Investigating the Spatio-Temporal Dynamics of the Syrian Civil War through Spaceborne Thermal Infrared Data

Implications for Human Rights
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This report was authored by:
Sara Hamilton, University of Oregon, Intern, AAAS SRHRL
Jonathan Drake, Senior Program Associate, AAAS SRHRL

Acknowledgement
Primary support for this project was provided by the Oak Foundation through grant number ORIO-15-052.

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Contact
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American Association for the Advancement of Science
Scientific Responsibility, Human Rights, and Law Program
1200 New York Avenue, NW
Washington, DC 20005 USA
**Background**

Many events associated with violent conflict result in the ignition of fires. This phenomenon can take the form of intentional acts of arson such as the burning of buildings, the unintended ignition of flammable materials from the effects of ordinance, the burning of debris as part of reconstruction efforts, or the destruction of evidence related to possible war crimes, to name just a few possible examples. While fires burn, the attendant high temperatures result in significant emissions of infrared radiation across a range of wavelengths defined by Planck’s law. This radiation can be detected by sensors optimized to collect data from the region of the electromagnetic spectrum known as the “thermal infrared”, which spans a region ranging from approximately three to fifty microns in wavelength. A large number of such sensors currently exist, some of which have been placed on Earth-observing satellites, and are used to study phenomena ranging from volcanic eruptions to forest fires to clandestine gas flaring.1,2 These sensors can also be used to study fires resulting from conflict, as shown by the work of Bromley (2010). Subsequent damage analyses by groups such as UNOSAT have likewise used infrared data to supplement high-resolution satellite imagery analysis of conflict zones in areas such as Georgia and Kyrgyzstan.3,4,5 Although the work of Bromley shows that trends in satellite fire detections can be related to conflict activity in Darfur on a regional scale after the fact, whether this data product can be used to identify spatial and temporal variation in conflict-related fires at the city level, whether it can provide relevant insights into a more industrialized conflict than the violence in Darfur, or whether it has the potential to be a leading indicator of events that later result in significant news events, remains unclear.6 If such insights can be obtained through infrared fire detections, the human rights implications would be significant, as it would allow a more rapid identification of and response to the escalation of violent conflict. This work attempts to answer these questions by exploring what trends can be discerned in thermal infrared satellite data of the Syrian Civil War at a variety of spatial scales.

**Data and Methods**

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a pair of instruments flying on two NASA spacecraft in orbit around Earth. These Earth-observing satellites, known as Terra and Aqua, provide near real-time global coverage in the visible and infrared wavelengths at spatial resolutions ranging from 250 meters to 1 kilometer per pixel. Data generated by the two MODIS instruments have been used by a large number of ongoing scientific projects, including MODVOLC, a hotspot detection algorithm developed by volcanologists from the University of Hawaii which monitors incoming MODIS data for all pixels that exhibit the distinct infrared signature of abnormally high temperatures. These hotspots, which are reported regardless of volcanic origin, are stored in a publicly available database which is updated daily. The archives of this database now span over a decade- a feature that is ideal for monitoring the evolution of conflict-related fires associated with the Syrian Civil War. For the purposes of this investigation, all MODVOLC fire detections between

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5 UNITAR (2008) “Update 2: Active Fire Locations for Tskhinvali, South Ossetia, Georgia” https://www.unitar.org/unosat/map/1247 accessed 31 August 2018  
6 Although UNOSAT’s work includes fire data, the primary data product for their analyses are high-resolution satellite imagery.
January 2005 and September 2016 were downloaded. The period from January 2005 through March 2011, before the war began, was used to develop a baseline of typical fire activity for peacetime Syria, while subsequent fire detections were analyzed in the context of relevant events associated with the conflict. To investigate the spatial clustering of individual fire detections, the MODVOLC detections were analyzed using the Optimized Hotspot Analysis tool in ESRI's ArcMap, which creates a map of statistically significant “hot” and “cold” regions at a scale determined by the spatial distribution of the input points.\(^7\)

**Results**

**Comparison of Pre-War vs. Post-War MODVOLC Detections**

At the national level, from January 2007 through the beginning of 2011, the MODVOLC database indicated an average of 17.6 fire detections per month in Syria. In the 79 months after the war began, however, the number of detections per month doubled to an average of 34.6 detections/month, a highly significant increase \((p\text{-value} = 0.000000007)\). Additionally, prior to the war, 87.3\% of the detections were observed to occur during the summer months of June, July, and August. Although the rough outlines of this annual pattern persist following the outbreak of the war, after the conflict began many more detections were observed in other months as well, especially during the period from 2012 to 2013, and the percentage of detections that take place in the summer months drops to 62.6\% (Figure 1).

![Figure 1: The number of MODVOLC heat detections in Syria by month from January 2005 to November 2016. The red dashed line represents the beginning of the war, March 2011.](image)

The spatial distribution of the detections changes after the war began as well (Figure 2). Before the war, the northwest and northeast corners of the country were the only areas that Optimized Hotspot Analysis identified as significant clusters of detections. These clusters overlay parts of Syria that appear very green in visible band satellite imagery, suggesting that the clusters may be associated with agricultural burning. After the war begins, however, the detection cluster in the northeastern part of the country was observed to shrink significantly, while new clusters appear, southeast of Aleppo and in the central-eastern part of the country. Additionally, the hotspot in the northwest corner of the country grows to touch the cities of Idlib and Hamah.

\(^7\) In the context of this analysis tool, “hot” and “cold” refer to high and low spatial densities of detected fires, and is unrelated to the fact that the fires themselves are literal “hot spots”.

Additionally, during the war, the detections are far more likely to come from cities compared to prior to the outbreak of hostilities. For the 57 months before the war, less than 1% of MODVOLC detections were located within the eight largest cities in Syria (Aleppo, Damascus, Homs, Latakia, Hama, Ar-Raqqah, Deir ez-Zor, and Al-Hasakah). In the first 69 months after the war began (March 2011-November 2016), this number rises to 7.6%, a highly significant increase (p-value = 0.0000024). The detections clustered around the cities are rarely in the densely populated center of the city, but rather congregate around the outskirts, especially in Aleppo, Deir ez-Zor, Ar-Raqqah, Al-Hasakah, and Homs (Figure 3).

Additionally, the radiance of bands 21 and 22 on the MODIS instrument are significantly higher in MODVOLC detections after the war begins. The mean radiance for band 21 shifts from 1.94 Wm$^{-2}$sr$^{-1}$µm$^{-1}$ before the war to 2.87 Wm$^{-2}$sr$^{-1}$µm$^{-1}$ after the war and for band 22 from 1.42 Wm$^{-2}$sr$^{-1}$µm$^{-1}$ to 1.57 Wm$^{-2}$sr$^{-1}$µm$^{-1}$. (p-value > 0.001 for both bands). According to the MODVOLC documentation, the
band 22 detectors often saturate over highly radiant surfaces, suggesting that this shift could result from a qualitative difference in the nature of the heat generated during the war compared to previously. A shift of similar magnitude in the radiance of these bands, however, was also observed outside of Syria. In a swath of central Turkey, the mean radiance for both bands increased by a similar amount over the same timeframe (p-values >0.001 for both bands), suggesting that this phenomenon may not be conflict-related.

Analysis of MODVOLC Detections During the War

It was unclear whether many of the spatio-temporal changes in MODVOLC detections were related to the civil war. In some cases, the algorithm appeared to be detecting hotspots associated with conflict events very precisely. For instance, in late 2012, news outlets began reporting that fighting between rebels and government forces in Aleppo was moving closer to the Aleppo International Airport. By February 2013, BBC News and CBS News were reporting that intense fighting over control of the airport had killed over 100 people.\(^8\)\(^9\) Indeed, although there were no MODVOLC detections near the Aleppo airport in the 5 years leading up to the war, 7 detections occurred within 2-3 km of the airport in February 2013 (Figure 4). Additionally, another cluster of detections took place about 4-5km away from the airport in January 2013. Similarly, in June 2015 fighting between ISIL and Kurdish forces broke out in the northern Syrian town of Kobani, which had been mostly peaceful up until that point in the war. Correspondingly, while Kobani and the surrounding has just 7 total detections in 2014 and 1 in 2016, there were 70 detections in 2015, 54 of which came in June (Figure 5).

Conversely, many events that should have emitted substantial amounts of heat were not detected by MODIS sensors. For example, on September 29, 2012, a fire razed the old central market in the heart of Aleppo. Although satellite images of the Aleppo old city that day show plumes of smoke

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rising from the heart of the city, the event caused no MODVOLC detections. Additionally, very few detections were found in the cities of Damascus and Daraa, some of the areas of the most intense fighting. In fact, out of the 2391 MODVOLC detections produced from March 2011 thru November 2016, only 9 of those were within 15km the heart of Damascus. Furthermore, some MODVOLC detections did not appear to be related to agriculture but neither did they match any news reports of conflict. For example, a series of strong hotspots appear in the Deir ez-Zur region from April 2013 to July 2013, but few media outlets reported any conflict in the area at that time. Only one violent event was reported in this 4-month range in the eastern part of the country (Figure 6). The detections were not likely to be related to agricultural activity since this area is desert. Whether this is because conflict existed but was never reported, or whether the detection is the result of some other phenomenon is unclear.

Hotspot Detections and News Interest

In order to explore the potential for fire detections as a leading indicator of events that would later appear in reporting, both Google News archives and the GDELT media archives were used to examine the amount of news interest generated surrounding the Syrian Civil War during the study period. MODVOLC detections did not correlate with the volume of news coverage derived from either of these archives. When correlating MODVOLC Detections against the Gdelt metric of news interest, the R-squared value was 0.0004 and against the Google News metric was 0.04. When the analysis of news was focused on a single city (Aleppo), similarly low correlations were observed. Using Google News metrics, the correlation between MODVOLC Detections and news interest by

Figure 4: Visual imagery of the southeastern section of Aleppo with MODVOLC detections represented by orange asterisks. The cluster of detections circled in red are within 2.5 km of the airport and all occurred in February 2013. The cluster of detections circled in green took place within 4.5 km of the airport and most occurred in January 2013. In the upper right-hand corner is the optimized hotspot analysis from January 2013, showing a 95% confidence spike in detections in the Aleppo area that month. North is up; scale is 1:80,000.
Figure 5: On the left is the Optimized Hotspot Analysis of MODVOLC detections across Syria in June 2015 with a 95% confidence hotspot centered over Kobani. On the right are all the detections that occurred within 30 km of Kobani in 2014 (in green, 7 detections), 2015 (red, 70), and 2016 (blue, 1), with those in 2015 symbolized as either in June (asterisks, 54) or Jan-May/July-Dec (circles, 16). Scale at right is 1:600,000; north is up.

Figure 6: On the left, red circle surrounds the city of Damascus and its suburbs. Orange dots represent ModVolc Detections, of which there were only 9 in the 6.5 years after the war began. On the right is the Optimized Hotspot Analysis for June 2013, which shows a large 95% confidence hotspot of ModVolc detections in the eastern part of the country. A similar hotspot occurred in April 2013 and July 2013, despite very few reports of violence in the area. Scale at right is 1:500,000; north is up.

week had an R-squared value of 0.007. The Aleppo example also gave some insight into why news coverage did not tend to follow the MODVOLC detections. The highest level that news interest in Aleppo ever reached was in September 2016 according to Google News. This did not relate to events on the ground in Aleppo, but was spurred by a verbal gaffe related to the city during an interview with US presidential candidate Gary Johnson. Overall, MODVOLC detections appeared to correlate with many newsworthy conflict-related events during the Syrian Civil War, but it missed many of them as well.
Conclusion

This study was undertaken to explore how and whether the spatio-temporal dynamics of hotspots identified in the MODVOLC data product could be linked to the Syrian Civil War. This correlation, if strong, could provide information of significant value to human rights and crisis response actors. Recent investigations into the remote sensing of violent conflict have found that conflicts often produce heat in the form of fires, incendiary bombs, etc., and that satellite based instruments can detect those heat events. (Bromley 2008). In light of this, if the MODVOLC algorithm detected heat events related to the civil war, one would expect to see the spatio-temporal dynamics of the detections change after the war began. Specifically, one would expect to see more detections in Syria as the area became inundated with incendiary bombs and scorched-earth military tactics. It would also be expected that detections would shift from the pre-war spatio-temporal distribution to a spatio-temporal distribution that more closely matched the distribution of violence throughout the war.

Our results support these hypotheses and suggest that MODVOLC detections were picking up a significant number of heat events that were related to violence during in the Syrian Civil War. Before the war, there were relatively few detections, the detections took place primarily during the summer months, and they occurred in green, vegetated areas in the northeast and northwest of the country. This would be consistent with the hypothesis that prior to the war MODVOLC detections were mostly heat events related to annual agricultural burning taking place during the growing season in the more verdant parts of the country. After the war began, however, this potential agricultural burning subsided. Following the commencement of hostilities, the number of detections doubled, and these detections shifted away from the summer months and out of the northeastern part of the country. Furthermore, more and more of the detections were observed in cities and deserts rather than in fertile, green agricultural areas. Not only were there more detections per month during the war, but fewer of them appeared to be coming from agricultural burning. This could be reflecting decreased agricultural production due to a wartime displacement of farmers and disruption in resource availability to those still farming. During the war the densest clusters of detections took place near areas of intense conflict, such as the regions southwest of Aleppo, in Idlib province, and near the cities of Hamah and Deir ez-Zour. Monthly optimized hotspot analysis shows clusters of detections that sometimes shift with the conflict e.g. moving from Aleppo in January 2013 to Kobani in June 2015. These shifts, however, were far from perfect in mirroring the progression of the conflict. They missed many violent events and sometimes clustered around areas where few reports of violence existed.

Why, if MODVOLC is picking up the signatures of some violent events related to the Civil War, would it fail to detect others? One reason may be that in cities, tall buildings surrounding a heat source may obscure the MODIS sensors’ view of the area. Such a phenomenon might explain why very few MODVOLC detections occurred in the heart of Syrian cities and why it did not detect the fire in the old market of Aleppo (Figure 3). Some of these heat events may also be of relatively short duration, and have been extinguished by the time the MODIS sensor overflew the area. Additionally, the presence of violence and conflict may not always result in heat emissions. Bombings, for example, do not cause damage primarily through fire, but rather through the emission of powerful shockwaves. Therefore, unless the bombs employed by forces on the ground are incendiary bombs specifically designed to start fires, the use of weapons such as suicide bombings, airstrikes, and other bombing events may not create substantial heat energy for MODVOLC to detect even though they may cause substantial damage. Another outstanding question concerns why MODVOLC detects heat events in areas that do not seem to have violent conflict or agriculture, such as Figure 6b. One possibility is that the heat event stems from unrelated events, such as (for example) an accidental fire at an industrial plant. Another possibility is that incidents of violence may have caused the detections, but were not reported by the international media.
Outside the country itself, a large component of current information regarding the conflict in Syria is drawn from reports by international media. These organizations have limited resources to use when covering a conflict, and in remote areas or areas that are particularly dangerous, coverage of conflict may be limited. Furthermore, a western-centric media may choose to cover events that relate to the western interests in Syria more so than the events happening on the ground in Syria. One explanation for the lack of correlation between MODVOLC detections and news interest in Syria could be that the media does not necessarily respond to events that cause MODVOLC detections.

While MODVOLC detections are interesting to look at retrospectively, proactively they could potentially be used as an early warning system for violent conflict. While the conflict in Syria has been intensely covered by the world’s media sources due to its political importance and relative geographic centrality, many conflicts are not, especially in the early weeks, months or even years of the conflict. This report suggests that MODVOLC detections, though not a perfect mirror of the Syrian Civil War, did increase in number, change their seasonality, and shift their spatial distribution at the sub-national and even city level in response to the violent conflict on the ground.