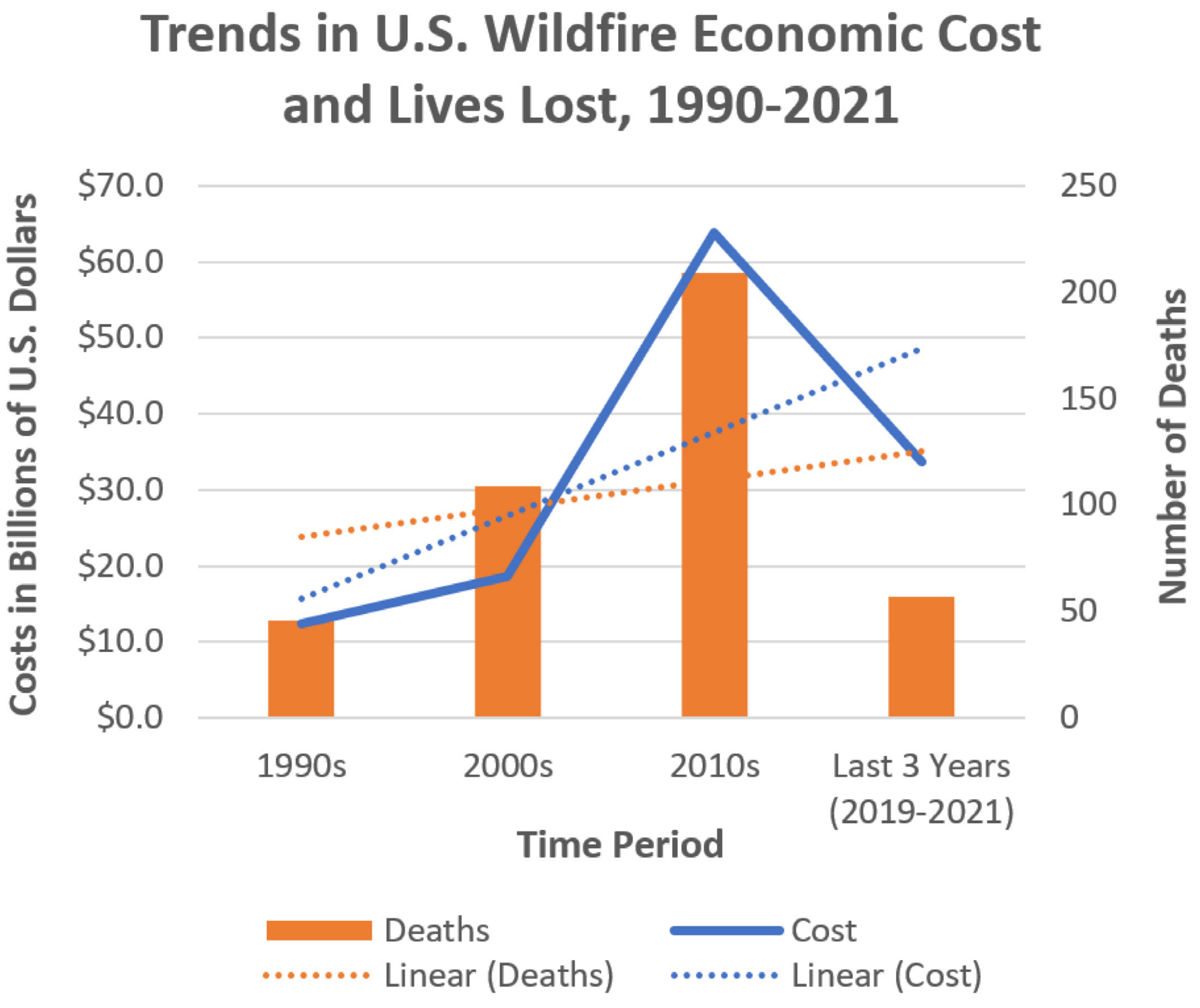
FEATURE 7

Fire Light at Night:

Quantifying Fire Combustion Phase Using the Visible Infrared Imaging Radiometer Suite (VIIRS)

The Woosley Fire burns brush and timber through the night near Malibu, California, November 2018. Source: Peter Buschmann, USDA Forest Service. https://csl.noaa.gov/projects/firex-aq/science/goals.html



Data source: NOAA National Centers for Environmental Information (www.ncei.noaa.gov/access/billions/summary-stats).

In recent years, wildfire has dominated headlines around the globe. Wildfire frequency, extent, and severity are increasing, meaning that more people and communities are impacted than ever before. Wildfire harms human health, property, and livelihoods. From 1990 to 2021 wildfires caused 418 deaths and $123.6 billion in economic losses ($10.8 billion in 2021 alone!) in the U.S., and these statistics are trending upward as shown by the dotted lines (linear trend) in the graph.

Another troubling trend: wildfire season is lengthening. In the U.S., what was typically a four-month season has stretched to seven months or more, starting earlier and ending later. More acreage is burning at a higher intensity than in previous decades, as evidenced by the data graphs at the top of the next page,, and studies make it clear that climate change is a contributing factor. With this comes

CLICK IMAGE TO ENLARGE. Left: Annual wildfire-burned area (in millions of acres) from 1983 to 2020. The two lines represent two different reporting systems though the U.S. Forest Service stopped collecting statistics (orange line) in 1997. Right: The distribution of acreage burned by large wildfires, based on the level of damage caused to the landscape—a measure of wildfire severity. "Unburned to low" indicates no or low burned areas and "increased greenness" indicates increased vegetation growth after a fire was extinguished. Large wildfires are defined as fires with an area larger than 1,000 acres in the western U.S. and 500 acres in the eastern U.S. The total acreage shown on the left is slightly less than the total on the right because the right graph is limited to large fires. Source: U.S. EPA (https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires).

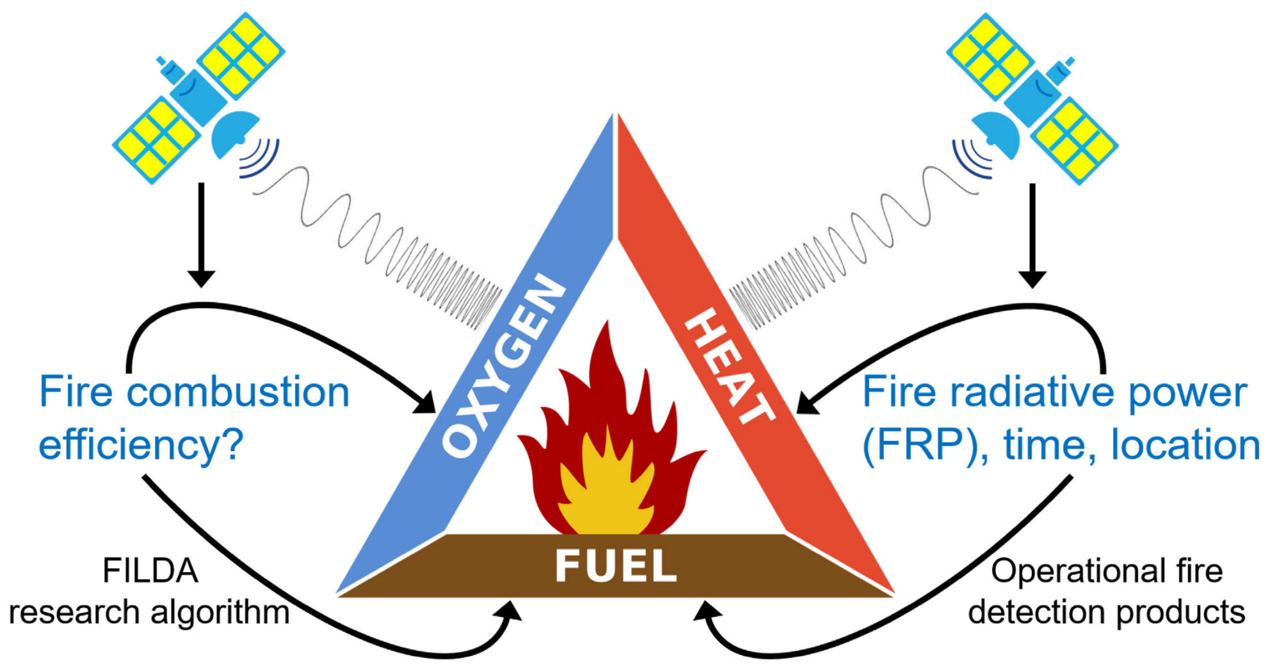
an increase in biomass burning that can cause hazardous air quality and a surge in hospitalizations. Unhealthy air conditions can persist for days or weeks, and wildfire smoke can travel hundreds of miles impacting communities far from the source.

Wildfires are also growing more intense at night, a time that used to mean slower growth from cooler temperatures and higher humidity. But the night air in some regions of the U.S. has become hotter and drier causing little relief during the overnight hours. Case in point: since 2003, the western U.S. has seen nighttime fire intensity increase by 28%. This is worrisome because it is difficult to monitor cooler and smaller fires in the dark with existing operational fire detection methods, which means responders may wake to find that a fire spread overnight in unexpected directions—the dreaded "sunrise surprise."

Climate change, extreme weather, and shifting fire regimes are challenging the status quo and new tools are needed to better characterize fires and their emissions. While many operational satellite data products detect and describe active wildfires, none quantitatively characterize the fire combustion phase. Using data from JPSS' Visible Infrared Imaging Radiometer Suite (VIIRS), Dr. Jun Wang, James E. Ashton Professor in the College of Engineering at the University of Iowa, Interim Chair of the Department of Chemical and Biochemical Engineering, and Assistant Director of the University of Iowa Technology Institute, answered this challenge. Professor Wang and his team developed a novel algorithm that describes the fire combustion phase at the satellite pixel level to improve emission estimates and fire detection at night. At the October 2021 JPSS Science Seminar, Wang shared progress and insights from the development and validation of the new research algorithm called the FIre Light Detection Algorithm (FILDA), as well as related research using VIIRS Day/Night Band to track fire emissions at night that will be discussed in summary.

WHAT THE FIRE COMBUSTION PHASE TELLS US

Fire has three elements: heat, fuel, and oxygen. For agencies to successfully battle fire and smoke, they need meaningful information about these elements, some of which can be measured from space. Current satellite-derived active fire products can estimate fire radiative power (the amount of total radiant energy emitted by a burning fire), fire location, fire size, and fire temperature—all important for understanding heat and fuel types. But less is known about how oxygen and fuel interact, which affects the fire combustion phase (whether a fire is flaming or smoldering) and fire combustion efficiency (the degree to which combustion is completed). Why does this matter? Two reasons: first, the combustion phase impacts how, where, and when firefighters and agencies respond. Second, combustion efficiency influences the accuracy of fire emission factors, which are critical inputs for models used to develop wildland fire emission inventories.



"In the literature, the fire combustion phase is often quantified in terms of modified combustion efficiency, MCE, which is the ratio between the amount of carbon dioxide emitted from a fire and the sum of carbon monoxide and carbon dioxide from that fire," explains Wang. The larger the MCE, the more complete the combustion, meaning that more carbon dioxide (CO_2) is emitted compared with other pollutants like carbon monoxide (CO), soot, organic carbon, particulates, and others. An MCE of 1 means that all carbon emitted was converted to CO_2—there is 100% combustion efficiency, complete combustion.

MCE has a significant impact on fire emission factors. For example, as MCE increases from 0.85 to 0.96, the emission factor for sulfate can grow 10 times larger, while the emission factor for organic carbon can shrink 10 times smaller. Wild swings in both directions! Wang emphasizes, "The importance of fire phase [MCE] for estimating fire emissions cannot be overstated." The issue is that MCE is difficult to estimate remotely for wildfires where flaming and smoldering occurs at once because satellite sensors "see" a mixture of both in each "fire pixel"—the satellite pixel where fire is detected. The FILDA product aims to tackle this problem.

MCE as a Proxy

*Combustion efficiency (CE) is a measure of how effectively a fire converts carbon in the fuel to carbon dioxide (CO_2) emissions. Calculating CE is not practical because it requires measuring all the carbon released during a fire. Instead, a proportion is used as a proxy—**modified combustion efficiency (MCE)**. MCE is the proportion of total carbon emitted by a fire released as CO_2.*

$$MCE = \frac{CO_2}{(CO + CO_2)}$$

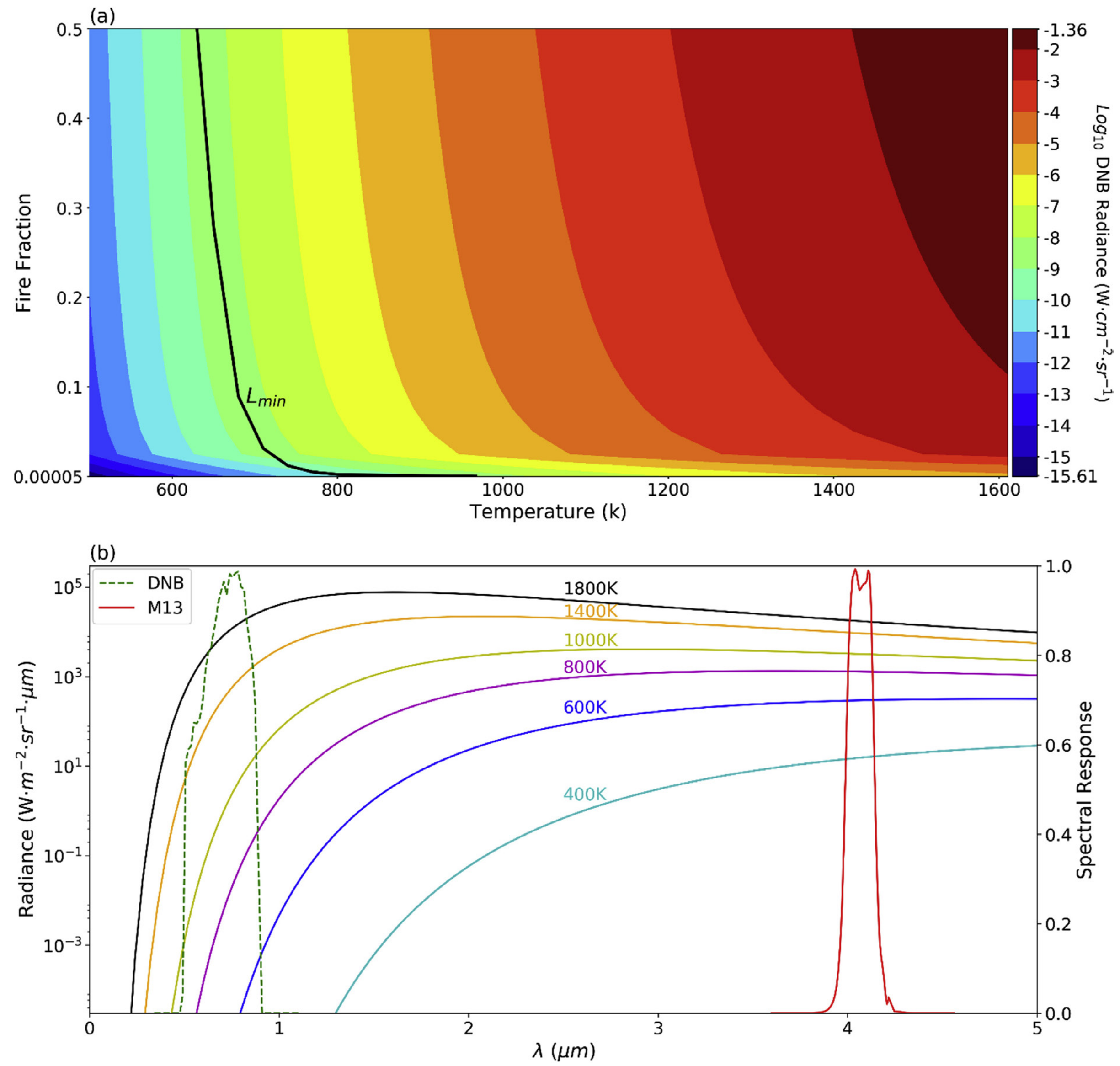
Fire Light: Flaming Versus Smoldering

The fire combustion phase is controlled by temperature, relative humidity, available oxygen, and fuel content. Light is an indication of the fire combustion phase and combustion completeness (efficiency). The flaming phase of a fire occurs above the ground where oxygen is plentiful, while the smoldering phase occurs near or at the surface where oxygen is limited. Smoldering is a slow, low temperature, flameless form of combustion of a solid fuel, like vegetation and wood, unlike flaming, which is high temperature and spreads easily with the wind.

By definition, a fire in the flaming phase emits visible light. Fire that does not emit visible light is defined as smoldering. Wang explains, "This is the key criteria for a flaming fire, it must have visible light, which are shorter wavelengths compared to smoldering fire that has no visible light because it emits radiation at longer wavelengths." Combustion efficiency is based on the principle that if a fire emits light, then it is flaming. More visible light means a greater amount of flaming. Knowing this, Wang saw the potential to link fire light to MCE using satellite data.

USING VIIRS TO CALCULATE FIRE COMBUSTION EFFICIENCY

The VIIRS instrument has three sets of bands that collect observations across visible and infrared (IR) wavelengths at two spatial resolutions, 375 meters (m) and 750 m. High resolution image bands (I-bands) and moderate resolution bands (M-bands) mostly measure infrared (IR) radiation, while the Day/Night Band (DNB) measures visible and near-infrared light. What makes the Day/Night Band unique is its ability to detect low levels of visible light in cloud-free conditions, meaning that it is sensitive to visible light from flaming fires at night. It can detect visible light intensity as low as the equivalent of a fire of 650 Kelvin (710°F/377°C) and 50 square meters (0.0001 area fraction in a Day/Night Band pixel). While 650 Kelvin does not sound like a low temperature, forest fires average about 1000 Kelvin (1472°F/800°C). With its high dynamic range, the Day/Night Band also detects white-hot fires burning at more than 1800 Kelvin (2780°F/1527°C). These capabilities are illustrated by the plots below.

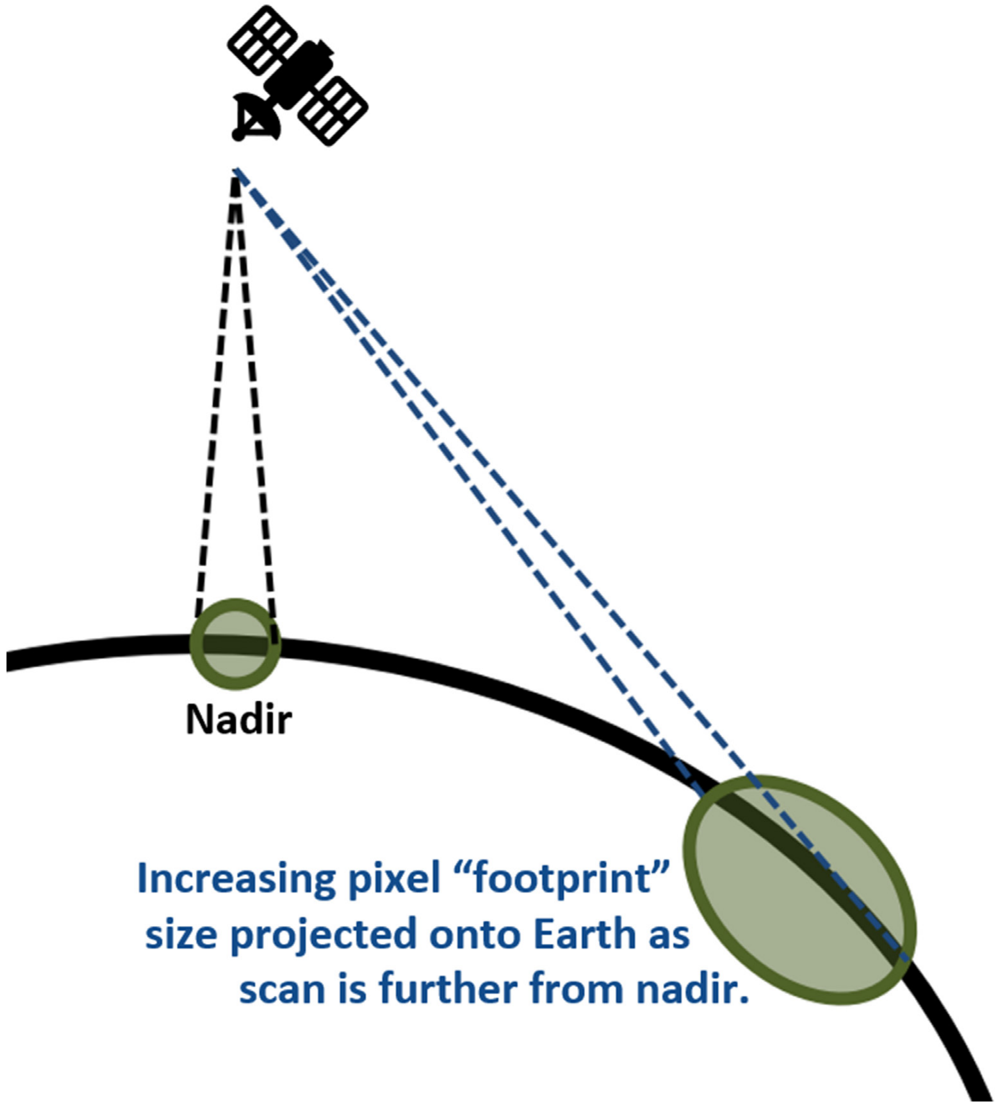


Top (a): Contour plot of simulated VIIRS Day/Night Band (DNB) radiances for different fire temperatures and fractions during nighttime (assuming no lunar or other illumination) using Unified Linearized Vector Radiative Transfer Model. The black line shows the minimum radiance (L_{min}) that DNB sensor can detect. The fires that fall into the left side of the black line are not detectable by DNB sensor. Bottom (b): Plot of VIIRS Day-Night band (DNB) and 4 μm moderate-resolution band #13 (M13) spectral responses along with different Plank curves for different temperatures. DNB is highly sensitive to high temperature (flaming) fires in the night while M13 is sensitive to all fire temperatures. M13 measures mid-infrared radiation while DNM measures visible light. Source: Wang et al. 2020.

VIIRS Day/Night Band imagery on June 12, 2012, showing the High Park Fire alongside city lights from Fort Collins, Greeley, and Loveland, Colorado.

The point is that detection of both small, cool fires and intense, large fires can be improved at night by using the visible light measured from VIIRS. Wang and his team realized this back in 2012, shortly after VIIRS first launched, when they saw the High Park Fire in Colorado clearly visible on VIIRS Day/Night Band nighttime images. The researchers got excited, and Wang wondered, "Can we use that to calculate the fire combustion efficiency?" The short answer is yes; the long answer is that it is complicated.

To Wang, the physics seemed promising because more light means more flaming. But several challenges were met in translating this concept to MCE. First, fires detected in a fire pixel (at the satellite pixel level) are a mix of flaming and smoldering parts and determining the fraction of each at a subpixel level is tricky. Second, to link fire light to MCE, the ratio of visible energy to total radiative energy needs to be known. Third, visible and total radiant energy are measured using different VIIRS bands (Day/Night Band versus M-band) that have differences in their pixel sizes and must be harmonized. To deal with these issues, the team blended and standardized the mismatched VIIRS bands, developed a method to calculate the ratio of visible energy for each VIIRS fire pixel (more on that later), and linked the visible energy fraction values to MCE and emission factors used for global modeling.

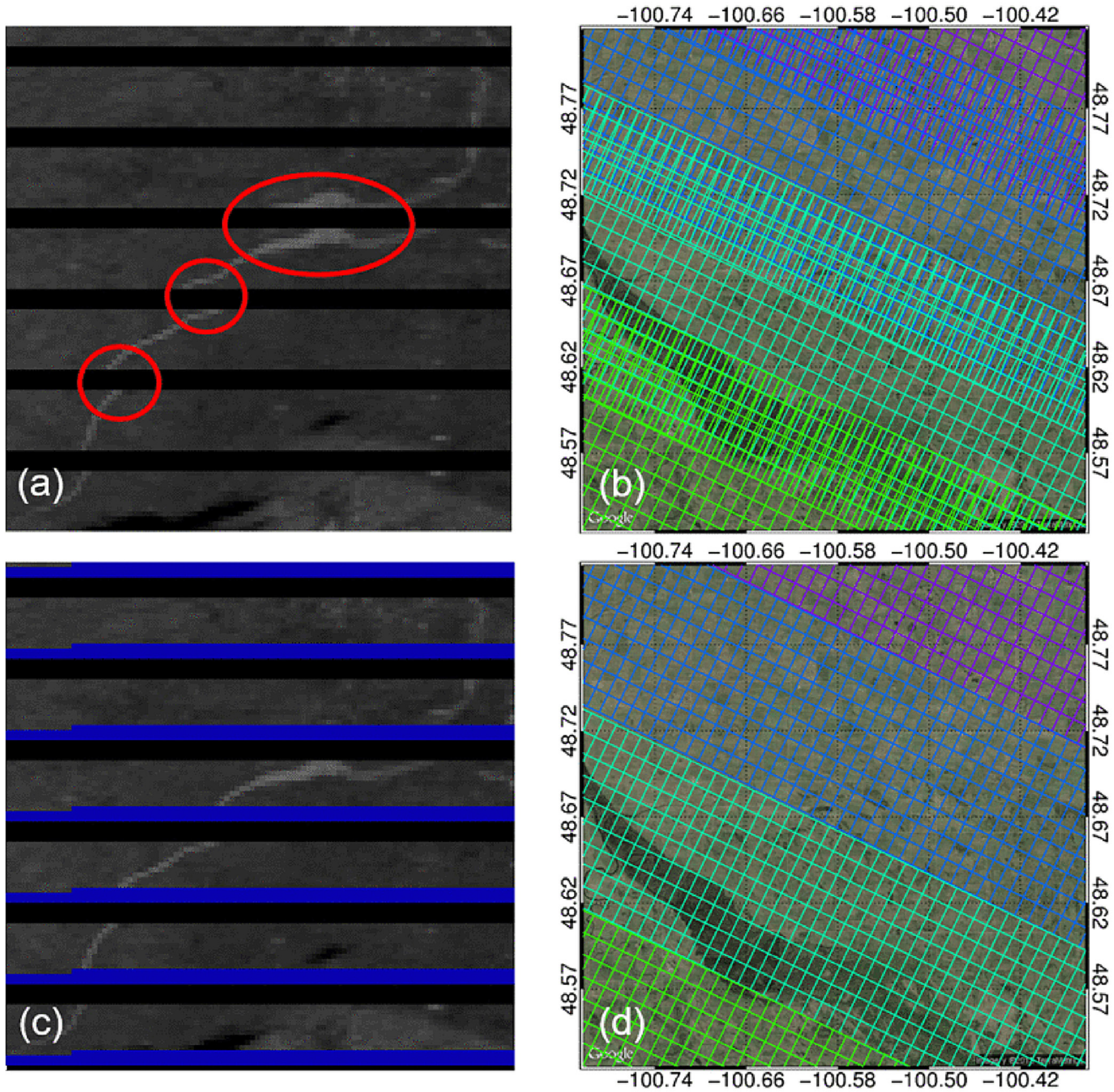


Adapted from Seaman 2013, https://rammb.cira.colostate.edu/projects/npp/Beginner_Guide_to_VIIRS_Imagery_Data.pdf.

Dealing With the Challenges of VIIRS Data

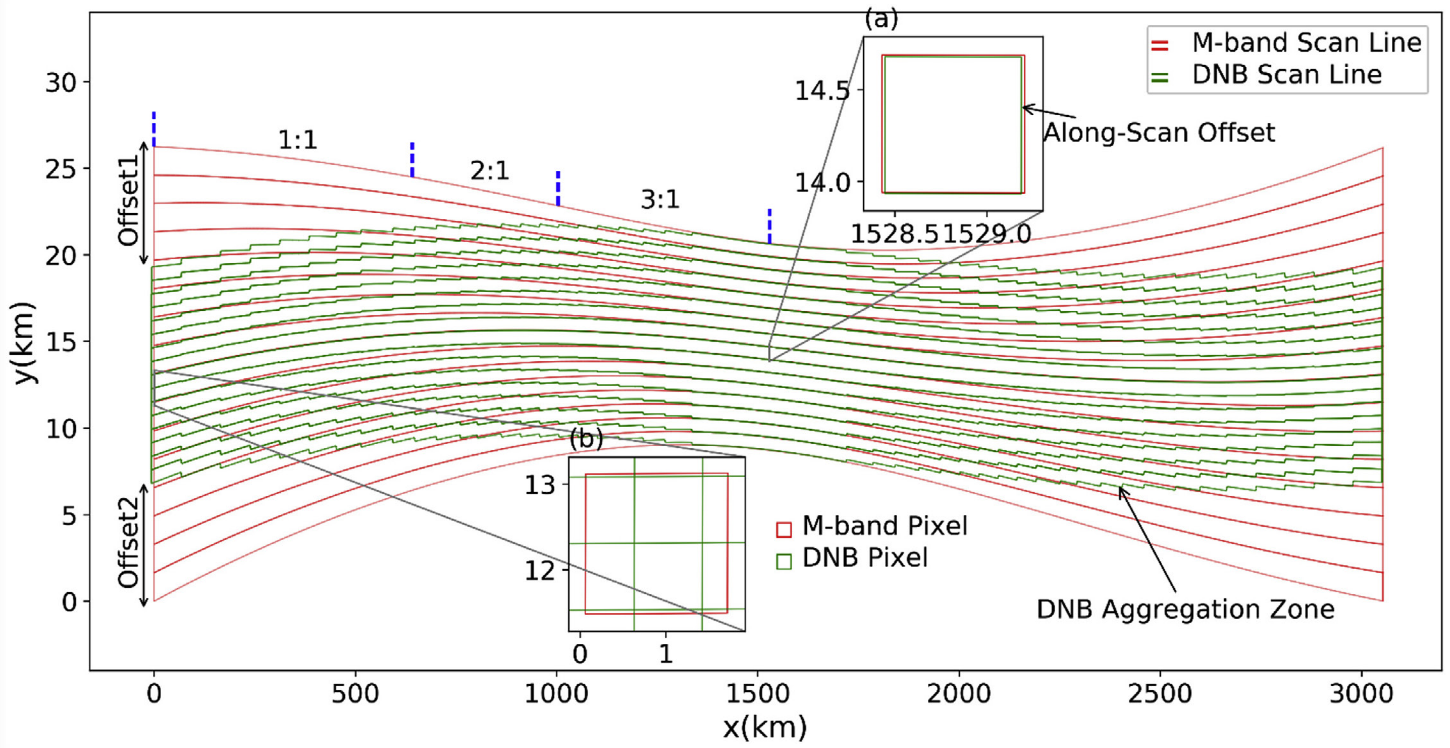
VIIRS pixels distort along the edge of its swath because of scan geometry and the Earth's curvature. Known as the "bow-tie effect," this distortion is especially pronounced the further away the scan is from nadir, the downward-facing viewing geometry, because the scanning process causes pixel size to grow as scan angle increases, which is shown in the illustration.

As a result, pixels from consecutive scans overlap along the edge of the swath, resulting in extra data. These overlapping pixels must be removed to avoid double counting detected fires in a fire pixel. Some of this happens during onboard processing, but much of it was completed by an efficient algorithm that Wang and his team designed and can be automated with computers. In the figure below, the top row shows overlapping, redundant data for a VIIRS scene. The bottom row is the same scene after overlapping regions were removed. Without overlap correction, the same pixel might be counted twice near the edge of the scan.



Correcting for pixel overlap. (a) VIIRS unprojected 4µm moderate-resolution band #13 (M13) scene before corrections. The red outlines highlight the duplicated river areas, and black lines are the bow-tie deleted areas done onboard VIIRS. (b) Pixel footprints for the M13 VIIRS scene including overlap (before corrections) with different colors representing different scans. (c) Image in (a) after corrections with additional overlapping regions removed (blue). (d) Projected scans after corrections. Source: Polivka, et al. 2016.

This is particularly noticeable for the VIIRS M-band. To address this, Wang applied aggregation schemes to compute the pixel growth and enlargement of the ground footprint at the edge of a scan, which can be seen in the plot below (Offset1 and Offset2). This is done so that the width and length of each pixel are accurately calculated throughout the scan zone.



VIIRS M-band/Day/Night Band (DNB) scan zone for the whole swath projected on a flat plane. The DNB scan line is shown in green; the M-band scan line is shown in red. The DNB pixels keep the same size throughout the whole scan while the M-band pixel size grows as a function of scan angle. Near the edge, there is an offset (Offset1 & Offset2) of 8 scan lines between DNB and M-band. Subset (a): the zoom-in view of the nadir M-band and DNB pixels in which the denoted along-scan empty space between M-band and DNB pixels is due to their nominal spatial resolution mismatch. Subset (b): the zoom-in layout of the edge M-band and DNB pixels. Each large near-edge M-band pixel can overlap with up to 12 DNB pixels from 4 different DNB scan lines. Note, the different scales for X and Y axes makes the figure exaggeratedly look curvy. Source: Wang et al. 2020.

Complicating things more, VIIRS M-band and Day/Night Band are mismatched at the pixel level. Wang's plan was to merge these bands, so these differences needed to be resolved, which they did by mapping Day/Night Band pixels to M-band pixels so that they matched in space and time. They also did other work to mechanically align data collected by Day/Night Band versus other bands since Day/Night Band is focalized differently. Overall, it took the team about two years to address the complex challenges encountered with VIIRS data.

Computing Modified Combustion Efficiency With the Fire Light Detection Algorithm (FILDA)

The point of this work was to enable Wang to use measurements from M-band (operational product) and Day/Night Band as inputs to the FILDA product. FILDA quantifies the fire combustion phase for each fire pixel to improve fire detection and characterize combustion efficiency at night. It does so by using fire radiative power (FRP) from M-band and visible light power (VLP) from Day/Night Band to calculate visible energy fraction (VEF), a measure of the relative portion of flaming versus smoldering phase within each fire pixel retrieved from the VIIRS 750m Active Fire Product. VEF is the ratio of VLP to FRP and is used to calculate MCE.

Definitions

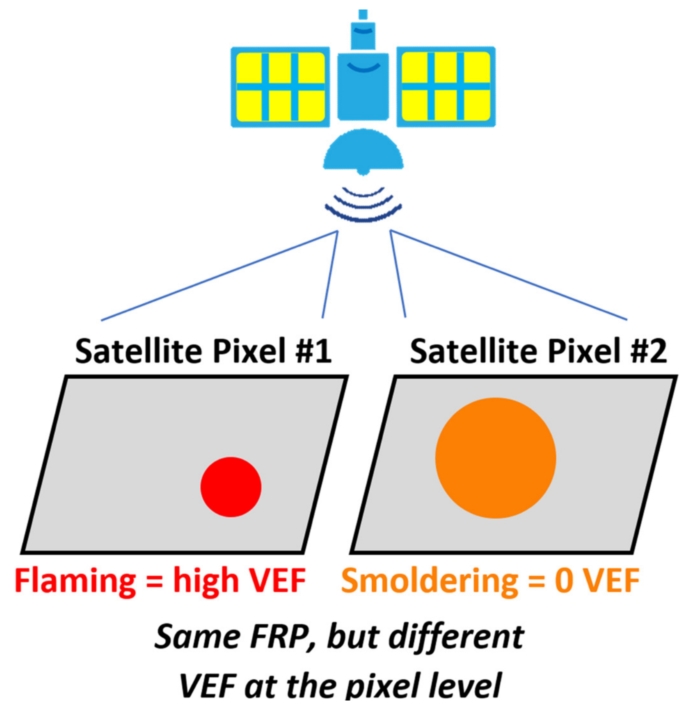
Fire Radiative Power (FRP): *Total radiative power in all wavelengths due to all fires in a pixel.*

Fire Visible Light Power (VLP): *Radiative power in the visible wavelengths due to all fires in a pixel.*

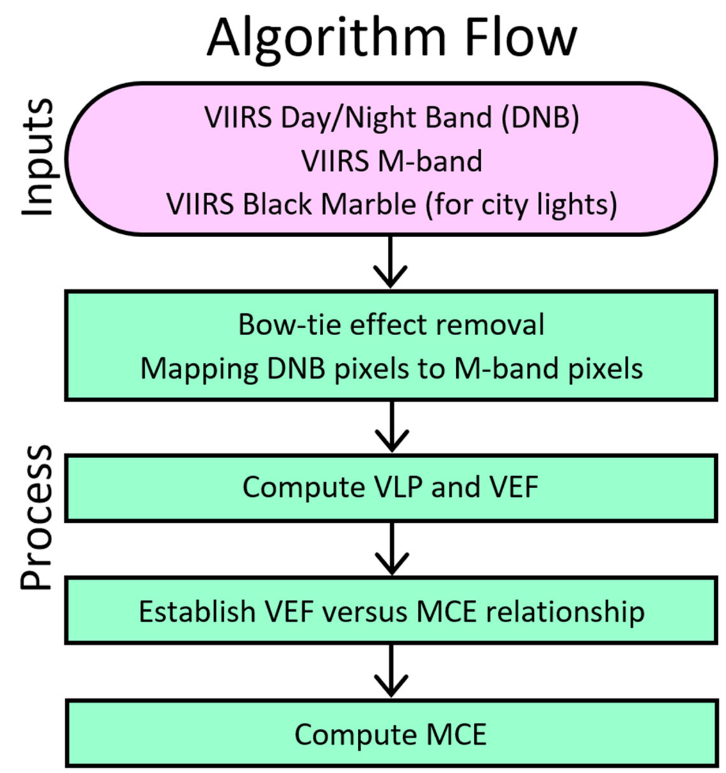
Visible Energy Fraction (VEF): *The ratio of visible light power (VLP) to fire radiative power (FRP) that quantifies fire combustion phase per fire pixel. VEF is the FRP of the visible spectrum.*

$$VEF = \frac{VLP}{FRP}$$

But why is VEF needed? Current operational satellite-derived fire products, like VIIRS Active Fire Products, use FRP to characterize active fires and quantify burning biomass emissions. While FRP provides an estimate of total radiant energy generated by fires in a satellite pixel, VEF describes how much of that radiant energy is visible light, that is, the fraction of fire that is flaming. A smoldering fire emits hardly any radiation in the visible spectrum, so VEF is zero for smoldering fires. In contrast, Wang explains, "For flaming fires, the higher the VEF value, the more complete the combustion because more radiant energy from the fire is due to flaming." VEF provides crucial information about the fire combustion phase and combustion efficiency that FRP has difficulty providing.



To illustrate this point, in the image on the right, satellite pixel #1 represents a small fire area and high temperatures (flaming) and satellite pixel #2 represents a large fire area and cooler temperatures (smoldering). While both fires might have the same or similar FRP, the VEF would significantly differ—the flaming fire (#1) would have a high VEF value while the smoldering fire (#2) would have an insignificant or zero VEF value. FRP tells little about combustion, but VEF reveals a lot.



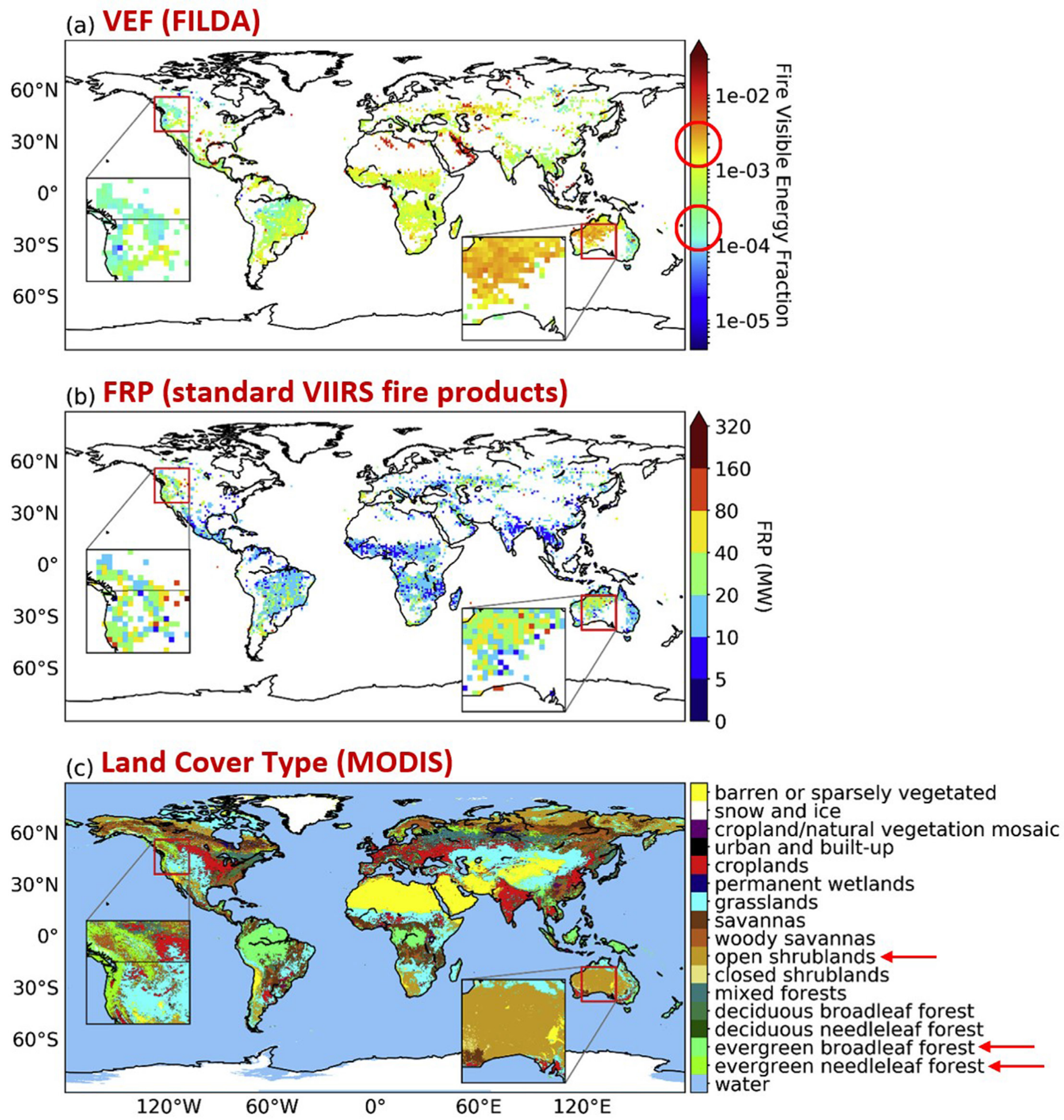
Once VEF is known, MCE can be calculated. Once MCE is known, fire emission factors can be estimated and used to calculate the amount of CO_2, CO, black carbon, and other pollutants that are being emitted from wildfires. This data is desired by climate modelers and fire agencies because it is more tangible than emission factors derived from FRP.

While the physics is clear, Wang and his colleagues have been working on this research algorithm for the better part of a decade, as their goal is to streamline the FILDA algorithm step by step so that it can be efficiently applied globally for fire detection. This work not only helps improve emissions inventories, but it also goes a long way in providing valuable information about the fire combustion phase needed by responders to better understand fire line (or flame) movement, extent, and ferocity.

Global Characterization of Fire Combustion Efficiency From Space—A First!

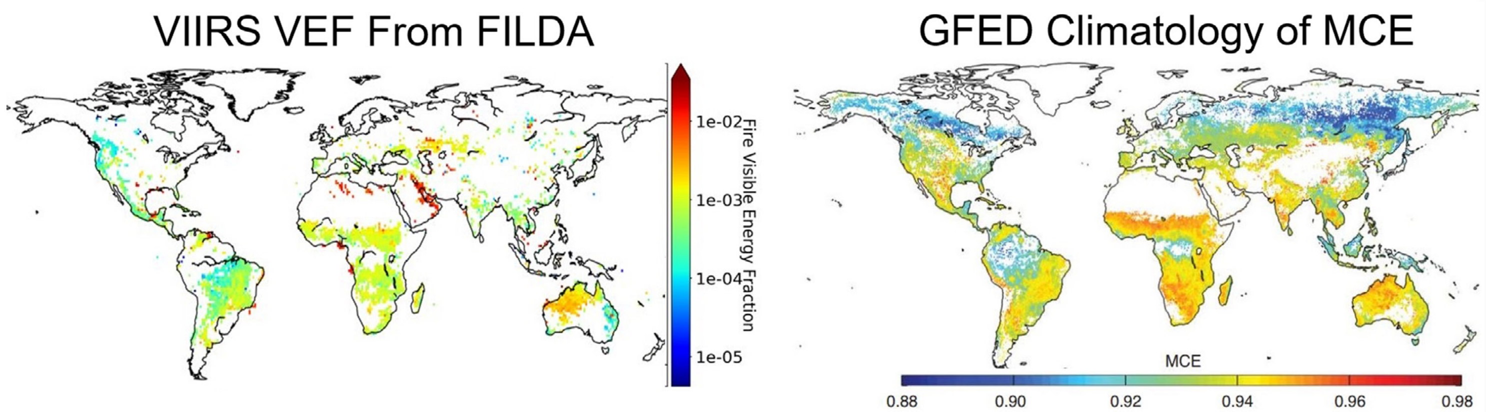
While evaluating FILDA, Wang made a fascinating observation when he calculated VEF and mapped the fire combustion phase across the globe (right, top and middle images). Here, the highest VEF values (red) point to gas flares along the west coast of Africa, Northern Africa, and the Middle East, which makes sense because gas flares are flaming and have very high complete combustion. Things get interesting when zooming into California and Australia (call out boxes), regions with long and intense fire seasons. VEF is much higher in Australia than in California. Why? Wang found an answer in land surface type.

VEF values (top image) mimic land cover (bottom image). "VEF in shrubland in Australia are much higher than the VEF values of evergreen forests in North America, which is consistent with the literature," says Wang. In other words, brush fires burn a lot hotter and have higher combustion efficiency than forest fires, which is consistent with VEF values. On the other hand, FRP in these regions do not show this difference (middle image). FRP are similar between regions in terms of how much radiant energy is emitted, which is expected given the definition of FRP (total radiant energy emitted by a fire at all wavelengths).

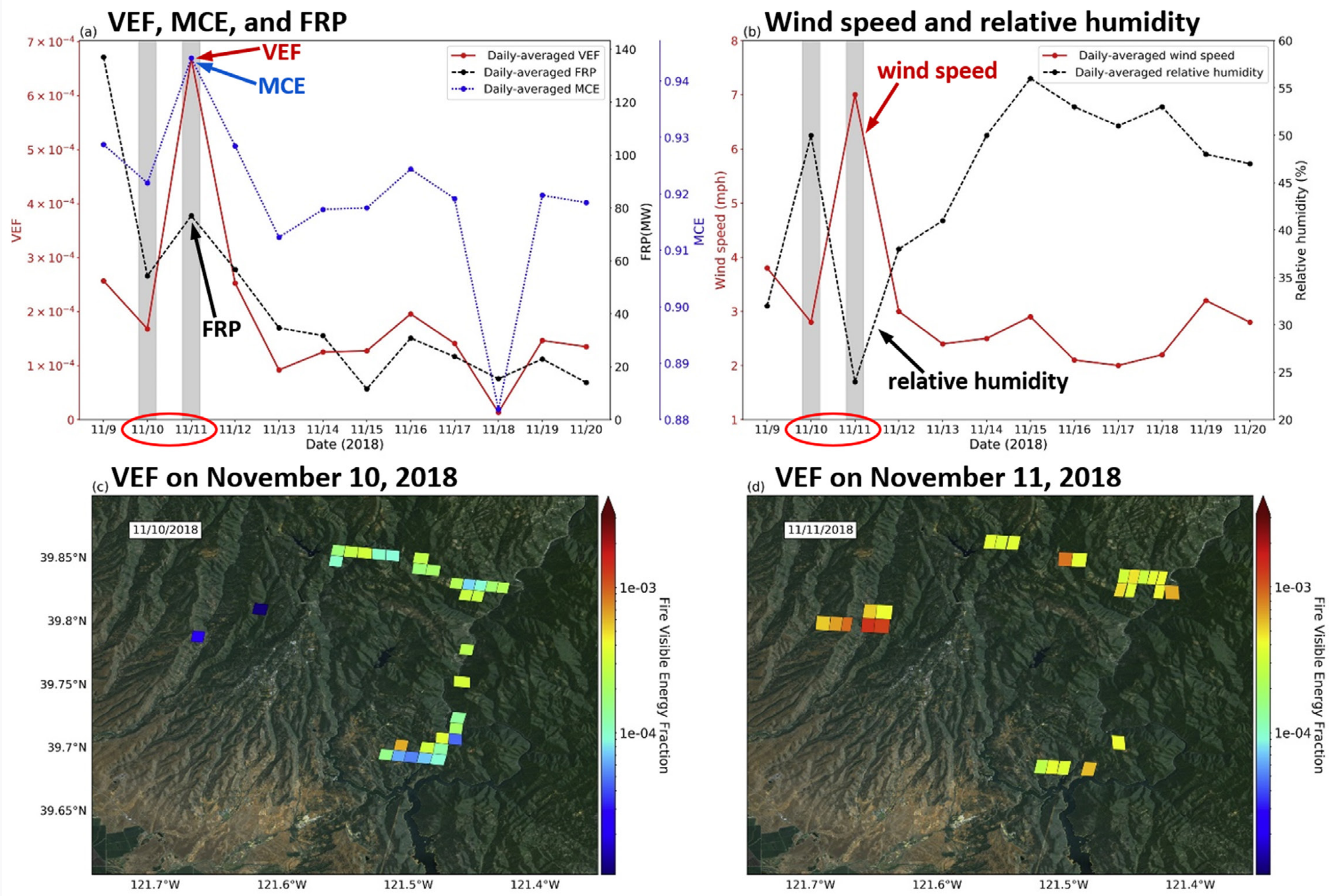


Top (a): Global map of VEF for 2017. Each 1° grid represents the average VEF value for the year 2017. The VEF map shows the transition from forest land cover type in North America (lower VEF) to shrublands in Australia (higher VEF). The red grids (highest VEF) are mostly corresponding to the gas flares while the lowest VEF (blue color) are where the evergreen forests are located. Middle (b): Global map of FRP for 2017. Each 1° grid represents the average nighttime FRP value for the year 2017. The FRP map does not capture the fire combustion phase differences based on the land cover type as the FRP spread for shrubland and forest are similar. Bottom (c): Global landcover map generated based on the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Climate Modeling Grid for the year 2017. The land cover categories are according to the International Geosphere-Biosphere Programme (IGBP) scheme. Source: Wang et al 2020.

Taking it a step further, Wang compared global VEF with Global Fire Emissions Database (GFED) climatology of MCE, the best knowledge available from fire emission and climate modelers. What he found was good correlation between values, which was statistically validated and is shown in the comparison images below.



“VEF clearly shows the influence of biome types on MCE—these matchups indicate that land cover has an impact on combustion efficiency,” says Wang. This was the first global characterization of fire combustion efficiency from space, providing validation that VEF from the FILDA product more accurately and completely describes the MCE variation of different vegetation types.



The Meteorological Impact on Combustion

“Historically, fire emission factors are often treated as constants in fire emission estimates, not affected by wind speed and relative humidity, which influence fire dynamics, or the life cycle of the fire,” says Wang. So, what is the relation of wind and humidity to VEF, FRP, and MCE? To answer this, Wang’s team compared these factors across the early days of California’s Camp Fire that occurred in November 2018. Retrievals (above, top left) show that VEF and MCE were highest on day 3 of the fire (November 11), but FRP was highest on day 1 (November 9). “It turns out this peak of MCE reflects the results of high wind speed up to 7 meters per second and low relative humidity down to 25% on the third day, as compared to low wind speed of 3 to 4 meters per second and high relative humidity of 30 to 50% on the first two days,” points out Wang. What happened was that a phenomenon called the Diablo wind—hot, dry wind from the mountains—came through on day 3 and influenced combustion (above, top and bottom right). The obvious link between this dramatic weather shift and the spike in VEF and MCE values shows the promise in using VEF and MCE for forecasting fire direction.

ESTIMATING FIRE GROWTH WITH FILDA

Besides computing combustion efficiency, the FILDA product with its combined VIIRS Day/Night Band and M-band detection does well at finding smaller and cooler fires that are missed by other products. To show this, Wang compared the performance of FILDA, VIIRS M-band, and VIIRS I-band fire detection products for the William Flats Fire in August 2019. For awareness, the standard VIIRS fire detection product relies on M-band to compute FRP. I-band is not used because of a saturation problem, but it detects smaller fires with relatively high accuracy making it a good comparison tool. In his analysis, Wang found that several fires detected by VIIRS I-band were not detected by VIIRS M-band (shown below). "But," he says, "with our algorithm using Day/Night Band together with M-band, we can detect the fires at a similar level of accuracy that is found using the I-band."

CLICK IMAGE TO ENLARGE.

In addition, FILDA has the potential to better predict fire movement. For example, looking at a 2020 California fire (below), the starting location on August 19 was confirmed by the highest VEF value (in red). The next day, August 20, the fire had grown and VEF along the southern edge (white line) was very high (red), but the FRP was low (blue-purple). So, where will the fire spread next? Fire growth is driven by the flaming phase and, if high VEF is a hint, then the fire should grow past its southern edge. This is indeed what happened on August 21—the fire expanded far past where VEF values were the highest the previous day. FRP tells a different story and little about where the fire might spread. Land cover affects growth, too, which is noticeable along the northern edge (circled) where fire growth was limited by the lack of vegetation to the north and east.

CLICK IMAGE TO ENLARGE.

The FILDA product gives responders a more complete description of fire. The increase in fire pixels detected is shown below—more than double when Day/Night Band is added! Wang emphasizes the importance of this additional data: "We can see more clearly where the fires started and what direction they went with more fire pixels—critical information for firefighters."

CLICK IMAGE TO ENLARGE.

A near real-time version of FILDA over the continental U.S. is available at http://esmc.uiowa.edu:3838/fires_detection/ for use by the research and response communities. The product is maintained by the University of Iowa Atmospheric and Environmental Research Lab (UIOWA-AER Lab) research group led by Wang. Below is an example of FILDA output showing the MCE, VEF, and FRP for the Cerro Pelado Fire that ignited in April 2022 near Santa Fe, New Mexico.

CLICK IMAGE TO ENLARGE. MCE (left), VEF (middle), and FRP (right) from FILDA for day 9 (April 30, 2022) of the Cerro Pelado Fire located about 35 miles west-northwest of Santa Fe, NM. The FILDA values overlay a VIIRS S-NPP True Color Image.

RELATED RESEARCH

Wang and his colleagues are also working on using VIIRS Day/Night Band to retrieve global smoke aerosol optical depth at night, a measurement currently only available in daytime. Doing so will improve model forecasting and the understanding of the role of aerosols in atmospheric chemistry. Wang also wants to know how high wildfire smoke can rise, which impacts how far it is carried by the wind. "Aerosol layer height is needed by air quality managers who want to know if the smoke layer is high or low so they can make accurate air quality advisories for the community," explains Wang. More can be found about this ongoing research in several recent publications:

- Wang, J., Zhou, M., Xu, X., et al. (2020). Development of a nighttime shortwave radiative transfer model for remote sensing of nocturnal aerosols and fires from VIIRS. Remote Sensing of Environment, 241:111727. https://doi.org/10.1016/j.rse.2020.111727
- Zhou, M., Wang, J., Chen, X., et al. (2021). Nighttime smoke aerosol optical depth over U.S. rural areas, first retrieval from VIIRS moonlight observations. Remote Sensing of Environment, 267:112717. https://doi.org/10.1016/j.rse.2021.112717
- Chen, X., Wang, J., Xu, X., et al. (2021). First retrieval of absorbing aerosol height over dark target using TROPOMI oxygen B band: Algorithm development and application for surface particulate matter estimates. Remote Sensing of Environment, 265:112674. https://doi.org/10.1016/j.rse.2021.112674

PERSPECTIVE

This research shows that VEF is better at describing the fire combustion phase than fire radiative power, which is valuable for fire response and emergency management. Earlier response is critical for reducing loss of life, health impacts, and property damage. Using FILDA to identify fires that have a higher threat of spreading will enable responders to focus their resources, which are often limited, especially when battling multiple fires in a region. The relationship between VEF and MCE is robust and appropriate for estimating emission factors at the satellite pixel level, which could have important implications on atmospheric modeling and the timeliness of air quality alerts. Wang and his colleagues continue to conduct nighttime field and lab work to further evaluate VEF and the FILDA product, which, under the support of NOAA and NASA, continues to improve and evolve. ✦

STORY SOURCE

The information in this article is based, in part, on the October 18, 2021, JPSS Science Seminar "Lighting the Dark: Insights of Fire Combustion Efficiency and Smoke Transport at Night From VIIRS" presented by Dr. Jun Wang, a James E. Ashton Professor in the College of Engineering at the University of Iowa, Assistant Director of the University of Iowa Technology Institute, and Director of the Atmospheric and Environmental Research Lab.

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Wang, Jun. (2020, October 21). Remote Sensing of Fire Combustion Efficiency & Smoke Plume Height [Video]. YouTube. https://youtu.be/oQTT2Te5Zuk