SPECTRAL ANALYSIS OF FLAMING AND NON-FLAMING INFRARED EMITTERS WITH NIGHTTIME VIIRS DATA: PRELIMINARY RESULTS

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ABSTRACT: Traditional satellite fire detection algorithms report out pixels with enhanced radiance in a single spectral band. In such case, it is impossible to calculate the temperature or source area because the fire radiant emissions are sampled at a single wavelength. Beginning in 2012, our team developed the VIIRS nightfire (VNF) algorithm, which searches for IR emitters in six spectral bands spanning near infrared (NIR), shortwave infrared (SWIR), and midwave infrared (MWIR). The original VNF used dual Planck curve fitting for a hot IR emitter and a cool background. The IR emitter Planck curve was then used the derive the IR emitter's temperature, source size, and radiant heat using physical laws. The analysis assumes that the IR emitters inside the pixel footprint have a constant temperature. Flaming phase combustion tends to dominate resulting temperature, a consequence of the T^4 term in the Stefan-Boltzmann Law. Our team has developed methods to resolve two IR emitter phases present in a single pixel. The approach is via triple phase Planck curve fitting for a cool background, and hot flaming phase and an intermediate temperature non-flaming phase, such as smoldering.

1. INTRODUCTION

Biomass burning is a long-standing global phenomenon occurring on land surfaces ranging from 60 south to 75 north (Figure 1). In recent years there is evidence that the frequency and severity of biomass burning has accelerated due to higher temperatures, drought, fuel buildups, and the expansion of anthropogenic ignition sources, from power lines to agricultural clearing (Running, 2006; Pechony and Shindell, 2010). The largest and deadliest fire in California history was the 2018 Camp Fire, which was ignited by power lines and destroyed the town of Paradise. But this is just one in a long line of mega-fire events that make it to the front pages. In July 2019, massive fire events spanned from the boreal forests of Siberia (Figure 2) to the Arc of Deforestation in the Amazon. Smoke from the Siberia fires has been detected in Canada and USA. According to Brazil's space agency (INPE), satellite observed hotspot numbers in 2019 are 82% higher than 2018 (Escobar, 2019). Clearly, we are living in an era where fires are increasingly reshaping the landscape, the atmosphere and climate.

Spatial and temporal information on biomass burning are used in several ways: 1) To plan fire-fighting activities and to evaluate progress in containing and extinguishing fires. 2) To inform the public and policy makers on the current fire situation. 3) To identify source areas for transboundary smoke and haze. And 4) To model greenhouse gas and particulate emissions for carbon cycle and climate studies. Up-to-date information on combustion phase, temperature, source area and heat output would be extremely valuable for all four of these use cases, however such data are currently unavailable from any systematic global data source.

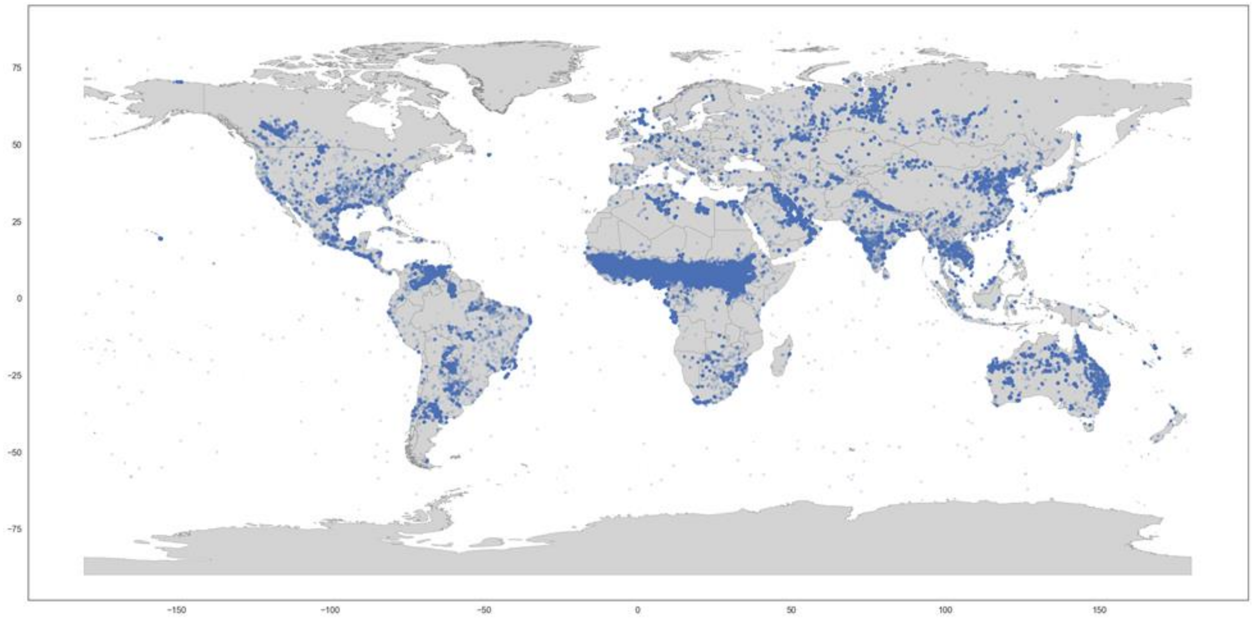

Figure 1. One-year accumulation of fire and flare detections from the VIIRS nightfire data product from 2018 (Elvidge et al., 2019).

There are two distinct phases to biomass burning: flaming and smoldering. The phases differ radically from each other in terms of the temperature, composition of trace gas emissions and quantity of aerosol (smoke) emissions. Ohlemiller (1995) defines smoldering as ‘a slow, low temperature form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel’. Flaming is a higher temperature form of combustion, where an open-air flame is fueled by gases released from temperature induced cracking of large chain polymer molecules present in biomass, such as cellulose and lignin (Lobert and Warnatz 1993). Flaming is typically initiated first, providing the necessary heat to achieve longer lasting smoldering combustion. The two combustion phases have vastly different character in terms of trace gas and particulate emissions related to the level of fuel oxidation, indexed as combustion efficiency. The smoldering phase produces more smoke and partially oxidized trace gases. The flaming phase in biomass burning can range from 750 to 1400 K. Smoldering is cooler, with smoldering peat fire cited to be in the range of 350 to 500 K.

Is there a way to distinguish the two phases in remote sensed data? This is not possible with the standard satellite fire product, which detect thermal anomalies in spectral bands in the 4 um range. It is clear that any attempt to distinguish flaming from smoldering combustion would require a larger set of spectral bands. Elvidge et al. 2015 reported that it is possible to distinguish flaming and smoldering combustion in peat fire burning in Indonesia with four spectral bands in Indonesia. In this paper we present preliminary results on the separation of flaming and smoldering radiant emissions present inside an individual pixel footprint collected at night by the NASA/NOAA Visible Infrared Imaging Radiometer Suite (VIIRS).

2. Why Focus on Nighttime Data?

VIIRS collects four daytime channels at night, two in the near infrared (NIR) and two in the shortwave infrared (SWIR). These channels are designed to record reflected sunlight. With sunlight eliminated, these channels record the background noise of the sensor, which is punctuated by high radiances for pixels containing IR emitters such as fires and flares. The daytime channels are particularly useful for the detection of IR emitters, such as fires and flares because they stand out clearly against instruments noise floor and the radiance can be fully attributed to the IR emitters present in the pixel footprint. The SWIR bands are particularly advantageous because they are centered in the clearest atmospheric windows, have extremely low detection limits due to low solar irradiance, and have an uncanny ability to see through smoke (Eck et al., 1999).

3. Spectral Simulation

The nighttime Landsat study on flaming and smoldering (Elvidge et al., 2015) ignored background and assumed that if a pixel had a long wave infrared thermal (LWIR) anomaly that there was no background present. That simplifying assumption was marginal given the 100 meter pixel size of the Landsat 8 thermal band data. But the pixel footprints of VIIRS are vastly larger, so we have to assume the flaming and smoldering will always be subpixel elements surrounded by cooler background in the VIIRS data. To examine the feasibility for spectral unmixing of flaming, smoldering and background with VIIRS, we used Planck's Law (Planck, 1901) to simulate the radiant emissions form a pixel containing 1% of its surface area in flaming at 800 K, 10% in smoldering at 450 K, and 89% background at 300 K. The resulting Planck curve radiant emissions are shown in Figure 2 overlain by the wavelength positions of the VIIRS spectral bands that collect at night.

What can be seen in figure two is that the three Planck curves are offset based on temperature. The flaming curve is shifted furthest to the short wavelength end, the background radiant emissions are concentrated in the LWIR, and smoldering is in-between. Another thing to note is that the peak radiance from flaming exceeds either flaming or smoldering. Even though flaming only occupies 1% of the pixel, there is a wavelength where its radiant emissions exceed the other components. This can be traced to the T^4 term in the Stefen-Boltzmann Law (Boltzmann, 1884).

In terms of remote sensing, the flaming phase Planck curve can be sampled quite cleanly in the two SWIR bands. The smoldering phase radiant emissions make a small contribution to the M11 spectral band but are absent in the M10 band. The background radiant emissions are absent in the SWIR spectral bands. This is anticipated based on the fact that clouds and erath surface features cannot be seen in the SWIR bands at night.

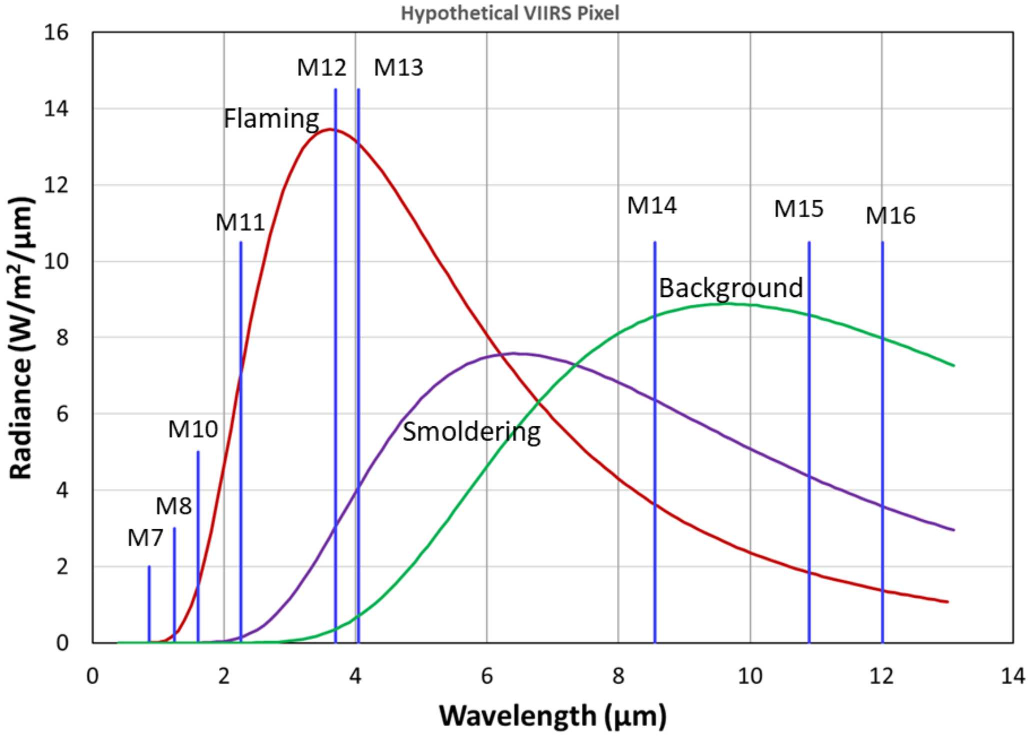

Figure 2. Simulation of a nighttime VIIRS pixel radiance containing 1% flaming at 800 K, 10% smoldering at 450 K and 89% background at 300 K. The spectral band centers of the nighttime VIIRS are marked as vertical lines.

4. Application to VIIRS Data

We are developing an algorithm for discriminating flaming and smoldering combustion in nighttime VIIRS data. This is being built on top of the VIIRS Nightfire (VNF) algorithm (Elvidge et al., 2013) which runs IR emitter detection on six spectral bands (M7-13) and dual Planck curve fitting for a single temperature IR emitter and background. For pixel with both SWIR and MWIR detection the new algorithm performs spectral unmixing by simultaneous triple curve Planck curve fitting for a flaming phase, smoldering phase and background. The fitting is performed using the observed radiances and is further constrained by a flaming phase temperature derived from the Planck curve fit from the short wavelength channels (M7-11). The intitila temperatures used in the fitting are 300 K for background, 500 K for smoldering and 1000 K for flaming. When the smoldering phase results are spurious, the pixel reverts back to dual phase Planck curve fitting of the original VNF algorithm. Atmospheric correction is advisable because Planck's Law assume the atmosphere is 100% transparent. At this point the algorithm is able to identify pixels with flaming only and others with a mixture of flaming and smoldering.

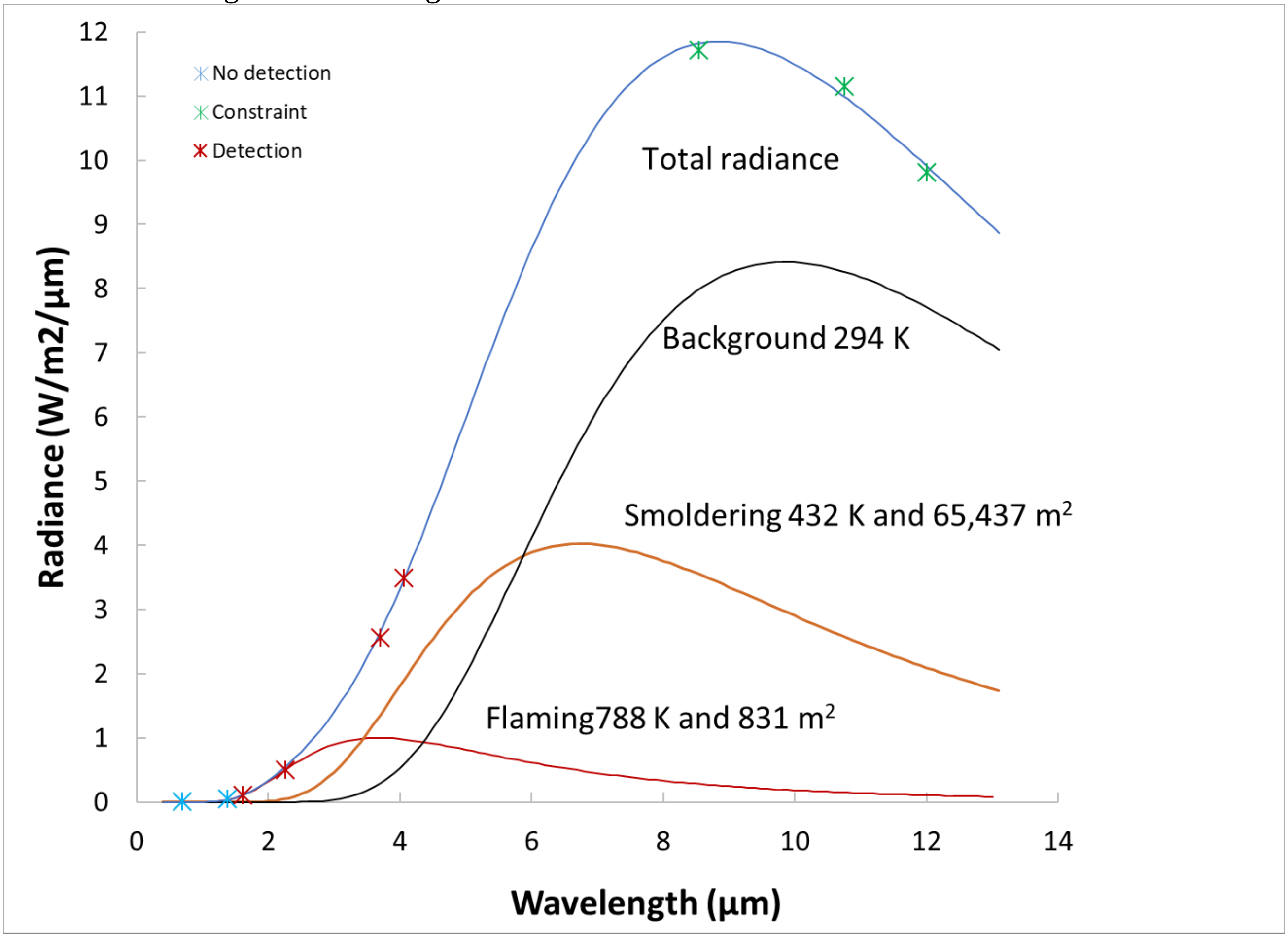

Figure 3. Results from simultaneous triple phase Planck curve fitting from a smoldering peatland fire in Sumatra observed by VIIRS on September 27, 2014. The VIIRS observed radiances are marked with asterisks.

5. Conclusion

We are conducting research on subpixel unmixing of flaming and smoldering phase combustion with nighttime VIIRS data. We aim for an fire algorithm that calculates temperature and source area for three phases – flaming, smoldering and background – a total of six variables. The VIIRS collects data in nine spectral channels at night spanning 0.8 to 12 um. The flaming versus smoldering analysis is only triggered when there is fire detection in at least the two SWIR and MWIR bands. The unmixing approach is simultaneous triple curve Planck curve fitting based on the observed radiances plus the flaming phase temperature derived from the NIR and SWIR radiances. Working with radiances in nine spectral bands and temperature there are nine degrees of freedom, in theory sufficient to calculate the six desired outputs. An atmospheric correction is important because Planck's Law is based on a scenario of zero atmospheric loss. The preliminary results are encouraging. The team is applying the current method to a wider range of test areas spanning boreal, to temperate to tropical ecosystems.

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