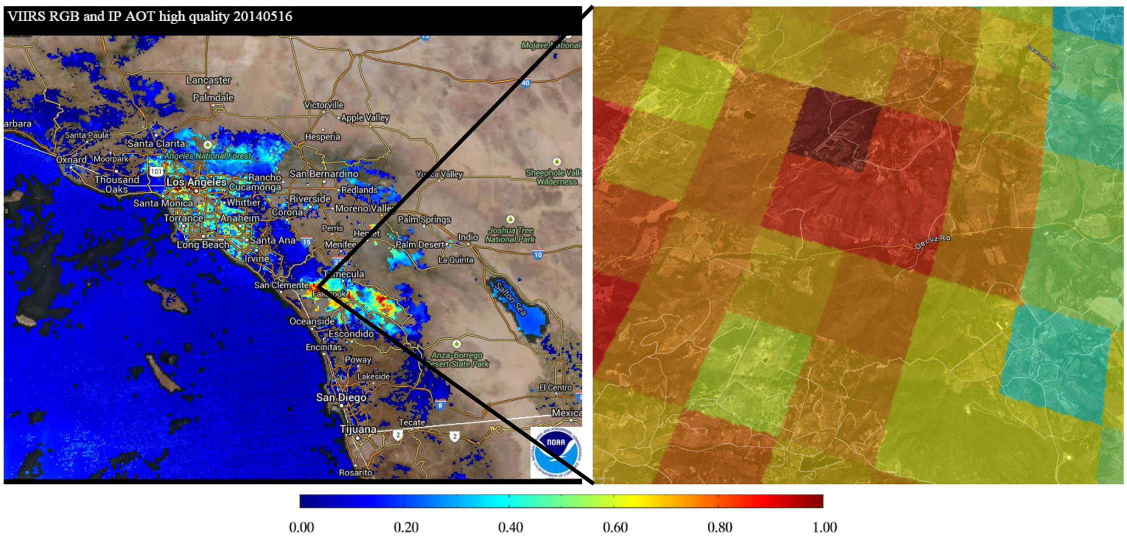

Figure 9. VIIRS 750-m resolution Intermediate Product (IP) aerosol optical depth (AOD) on May 16, 2014, showing the full resolution (right panel) of the AOD data on the neighborhood scale for a community west of Temecula, CA. The scale of the right panel is 5-km × 5-km, with each square AOD pixel measuring 750-m × 750-m. Note that the AOD data are overlaid on a street map, illustrating the potential for tracking smoke plumes on the neighborhood scale.

To assess the relevance of satellite-derived fire products for wildfire applications, NOAA will also calculate several socioeconomic factors related to wildfire impacts, such as mortality risk to smoke exposure and fire suppression costs. Using data from the 2013 and 2014 fire seasons, smoke exposure data will be generated by computing a mortality risk factor to analyze the health impacts of smoke from fires in exo-urban regions. Additional economic impact data, such as fire suppression cost statistics, will be generated for each state and compared to National Interagency Fire Center estimates. These data are expected to provide operational users with information to aid in short-term planning to reduce the risks of human populations and forest ecosystems from wildfires in the Western US, particularly in the exo-urban environment.

Future Outlook

The next-generation fire and smoke products from VIIRS have the resolution to be extremely useful in assessing the spatial extent of natural hazards, such as wildfires. The high-resolution fire channels on VIIRS are capable of detecting fires as small as 10 MW with a spatial resolution of 750-m × 750-m, allowing analysis of wildfires down to the neighborhood scale. In an exo-urban setting, fire counts can be pinpointed to street-level accuracy. VIIRS satellite observations do have limitations, however, including lack of observations under cloudy conditions and nontemporal matching. In particular, the overpass time of VIIRS at approximately 1:30 PM local time does not provide dynamic information on fire movement and growth. In contrast, the current-generation imagers on NOAA's Geostationary Operational Environmental Satellite (GOES) system provide data every 30 minutes in one visible channel and in multiple infrared channels. Fire counts at this time scale are extremely useful for monitoring the movement of fire fronts. The fire counts are generated on a 4-km × 4-km average pixel size, however, which is too coarse a resolution for location of a nascent fire without further ground detection or airborne spotting.

Within two years, NOAA will launch the first of the new generation of imagers, the Advanced Baseline Imager (ABI) on the GOES-R satellite, which will have much higher temporal resolution compared to the current generation of GOES imagers.[29,30] Fire and smoke detection by the ABI are expected to be comparable with what is now achieved from MODIS and VIIRS but at 5-minute resolution in the CONUS scan and at 30-second resolution in targeted regions during the so-called "Flex Mode." For cases in which a hazard needs more critical monitoring, whether it is a weather-related or anthropogenic one, the new GOES-R ABI instrument will provide operational users with real-time situational awareness that is currently not available from space. In the interim, the new high-resolution VIIRS aerosol products, accessible in NRT through IDEA, provide operational users with unprecedented spatial resolution of smoke plume evolution and transport, which can help reduce the risks of wildfires to humans and forests in the exo-urban environment.

Acknowledgments

The authors gratefully acknowledge the NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) Joint Polar-orbiting Satellite System program office and Dr Mitch Goldberg for their support. The NOAA calibration/validation team conducted the validation of VIIRS AOD retrievals, and we thank the team for their efforts. The authors also thank Liam Gumley and Kathy Strabla of the University of Wisconsin–Madison and Scott McFarlane of the University of Alaska–Fairbanks for providing access to Direct Broadcast data for the continental US and Alaska, respectively.

Author Contributions

Developed product algorithms: SK, HZ. Analyzed the case studies: AKH, SK, RMH. Wrote the first draft of the manuscript: AKH. Contributed to the writing of the manuscript: SK, RMH. Agreed with manuscript results and conclusions: SK, HZ, RMH. Jointly developed the structure and arguments for the paper: AKH, SK, RMH. Made critical revisions and approved final version of the manuscript: SK, HZ, RMH. All authors reviewed and approved of the final manuscript.

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