

A COMPARISON OF GOES WF_ABBA
AND MODIS FIRE PRODUCTS

by

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Abstract

Satellite remote sensing provides an automated means of locating and characterizing active fires in near real-time. Diagnostic and prognostic applications, such as climate and air quality monitoring and modeling; land use and land cover change studies; and fire fighting benefit from the use of satellite fire products where it is important to identify emission sources to model total emissions and emission transport. Every satellite fire product has strengths and limitations. Geostationary satellites have the high temporal resolution necessary to identify diurnal fire signatures while low earth orbit satellites provide the higher spatial resolution necessary to enable the detection of smaller fires. Data fusion provides the opportunity to present more information than one satellite product can offer by taking advantage of the strengths of each fire product. One of the largest problems the modeling community faces is the real-time assimilation of active fire products. To produce an accurate multi-satellite merged fire product it is necessary to discriminate and understand the differences between fires detected by multiple satellites and fires detected by only one satellite. Fire product differences are not necessarily due to false detections. Some differences are expected due to orbit, instrument, and algorithm differences while other observed differences can be attributed to fire properties. The disagreement between fire products generates some confusion in the user community. To improve user confidence, this study employs new methods to characterize and understand the differences between the GOES WF_ABBA and MODIS fire products for improved applications by a broad user community and especially in model assimilation.

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1 Introduction

Biomass burning consumes millions of acres each year with significant costs associated with fire suppression and destruction of life and property. Gas and particulate matter emissions from biomass burning can reduce visibility and are associated with the study of climate change. In many parts of the United States and throughout the world, fire is used intentionally in agricultural practices. Fire can be an important part of a healthy ecosystem, but burning in some cases can scar an ecosystem when not properly managed. Prescribed or managed burns are used to prevent larger fires and in many cases help promote a healthy ecosystem by simulating fires that would occur naturally if fire suppression techniques had not been in place. Biomass burning is defined herein as any anthropogenic or naturally occurring fire fueled by plant material resulting in land cover change (i.e. deforestation). Other definitions of biomass burning in literature might be more limiting by excluding either anthropogenic or naturally occurring fires, while still other definitions might be more inclusive by also including biofuels (i.e. biodiesel and ethanol). Unlike many sources of aerosol pollution that can be estimated by tracking emissions from well-known industrial sources, biomass burning is variable and difficult to parameterize [Reid et al., 2004]. In addition to the challenges of detecting and parameterizing fires, different satellite fire products provide different information about fire activity. Disagreement among fire products can cause confusion in the user community; however, instrument characteristics and fire algorithm differences predispose product differences. With a better understanding of fire product similarities and differences data fusion can provide a merged fire product that combines the strengths of each fire product to provide more information than a solitary fire product could provide.

2 Satellite fire detection

Satellite remote sensing technology provides the only automated fire detection method capable of detecting fire locations over large areas. Ground-based sensors directly monitor air pollution concentrations and are well suited to measure point source emissions such as smoke stacks. Ground-based sensors only measure ambient pollution concentrations at fixed locations or, in the case of LIDAR, measure a vertical profile of pollution of a single column, but there is no way to locate emissions from wildfire sources with ground-based sensors. Backward trajectory modeling can be used to estimate the location of emission sources however this does not have real-time applications [Begum et al., 2005]. Forward modeling can forecast aerosol transport, but model accuracy is limited by the accuracy of emission source data. Current meteorological satellites can provide valuable regional and global fire products in near real-time, and are critical for fire detection and monitoring in remote locations where fires would otherwise burn out of control for days before being reported on the ground [Prins et al., 2004].

For over 25 years meteorological and environmental satellites have been utilized to detect, monitor, and characterize fires. Satellite fire detection has been possible since the first 4 μm and 11 μm channels became available on the NOAA (National Oceanic and Atmospheric Administration) AVHRR (Advanced Very High Resolution Radiometer) sensor, first available in 1979 on the NOAA 6 polar orbiting satellite. Two popular automated environmental satellite fire detection techniques are the GOES WF_ABBA (Geostationary Operational Environmental Satellite Wildfire Automated

Biomass Burning Algorithm) and the MODIS (Moderate Resolution Imaging Spectroradiometer) Fire Product algorithms. Both techniques use the 4 μm and 11 μm infrared window bands to identify potential fires in near real-time. Once a 4 μm hot spot is identified the potential fire pixel must pass a series of requirements specified by the fire detection algorithm.

2.1 Usefulness of fire detection

Fire location and fire detection confidence are the two main deliverables in both the GOES and MODIS fire products. Fire weather forecasters use these products in combination with other meteorological data to provide more informed forecasts to those involved in fire fighting efforts. Satellite fire data can provide a consistent source of fire locations that can be applied to climate change analyses and land use and land cover change studies [Cahoon et al., 1992; Feltz et al., 2003; Gerard et al., 2003; Giglio et al., 2006; Kaufman et al., 2003; Prins and Menzel, 1994; Prins et al., 2001; Roberts et al., 2005; Wang et al., 2006]. Satellite observed fires have applications in air quality forecasting and air quality research where they can be applied to model active fire emissions in near real-time. Modeled emissions based on satellite fire detection are also be used in climate studies.

For all applications it is important to understand the strengths and limitations of various satellite fire products. Different satellites have different performance characteristics that are important to understand before limiting a study to one satellite fire product over another or before producing a product of merged fire product data. Performance characteristics are a function of instrument design, and also a function of

fire size, temperature, land type, time of day, location of the fire relative to the satellite, and atmospheric conditions.

Biomass burning plays a key role in public health and environmental issues. It is important for decision makers to be aware that satellites can be used to continuously monitor biomass burning. To achieve even a fraction of the satellite fire product coverage in remote areas with continual monitoring fire detection and monitoring by aircraft quickly becomes more expensive than satellite monitoring. Satellite technology as well as modeling and forecasting techniques that correctly utilize satellite data can be beneficial in terms of forming a better understanding of issues such as air pollution or land use changes associated with burning. Furthermore, improving the information that decision makers receive facilitates better informed policy decisions impacting long term public health and environmental issues in a cost effective way.

Each user group has to make decisions about how to handle the tradeoffs between the performance characteristics of different satellites. Different user groups use the same data to make quite different decisions. The hazards community might not be able to wait on the order of 12 hours for polar orbit satellite coverage when geostationary coverage can provide fire location information as frequently as every half hour (or less if fire detection is applied in rapid scan mode). However, a climate modeler might be able to wait to include fires from multiple fire products where the emphasis is on collecting the most complete fire dataset and there is less of a need for real-time data.

2.1.1 Modeling applications

There is currently no complete and accurate database for regional, national, or global fire activity. For this reason climate change and aerosol and air quality diagnostic and prognostic models are relying on satellite derived fire products to augment more traditional data sets. Satellites products can identify fires and emission sources while surface based stations offer point measurements of pollution levels. Incorporating both surface based and satellite measurements into models has the potential to provide much more information about air pollution and chemical constituency than is provided by surface based measurements alone. Further research is necessary to improve the accuracy of the emission factors, but studies have shown that it is possible to derive emission rates from satellite fire detection [Ichoku and Kaufman, 2005; Reid et al., 2004; Roberts et al., 2005; Wang et al., 2006; Wooster et al., 2005].

2.1.2 Air quality applications

Satellite biomass burning detection can play an important role by identifying pollution sources. Although biomass burning contributes a relatively small percentage of air pollution compared to industrial and transportation sources, biomass burning emissions are significant in terms of peak emissions during fire episodes that sometimes cause non-attainment of the EPA's National Ambient Air Quality Standards (NAAQS). Biomass burning is important in terms of the local and transported emissions that the air quality management community is concerned with. Transported pollution is difficult to regulate because the source of the pollution may be outside the jurisdiction of the areas suffering from poor air quality. For example urban areas in the United States might be

emitting pollution at an acceptable rate to achieve NAAQS attainment, however burning in a nearby rural area or even distant international smoke transport might cause non-attainment resulting in costly measures to reduce local emissions that would otherwise be acceptable under the law.

2.1.3 Land-use / land-change applications

Fire plays an important role in changing the landscape. Fire can be a natural process that plays an important role in maintaining the health of many ecosystems. Managed burns are used to simulate natural fires that would have occurred if other forms of fire suppression were not in place. Satellites can track the frequency of burning in a region, which helps determine the risk of fire or the need for a prescribed burn. In other areas fire devastates regions by destroying life and property. Satellites monitor these regions as well to identify when fires might be particularly destructive.

Agricultural burning is another important source of biomass burning. Satellite remote sensing is used to monitor burning in agricultural areas to determine if the same region burns every season, suggesting that the same land is being reused every year, and where new land is being burned, indicating potential deforestation. Satellite fire detection also tracks the expansion of burning into new areas. In South America, for example, linear features have been identified in the satellite fire detections that are directly related to new road construction [Prins et al., 2001].

Regions and ecosystems are known to have unique emission characteristics and each satellite fire product will have slightly different land type classifications due to spatial resolution and navigation differences. This can result in substantial differences in

satellite derived fire characterization. Land and vegetation type also limit the effectiveness of fire detection because some land types have properties that make it difficult to detect fires [Feltz et al., 2003; Giglio et al., 2003]. Certain types of vegetation and bare surfaces (such as desert or exposed rock) might be warm enough to cause a false fire signal. Fortunately, bare surfaces have little or no biomass to burn so fires detected in these areas can be treated as likely false detections. Misclassification of land type is a problem because if a hot bare surface is misclassified as a forest, it could result in erroneous fire detections with erroneous emissions. Mountainous regions provide challenges for fire detection since fires may occur in valleys or along the side of a mountain and are hidden from the satellite.

2.2 Theoretical fire detection

Satellite remote sensing provides the only automated method of fire detection over large regions; it does not require human involvement to actively locate and monitor fires (i.e from an airplane or tower).

Matson and Dozier developed a technique using NOAA-6 AVHRR 3.8 μm and 11 μm channels to identify fires and estimate fire size and temperature [Matson and Dozier, 1981]. These channels were selected for a number of reasons. Most importantly, the bands are in an atmospheric window where atmospheric attenuation is minimal over the wavelengths used measure the surface. A fire signature is detected when the observed 4 μm brightness temperature is significantly warmer than the background 4 μm brightness temperature and when the observed 4 μm minus the 11 μm brightness temperature is substantially higher than the 4 μm background minus the 11 μm

background brightness temperature, or $T_4 - T_{11} > T_{4b} - T_{11b}$. The 4 μm and 11 μm bands are chosen because the change in radiance with change in temperature, $\frac{\partial L_\lambda}{\partial T}$, is much greater between 3 μm to 5 μm than the 10 μm to 12 μm interval, as shown in Figure 2.2.1.

Figure 2.2.2 further illustrates that $\frac{\partial L_\lambda}{\partial T}$ is greater at 4 μm than 11 μm .

Radiance, L_λ , is calculated by Equation 2.2.1, where λ is wavelength, ϵ is emissivity, B_λ is the plank function, τ_λ transmittance to the top of the atmosphere, P is the atmospheric pressure level, and s represents the earth surface.

$$L_\lambda = \epsilon_\lambda B_{\lambda s} \tau_{\lambda s} + \int_{P_s}^0 B_\lambda \frac{d\tau_\lambda(P)}{dP} dP \quad (2.2.1)$$

The total radiance for a fire pixel is the sum of the radiance of the fire (including flaming and smoldering components), the radiance for the non-burning portion of the pixel, solar reflection, and atmospheric attenuation. To estimate the temperature or radiance associated with the fire, it is critical to determine the temperature of the non-burning portion of a fire pixel, which can be approximated by assuming the average temperature of surrounding, non-burning, cloud-free, land pixels is representative of the average temperature of the non-burning portion of a potential fire pixel. A system of equations, Equation 2.2.2 and Equation 2.2.3, can be used to derive the instantaneous estimates of sub-pixel fire size and temperature [Matson and Dozier, 1981]. Where $L_4(T_4)$ and $L_{11}(T_{11})$ are the 4 μm and 11 μm observed radiances taken from satellite measurements,

$$L_4(T_4) = pL_4(T_t) + (1-p)L_4(T_b) + (1-\epsilon_4)\tau_{4s}L_{4\text{solar}} \quad (2.2.2)$$

$$L_{11}(T_{11}) = pL_{11}(T_t) + (1-p)L_{11}(T_b) \quad (2.2.3)$$

$L_{4\text{solar}}$ is the solar radiance at the earth surface, T_b is the estimated background temperature of the non-burning portion of the pixel, T_t is the fire temperature, and p is the portion of the pixel on fire. Not all of the energy from a fire is measurable by satellites because fires are not ideal blackbodies, radiation can be scattered by the atmosphere, some energy is lost to flux into the ground, and energy is lost to convective and evaporative processes.

There are limitations to the satellite observable minimum detectable fire size. The smallest detectable fire size depends on many factors including the fire temperature, geographical extent, atmospheric conditions, surface characteristics, and the position of the satellite relative to the sun and to the fire. Despite these potential limitations it is not uncommon to detect fires smaller than 0.1% of the area of the pixel. Fire detection algorithms are developed with subjective thresholds that determine the minimum criteria for a pixel to be considered a fire pixel. Loosening detection criteria might yield more fire detections but it also raises the false detection rate because noise, sun-glint, and surface temperature variations would be more likely to be errantly flagged as fire pixels. Satellite fire detection methods are limited by the resolution, accuracy, and precision of the satellite instrumentation.

Cloud cover is another important limiting factor. Clouds are opaque in the short-wave IR window channels (near $3.9 \mu\text{m}$) used to detect fires. Clouds, water vapor, and optically thick aerosols all inhibit the ability to detect fires by absorbing the IR radiation. Opaque clouds will completely obscure the fire. Optically thin clouds, water vapor, and optically thick aerosols also present a challenge because if not correctly identified, they can result in temperature retrieval errors by masking the true temperature of the fire or

background pixel. Topography can inhibit satellite fire detection where the topography blocks the line-of-sight between the fire and satellite. In addition, forest fires can be at least partially obscured by the canopy. Furthermore, a fire burning undergrowth and trees has unique emission characteristics different from a fire burning only undergrowth or only trees. Fires may behave differently based on the type of fuel being consumed. Moisture and wind also play an important role in how fires behave.

The land type and vegetation type limit the effectiveness of fire detection because some land types have properties that make it difficult to detect fires [Feltz et al., 2003]. Certain types of vegetation and bare surfaces (such as desert or exposed rock) might be warm enough to cause a false fire signal. Fortunately, bare surfaces have little or no biomass to burn so fires detected in these areas can be treated as likely false detections. Misclassification of land type is a problem because if a hot bare surface is misclassified as a forest, it could result in erroneous fire detections and erroneous fire characteristics and emissions estimates. Mountainous regions also provide challenges for fire detection since fires may occur in valleys or along the side of a mountain and are hidden from the satellite.

Planck radiances for temperatures from 300 K to 800 K

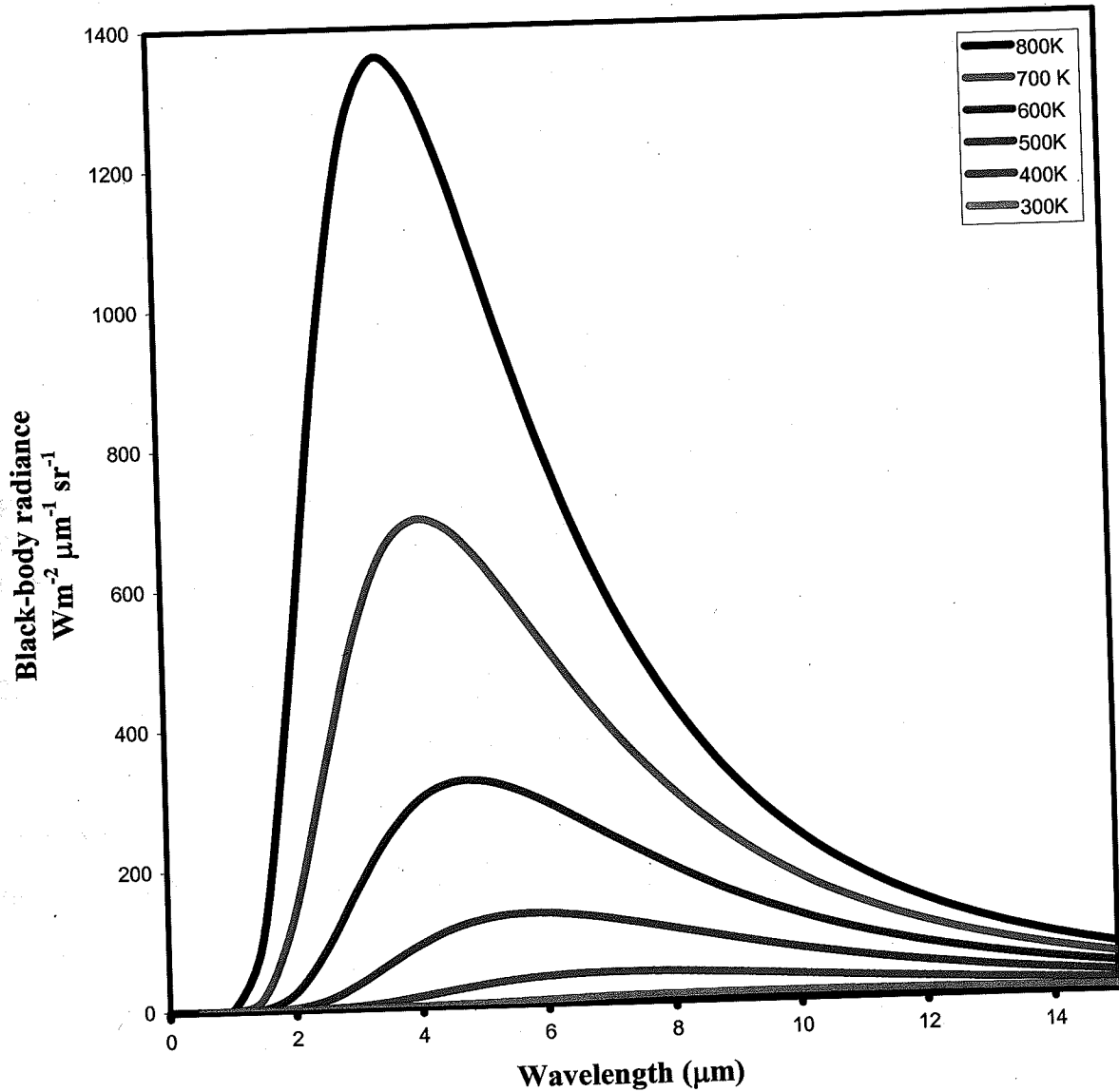


Figure 2.2.1
 Planck radiances showing the increase in radiances with increasing temperatures from 300 K to 800 K. Notice the slope of curve is steeper and the function is more sensitive around 4 μm than around 11 μm. For a given increase in temperature, the relative increase in radiance is greater near 4 μm than 11 μm.

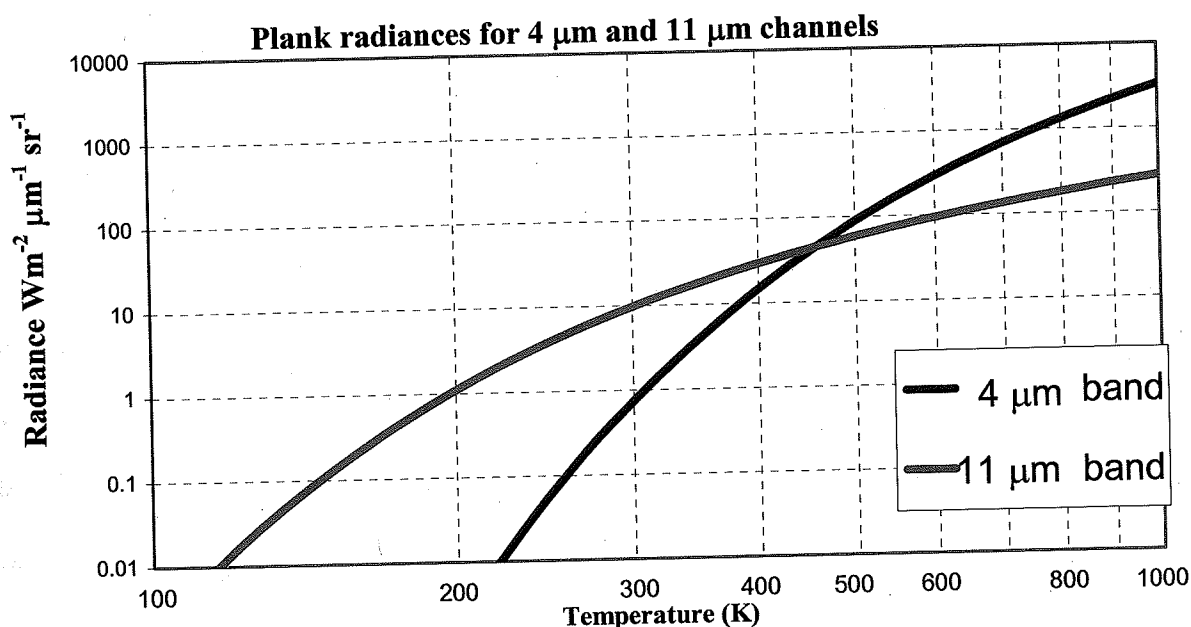


Figure 2.2.2
Planck radiances at 4 μm and 11 μm . Notice that $\frac{\partial L_4}{\partial T} > \frac{\partial L_{11}}{\partial T}$ over the range of potential fire temperatures.

2.3 History of geostationary satellite fire detection

Soon after the launch of NOAA 6 in 1980 GOES-4 VAS (Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder) became the first geostationary satellite that was capable of fire detection. The initial satellite operation schedule limited the availability of the 4 μm band to only a few time periods each day. The GOES VAS began to provide multispectral coverage over North and South America necessary for fire detection in 1980 [Prins and Menzel, 1994]. The GOES 4-7 VAS was capable of detecting fires every 3 hours with a resolution of 7 and 14 km at 4 μm and 11 μm respectively [Kaufman et al., 1998]. The next series of GOES satellites, GOES I-M (GOES 8-12) had improved temporal and spatial resolution. The GOES-8 Imager, launched in 1994, had a 4 km spatial resolution in the 4 μm channel compared to the 13.8

km resolution on GOES-7. The GOES-8 Imager also included oversampling in the East/West direction (by a factor of 1.75) which provided increased opportunity to capture more of a fire within in a single pixel. As new satellites were developed, so too were fire detection techniques and algorithms.

Manual fire detection was necessary before the development of the GOES ABBA (Automated Biomass Burning Algorithm), and this time intensive process was based on subjective decisions where it is difficult to assess consistent positive and false fire detection statistics. Furthermore, studies were limited to regional cases over a limited time series because it was too time intensive to compute fire statistics on a large scale. These studies were primarily limited to South American fire season case studies. With the development of the ABBA [Prins and Menzel, 1994; Prins et al., 1998] and later the development of WF_ABBA (Wildfire Automated Biomass Burning Algorithm) in 2000 [Prins et al., 2001], automated, diurnal, large scale fire detection was possible. The technique of Matson and Dozier (1981) was applied to determine fire size and subpixel fire temperature based on the 4 μm and 11 μm bands.

In addition to the current GOES WF_ABBA, algorithms are in development to provide diurnal fire detection with current and future American GOES series satellites and in other parts of the world including the European Meteosat Second Generation (MSG) series, the Japanese Multifunction Transport Satellite (MTSAT) series, the Chinese FY-2C, the Indian INSAT-3D, the Russian GOMS-Elektro, N2, and the Korean COMS satellites.

2.4 Polar orbiting satellite fire detection

Unlike geostationary satellites that orbit above the same location on earth, polar orbiting satellites provide coverage over the entire earth with each crossing of the equator at roughly the same local time (for sun-synchronous polar orbits). This orbit yields poor temporal coverage at low latitudes, and frequent temporal coverage at high latitudes. An advantage of this low earth orbit (~700 km) is that spatial resolution (1 km nadir resolution for 4 μm MODIS band) is much better than the spatial resolution of geostationary satellites (4 km nadir resolution for 4 μm GOES band) because geostationary orbits are much further away from the earth (~36000 km).

2.4.1 History of polar orbiting satellite fire detection

The application of environmental weather satellites for fire detection and characterization began with polar orbiting satellites.

2.4.1.1 AVHRR

The series of AVHRR sensors onboard NOAA 6 through NOAA 18 Polar Orbiting Environmental Satellites (NPOES) have been in continuous operation since October 1978. The AVHRR sensor was designed for ocean, land, and cloud monitoring [Kaufman et al., 1998]; AVHRR saturates at a relatively low temperature, which limits its usefulness for fire monitoring. The 3.75 μm and 11 μm AVHRR channels were designed, and are well suited for ocean and cloud observations. Saturation occurs at 325 K (or lower) and AVHRR has a non-linear response near saturation, making fire detection is difficult despite a spatial resolution of 1.1 km [Kaufman et al., 1998]. In

addition to relatively low saturation, AVHRR is not the best sensor to use for fire detection because despite 1.1 km resolution at nadir, at a scan angle of 55 degrees the pixels are ten times larger than at nadir [Kaufman et al., 1998]. Despite the limited value of AVHRR in terms of operational fire detection, AVHRR is important from a historical sense because Matson and Dozier [1981] first used AVHRR data to develop their fire detection technique that has become the foundation for the GOES and MODIS fire detection algorithms. The first case studies using AVHRR fire detection were done using nighttime data over industrial Detroit, Michigan and Persian Gulf gas flare fire sources [Matson and Dozier, 1981]. Nighttime observations provided a better opportunity to detect fires because solar reflection is not an issue and background temperatures are often easier to define since temperature gradients at the surface are typically weaker at night and the surface temperatures are in general cooler which enhances the contrast between fire induced 4 μm and 11 μm brightness temperature differences. Unfortunately, fire activity reaches a minimum during the nighttime hours [Prins et al., 2001], and so monitoring only nighttime fires has its drawbacks because it is not representative of the total burning throughout the entire day. With time, fire detection expanded to daytime fires and vegetation fires. Flannigan and Vonder Haar [1986] developed automated fire detection criteria using NOAA-7 data over Alberta, Canada. Lee and Tag [1990] also presented a fire detection method using nighttime imagery in the Persian Gulf and California.

2.4.1.2 DMSP

Fire detection with the Operational Linescan System (OLS) on the Defense Meteorological Satellite Program (DMSP) utilizes a different technique to identify fires only at night [Cahoon et al., 1992; Elvidge et al., 1996]. Starting in the early 1970s, DMSP has operated low light sensors [Elvidge et al., 2001] and unlike other methods that use IR channels to detect fires, DMSP-OLS uses visible and NIR ($0.58 \mu\text{m}$ - $0.91 \mu\text{m}$) data to detect fires against the dark night-time background [Elvidge et al., 1996]. The advantage of nighttime fire detection is that errors associated with daytime solar reflection are eliminated. Although with DMSP it can be difficult to distinguish between other light sources and fires even when using a dynamic stable light source database to screen out stable lights. However, the main drawback of limiting fire detection to only nighttime fires is that fires in many biomes have a strong diurnal signature with a nocturnal minima; observing only nighttime fires results in an underestimation of daily fire activity.

2.4.1.3 BIRD

The BIRD (Bi-spectral InfraRed Detection) is a small, experimental satellite designed primarily for fire detection [Zhukov et al., 2006]. The Hot Spot Recognition System (HSRS) is the imager on BIRD and has a band at $3.4 \mu\text{m}$ - $4.2 \mu\text{m}$ and a band at $8.5 \mu\text{m}$ - $9.3 \mu\text{m}$ with a resolution of 370 m [Zhukov et al., 2006]. With spatial over-sampling and on-board processing, HSRS has a dynamic saturation temperature at about 600 K; if an initial measurement nears saturation at 370 K, the detector adjusts so that a second measurement saturates at 650 K [Siegert et al., 2004]. Because of the fine spatial

resolution and high saturation temperatures, BIRD has been used in numerous studies [Briess et al., 2003; Oertel et al., 2003; Oertel et al., 2004; Wooster et al., 2003; Zhukov et al., 2006], however the main drawback that limits the usefulness of BIRD has a swath width of only 190 km, a full order of magnitude smaller than MODIS [Zhukov et al., 2006]. As a result BIRD is currently limited to research applications.

2.4.1.4 Other techniques

Another category of fire detection and characterization is burn scar detection and monitoring. Satellites typically associated with land and not atmospheric applications, such as Landsat and SPOT (Système Pour l'Observation de la Terre), and even the vegetation bands of MODIS, ASTR (Advanced Spaceborne Thermal Emission and Reflection Radiometer), and AVHRR are used to detect changes in the land surface caused by fire [Fuller, 2000; Gerard et al., 2003; Miller and Yool, 2002]. Comparisons of landscape images from multiple overpasses are used to detect scarring on the land surface caused by fire. This technique is different from the techniques discussed in the rest of this paper because it does not detect any of the radiative properties of active fires. The main advantage of fire scar detection is that it provides an estimate of burned area by measuring the burn scar. The main drawback is that because fire scar detection does not measure radiative properties of active fires, it cannot be applied to the same type of real-time applications that are possible when active fires are detected. Furthermore, for high resolution polar orbiting sensors, the time between successive cloud-free overpasses can be quite long. During this time the burned area can green up with secondary types of vegetation.

Yet another method detects hot CO₂ emissions with high-spectral resolution instruments between 2400 to 2500 cm⁻¹ [McCourt et al., 2004].

2.4.2 MODIS AQUA and TERRA

Today, a popular polar orbiting fire detection product is the MODIS fire product. Unlike AVHRR, from its inception, the 3.9 μm bands on the MODIS instrument were designed with fire detection in mind. The 1994 SCAR-C (Smoke Cloud and Radiation – California) and the 1995 SCAR-B (Smoke Cloud and Radiation – Brazil) experiments were important case studies that used the MAS (MODIS Airborne Simulator) to take measurements over regions with fires from aircraft in support of the development of the MODIS instrument, fire product development, and validation.

Before the 1999 launch of the first MODIS instrument on the TERRA satellite [Justice et al., 2002], the best polar orbiting satellite near real-time fire detection application was Brazil's INPE AVHRR fire algorithm that had been operational since 1987 [Prins and Menzel, 1994]. In 2000 data from the TERRA satellite, known before launch as Earth Observing System (EOS) AM-1, became available, and in 2002 the AQUA satellite (EOS PM-1) data became available. With two satellites, coverage is improved compared to only having one satellite.

3 Instrument characteristics

Instrument characteristics are important and for the most part operational environmental satellites have not been designed to measure fires. Environmental satellite derived fire products have differences as a result of instrument difference. Every

satellite instrument has different sensitivities in the fire channels that determine the detectability of fires with certain fire size and temperature combinations. To a certain extent, satellite instruments are designed with consideration for the eventual products. GOES and MODIS have different satellite characteristics. The resolution, spatial coverage, temporal coverage, the location of a fire relative to the satellite, and instrument characteristics are all contributing factors to the detectability of a fire.

3.1 Resolution

MODIS, with a lower earth orbit (~700 km) has a 1 km nadir resolution while GOES, in geostationary orbit (~36000 km) has 4 km resolution at nadir. Most fires, however, do not occur near nadir. MODIS pixels become elongated with increasing scan angle, and along scan resolution can be less than GOES resolution at nadir. GOES resolution also decreases as scan angle increases, however resolution decreases at a slower rate than MODIS. Still, near the edge of GOES coverage pixels exceed 100 km².

Although resolution is a factor, the minimum detectible fire size is not an absolute size, instead it is a function of the proportion of the pixel that is at fire temperature and other more complex terms such as the instrument sensitivity, surface emissivity, and atmospheric attenuation. With finer resolution smaller fires can be measured. It is equally important to consider that a single pixel may contain more than one hotspot and coarse resolution provides the opportunity for more numerous small hotspots that individually might be too weak to be identified but combined can be detected as a fire due to the additive properties of radiation.

Related to resolution, over-sampling and under-sampling is also significant. GOES over-samples in the along scan dimension such that 4 km samples are taken approximately every 2 km. MODIS has a bow-tie shaped coverage pattern resulting in a complex pattern where in a MODIS swath some areas are over-sampled while other areas are under-sampled. Fire products can come from other satellites that have even more complex coverage patterns that can make it even more difficult to geo-locate hotspots. The consequence of over-sampling is that a single fire might appear as two or more fire detections in neighboring pixels while under-sampling can result in missing a fire that was believed to be in an area covered by the satellite.

3.2 Viewing geometry

Related to resolution, satellite zenith angle is also an important factor in fire detection. Figure 3.2.1 shows the factor by which the along scan resolution increases with increasing scan angles. For large zenith angles, the pixel footprint is larger than at smaller zenith angles and the spatial response becomes distorted. As a result of a larger footprint, a fire must be hotter or occupy a larger area than is needed for detection in smaller footprints. GOES zenith angle is a function of only latitude and longitude whereas MODIS zenith angle adds an additional orbit parameter that is a function of time. With varying zenith angles for a given fire in consecutive MODIS overpasses, it is difficult to determine if a fire burned continuously between overpasses because the footprints from consecutive overpasses can be dramatically different and a fire that appears to be in the same spot as a previous fire could in fact be two separate fires. GOES can detect fires at satellite zenith angles up to around 80 degrees, while MODIS is

limited by a maximum scan angle of less than 70 degrees. The area of coverage increases with increasing scan angles, but only fires with very strong fire signatures will be detectable at large zenith angles. In addition, atmospheric attenuation increases with increasing satellite zenith angle because the path through the atmosphere lengthens since the surface of the earth is farther away from the satellite than at nadir.

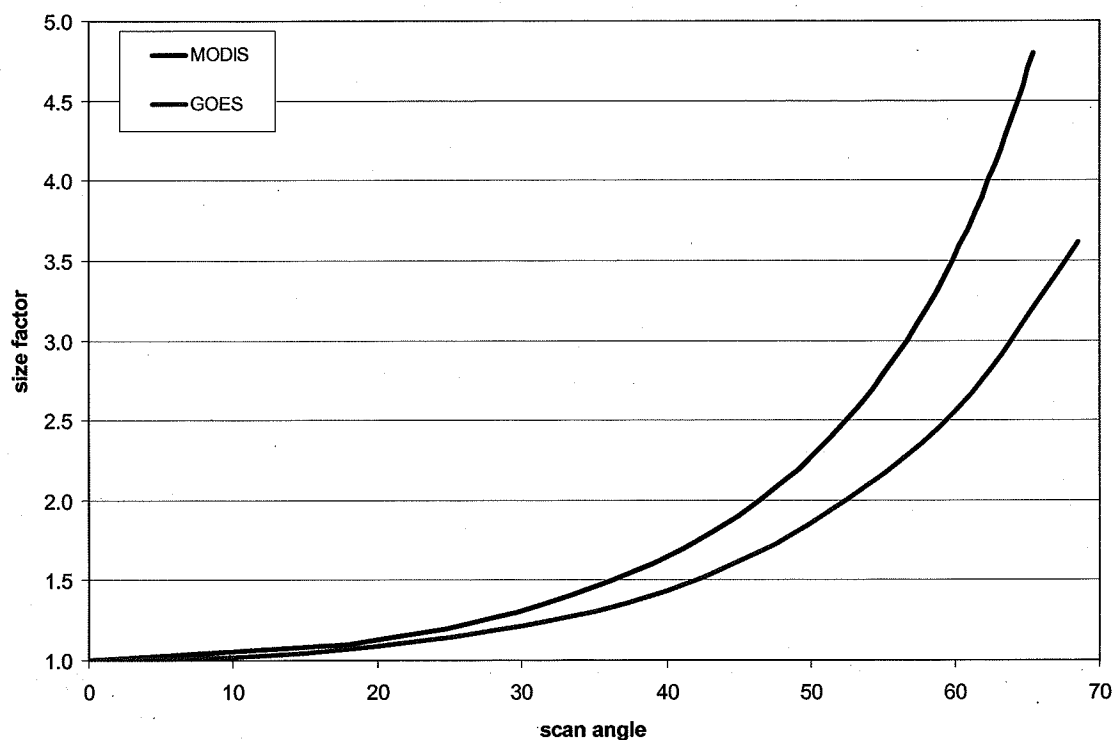


Figure 3.2.1

Along scan resolution is a function of scan angle. The size factor increases with increasing scan angle where MODIS pixels become elongated more quickly than GOES.

3.3 Spatial coverage

GOES provides nearly complete coverage over the entire western hemisphere, however very high latitudes are not covered and at high viewing zenith angles resolution becomes increasingly coarse. MODIS provides global spatial coverage however there are coverage gaps over the course of a day. GOES provides a full disk scan of the

hemisphere every 3 hours, and depending on the operation schedule, most areas are covered every half hour. In contrast, MODIS repeats its coverage pattern as AQUA and TERRA repeat their orbits every 16 days. While it is rare for coverage gaps to exceed 24 hours, the zenith angle and time of overpass do not repeat for 16 days. Inconsistent MODIS spatial coverage presents a problem when trying to track the activity of a continuously burning fire or monitoring diurnal fire activity. Each unique orbit has a unique coverage pattern and within that are areas where fire detection is enhanced and other areas where fire detection is more difficult.

3.4 Temporal coverage

Temporal coverage is important in terms of tracking diurnal fire trends and necessary to try to integrate fire radiative power or total emissions. Since there is diurnal variability of fire activity, a snapshot of fire activity at an off peak time will result in an underestimate of daily fire activity. Even fire activity during the diurnal maximum is an underestimate of the daily fire activity because additional fires might have extinguished before the diurnal maximum or might still ignite after the maximum. Studies have shown that in South America, when analyzing 3 hourly fire products, 80% of the fire pixels are unique to a given time period [Prins et al., 2001].

With GOES full disk coverage as frequent as every half hour it is possible to monitor diurnal fire activity. Furthermore, it is possible to track the life-cycle of individual fires and integrate fire radiative power over a time series to come up with a measurement of fire radiative power. Studies have been conducted to even look at fires

in rapid scan mode where fire activity can be monitored with five-minute intervals [Weaver et al., 2004].

The operating schedule of geostationary satellites is complex. Normal operating procedures allow for full coverage every 30 minutes over the continental United States, while the rest of North America and South America receive less priority in the operating schedule. NOAA owns and operates the suite of GOES satellites; the United States makes the satellite operation schedule and policy decisions that dictates the frequency of data coverage. NOAA can change the satellite operation schedule to increase coverage to monitor severe or otherwise interesting weather conditions - at the expense of coverage over other areas. Hurricane season in the United States, for example, is a time when NOAA frequently departs from the normal satellite operation schedule to monitor hurricane activity in the Atlantic Ocean and Gulf of Mexico. Hurricane season, however, occurs simultaneously with the South American fire season. Consequently, NOAA changes the operation schedule of the GOES satellite to improve hurricane coverage while South American fire coverage is compromised. Instead of every 30 minutes as in the normal operating schedule, much of southern South America is only covered once every 3 hours by GOES. In June 2006 GOES-11 replaced GOES-10 as the GOES West satellite and GOES-10 was dedicated to coverage of South America to minimize coverage gaps that exist when GOES deviates from its normal operation schedule. New satellites are being developed with improved temporal resolution that will allow for more frequent coverage of the hemisphere [Weaver et al., 2004].

The EOS platforms carrying the MODIS instruments cross the equator at approximately the same local time for each overpass, 10:30 A.M. for Terra and 1:30 P.M.

for Aqua. As a result most low latitude locations will have a morning and afternoon overpass as well as an overpass within approximately an hour and a half before or after local midnight. The exact time of the overpass is variable and a function of the exact location of the region of interest as well as the position of the satellite. The satellite makes 233 revolutions with unique tracks in a 16 day cycle before repeating.

3.5 Coverage bands

The 4 μm and 11 μm infrared window channels are critical for 24 hour fire detection. While other channels might be more sensitive to radiation emitted by fires, these channels might also be more sensitive to solar reflection or more sensitive to atmospheric conditions. While referred to as 4 μm and 11 μm channels, these are not point measurements at one specific wavelength, instead they are measurements of radiation over a range of continuous wavelengths. Also, different satellites instruments will have different design specifications such that the bands will have varying widths, be centered at slightly different wavelengths, and have different sensitivities to different wavelengths within the band depending on the design of the instrument.

On MODIS, Bands 21 and 22 cover the range of 3.929 μm – 3.989 μm ; the difference is that Band 21 saturates at a higher temperature while Band 22 has a better signal to noise ratio but saturates at a lower temperature. MODIS Band 31 covers the 10.780 μm – 11.280 μm range. Channel 2 on GOES I-M spans 3.80 μm – 4.00 μm , while Channel 4 on GOES I-M spans from 10.20 μm – 11.20 μm .

3.6 Saturation

An instrument becomes saturated when temperatures are so hot (or bright) that the instrument has no sensitivity to measure an additional increase in temperature (or brightness). Saturating at low temperatures limits the ability to detect and characterize fires. It might be possible to determine that a fire caused a pixel to saturate, however, fire characterization in terms of determining fire radiative power or estimating fire temperature and size is not possible when the pixel is saturated because the true brightness temperature is not known. The 4 μm channel is more sensitive to fires and should be designed to allow for a higher saturation point than the 11 μm channel.

On MODIS the low saturation 4 μm band (Band 22) saturates at ~ 330 K while the high saturation band (Band 21) saturates at ~ 500 K (~ 480 K on TERRA or ~ 505 K on AQUA). The 4 μm band on GOES-12 (Channel 2) saturates at ~ 335 K. The 11 μm band (Band 31) on MODIS saturates at ~ 400 K (~ 400 K on Terra or 340 K on Aqua) while the 11 μm band on GOES-12 (Channel 4) saturates at 320 K. While MODIS saturates at higher temperatures than GOES, that does not necessarily mean that a fire that saturates MODIS would also saturate the GOES imager. In the case of a small hot fire with fine resolution – from MODIS – a fire might occupy a relatively large proportion of the pixel and could saturate the sensor. From GOES the hotspot would occupy a smaller proportion of the pixel and may remain unsaturated. Only about 2% of GOES fire pixels are flagged as saturated pixels. For MODIS, saturation becomes a problem in cases where Band 22 saturates (near 335 K) and Band 21 provides a noisy signal.

In truth, saturation values are only estimates. Often the instrument has not been calibrated. Calibration and saturation thresholds can drift significantly as a sensor ages and in extreme cases may vary on a daily basis. On some instruments as the temperature nears saturation sensitivity decreases and the response can become extremely non-linear.

4 Fire detection algorithm similarities and differences

Coupled with instrument design, each fire algorithm is tailored to a particular satellite instrument where some algorithm differences are necessary due to instrument differences while other algorithm differences are independent of satellite design.

4.1 GOES fire algorithm

The current GOES fire product algorithm is named WF_ABBA (Wildfire Automated Biomass Burning Algorithm). Both the GOES and MODIS active fire detection algorithms are dynamic contextual algorithms where the data surrounding the pixel being evaluated are used to determine if the pixel contains a fire. Figure 4.1.1 and Figure 4.1.2 are flowcharts of Part I and Part II of the WF_ABBA. They provided a detailed outline of the algorithm, although the specifics are more complex. Part I of the algorithm identifies the most probable fire pixels and solves for sub-pixel characteristics when appropriate. Part II further evaluates the pixels identified in Part I and eliminates many false alarms.

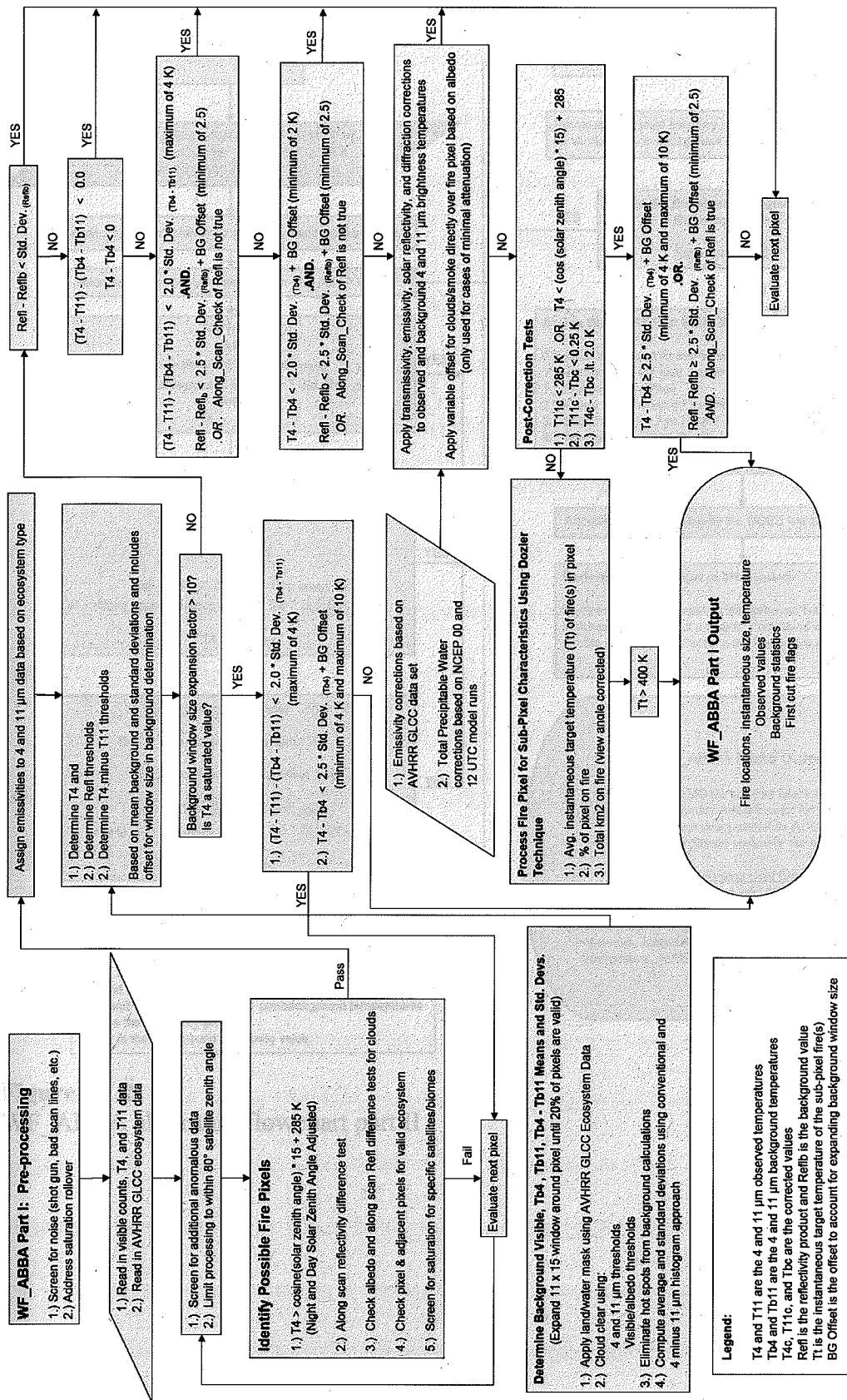
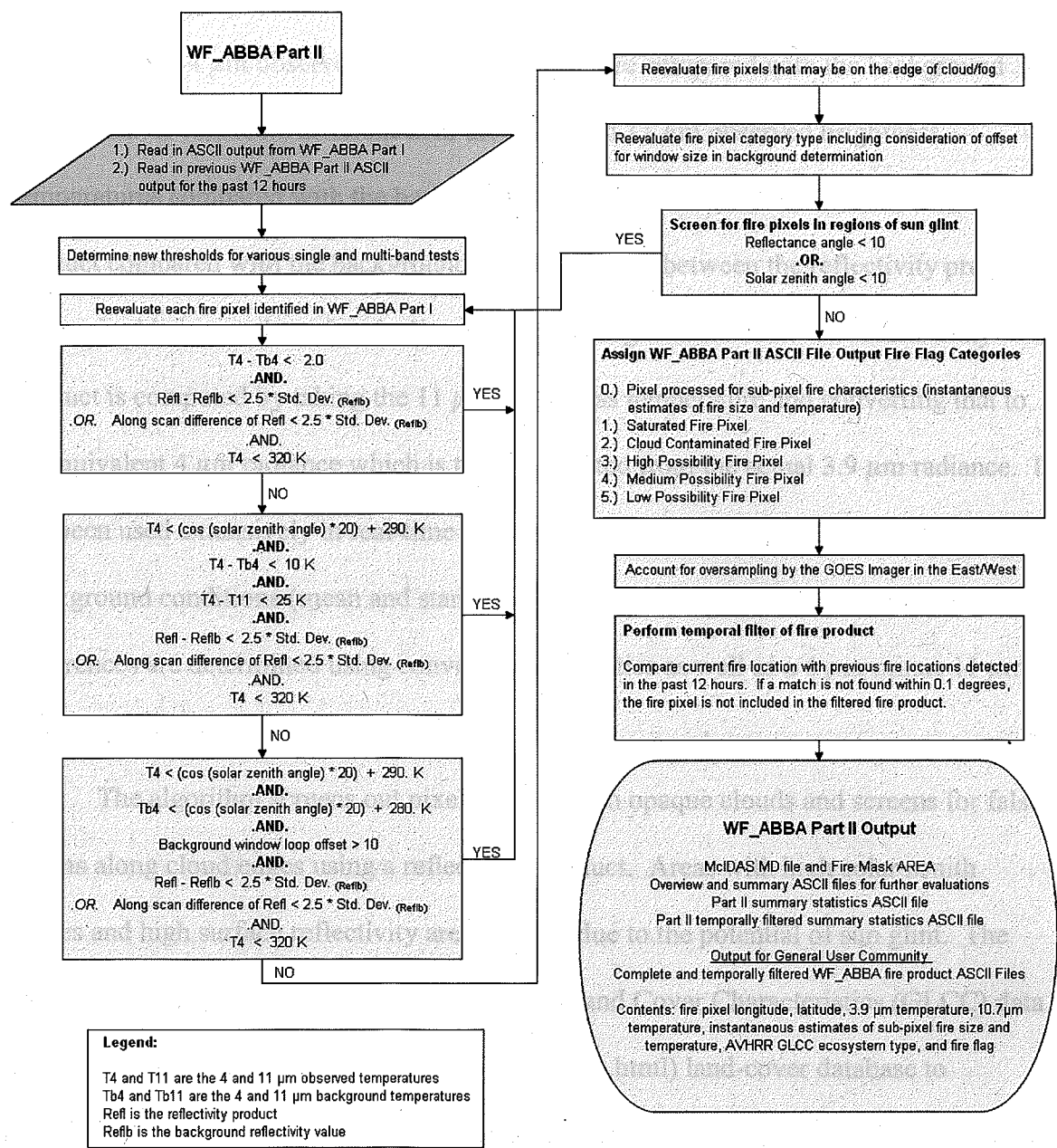


Figure 4.1.1
WF_ABBA algorithm flowchart part I

Legend:
T4 and T11 are the 4 and 11 μm observed temperatures
Tb4 and Tb11 are the 4 and 11 μm background temperatures
T4c, T11c, and Tbc are the corrected values
Refl is the reflectivity product and Reflb is the background value
Tt is the instantaneous target temperature of the sub-pixel fire(s)
BG Offset is the offset for expanding background window size



Legend:

T4 and T11 are the 4 and 11 μm observed temperatures
 Tb4 and Tb11 are the 4 and 11 μm background temperatures
 Refl is the reflectivity product
 Reflb is the background reflectivity value

Figure 4.1.2
 WF_ABBA algorithm flowchart part II

The GOES algorithm initially finds a fire pixel by identifying pixels with a relatively high $4\ \mu\text{m}$ observed brightness temperature compared with the background conditions. It considers differences in the $4\ \mu\text{m}$ and $11\ \mu\text{m}$ observed brightness temperatures compared with the background. It also considers the GOES reflectivity product compared with the background and differences between the reflectivity product of the pixel being evaluated and adjacent pixels along the scan line. The reflectivity product is computed by taking the $11\ \mu\text{m}$ brightness temperature and converting that to an equivalent $4\ \mu\text{m}$ radiance which is then subtracted from the actual $3.9\ \mu\text{m}$ radiance. It has been used extensively in real-time for manual fire monitoring and for fog detection. Background conditions (mean and standard deviation) for each of these parameters and differences are determined using conventional statistics as well as a $4\ \mu\text{m}$ minus $11\ \mu\text{m}$ histogram approach.

The algorithm screens out pixels that contain opaque clouds and screens for false alarms along cloud edges using a reflectivity product. Areas with high solar zenith angles and high surface reflectivity are screened due to the potential of sun glint. The algorithm refers to the AVHRR derived Global Land Cover Characteristics (GLCC) data base (version 2.0, <http://edcdaac.usgs.gov/glcc/glcc.html>) land-cover database to determine ecosystem type and estimate surface emissivity via an associated look-up table. It screens out false alarm fire detections in urban areas, over water, and over bare surfaces such as exposed rock and desert and in transition zones. A correction is applied for solar reflectivity in the $4\ \mu\text{m}$ band, surface emissivity in the $4\ \mu\text{m}$ and $11\ \mu\text{m}$ bands, and attenuation by water vapor in the $4\ \mu\text{m}$ and $11\ \mu\text{m}$ bands based on total column precipitable water data from a NCEP (National Centers for Environmental Prediction)

model. The corrected brightness temperatures are then applied in the algorithm allowing for less stringent absolute and comparative thresholds and improved fire detection and characterization. In Part II of the algorithm, the fire product is adjusted for oversampling by the GOES Imager. A temporal filter is used to screen out fire pixels that do not occur more than once over a 12 hour period. This often screens out false alarms, but it can also eliminate small short-lived agricultural fires.

The GOES WF_ABBA ASCII fire product contains information about the detected fire pixels including location, observed $3.9 \mu\text{m}$ and $10.7 \mu\text{m}$ brightness temperatures, estimates of instantaneous sub-pixel fire size and temperature, ecosystem type, and fire classification. The six classification categories, shown in Table 4.1.1, are processed pixels (fire pixels that satisfy the criteria to have sub-pixel temperature and size calculated), saturated pixels (the observed $3.9 \mu\text{m}$ brightness temperature exceeds the maximum temperature that the GOES Imager is capable of quantifying), cloudy pixels (a fire pixel with relatively thin cloud cover), high possibility fire pixels, medium possibility fire pixels, and low possibility fire pixels. The latter category represents the largest number of false alarms as it has the least stringent requirements for fire identification.

GOES fire characterization uses the Dozier technique to estimate fire size and temperature. For example, suppose a fire pixel where $T_4 = 325 \text{ K}$, $T_{11} = 297 \text{ K}$, and $T_b = 295 \text{ K}$. Figure 4.1.3 shows possible solutions of the Dozier equation for fire temperatures ranging from 300 K to 1000 K. To find the solution, Figure 4.1.4 includes the constraint that $T_4 = 325 \text{ K}$ and must intersect $T_4 - T_{11} = 28 \text{ K}$ ($325\text{K} - 297\text{K} = 28\text{K}$). The resulting fire temperature is 613 K with the fractional area 0.0038. To find the fire size, as Equation 4.1.1 shows, fire size is found by multiplying p by the total area of the pixel.

$$\text{Area}_{\text{Fire}} = p \cdot \text{Area}_{\text{pixel}} \quad (4.1.1)$$

For example, with a 16 km² GOES fire pixel, and fractional area 0.0038, the fire size would be 0.0608 km².

GOES Fire Confidence Categories	
Flag	Category
1	saturated fire pixel
0	processed fire pixel
2	cloudy fire pixel
3	high probability fire pixel
4	medium probability fire pixel
5	low probability fire pixel

Table 4.1.1

GOES flags and fire confidence categories where a saturated fire is in the most confident fire category decreasing in confidence to low probability fire pixels that are often removed from consideration due to a high likelihood of false detection. Notice that flag during algorithm development processed fires were believed to be more confident than saturated fire pixels due to noise. Results have shown more confidence in saturated fire pixels. For statistical applications, a nominal value of 100 is assigned to saturated fire pixels, 90 for processed and on down to 50 for low probability fire pixels.

Dozier solution for an example fire
 $T_4=325$ K, $T_{11}=297$ K, and $T_b=295$ K

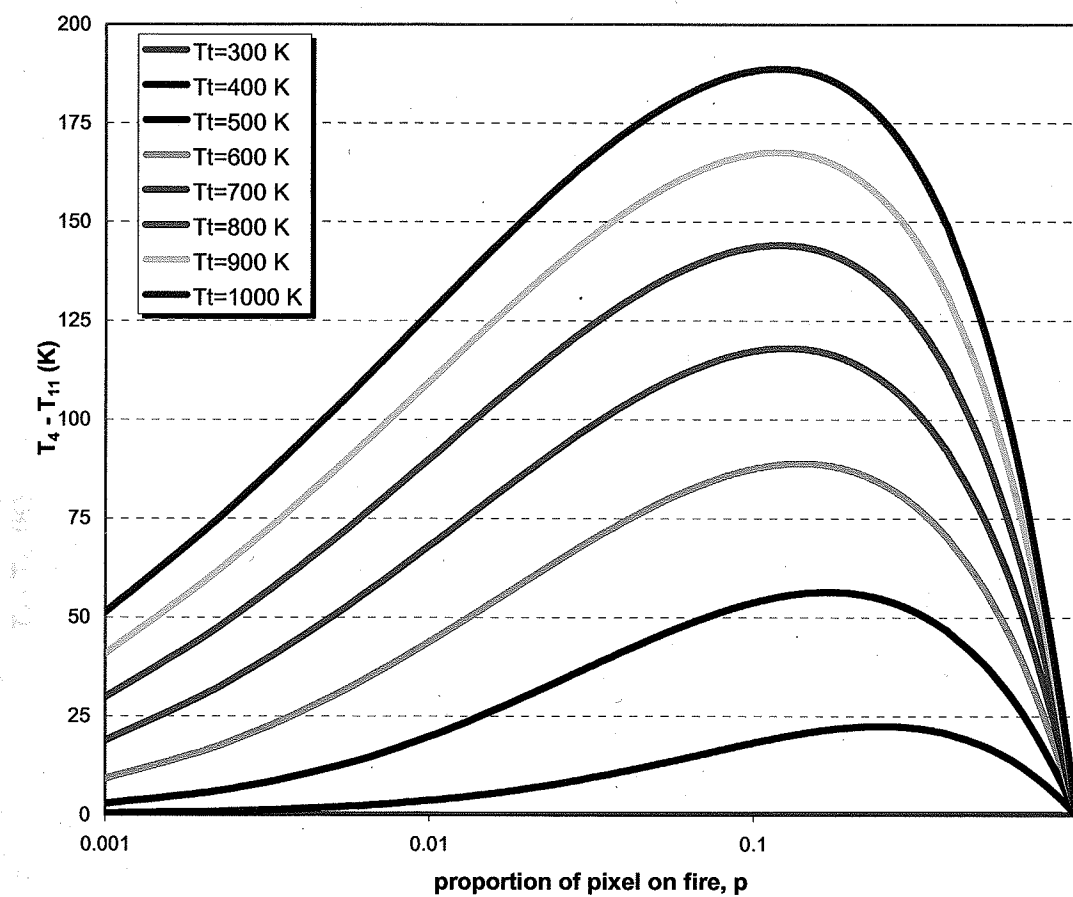


Figure 4.1.3

Example fire where each line represents a possible solution where the difference between the 4 and 11 μm background temperature is a function of the fire temperature, T_b , and proportion of the pixel on fire, p .

Dozier solution for an example fire
 $T_4=325$ K, $T_{11}=297$ K, and $T_b=295$ K

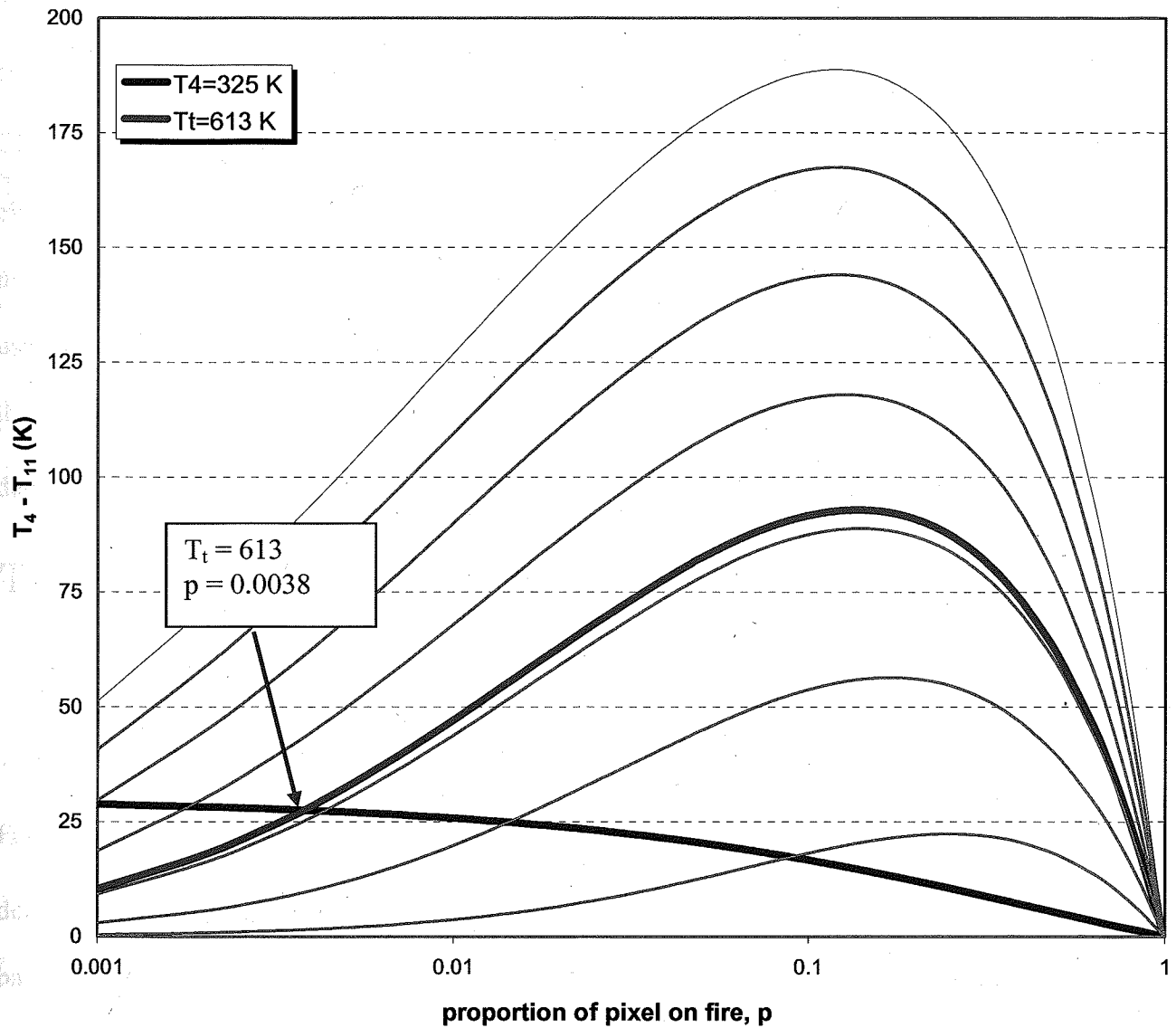


Figure 4.1.4

Example Dozier fire solution where the combination of 613K fire temperature, T_t , and proportion of pixel on fire, p is 0.0038 intersects with the curve corresponding to the observed 4 μ m brightness temperature of 325K.

4.2 MODIS fire algorithm

The MODIS contextual fire detection algorithm, version 4, is described in Giglio et al. [2003]. Like the WF_ABBA, the MODIS fire algorithm uses the 4 and 11 μm channels. Channels 21 and 22 are the low and high saturation 4 μm channels and Channel 31 is the 11 μm channel. The algorithm classifies every pixel as missing data, cloud, water, non-fire, fire, or unknown. The first step in the algorithm screens invalid or missing data and classifies the pixel as missing data. Next, the MODIS cloud mask is used to assign cloud pixels which will no longer be considered potential fire pixels. For the daytime, Equation 4.2.1 describes the conditions required to satisfy daytime cloud detection, where $\rho_{0.65}$ and $\rho_{0.86}$ are the 0.65 μm and 0.86 μm channel reflectivities and T_{12} is the 12 μm channel brightness temperature.

$$(\rho_{0.65} + \rho_{0.86} > 0.9) \text{ or } (T_{12} < 265K) \text{ or} \\ [(\rho_{0.65} + \rho_{0.86} > 0.7) \text{ and } (T_{12} < 285K)] \quad (4.2.1)$$

For nighttime only the ($T_{12} < 265$) test is required for cloud detection. After cloud detection, a water mask is applied to eliminate pixels that correspond to water pixels based on a land type mask file. The remaining pixels, potential fire pixels and non-fire pixels are classified; passing the conditions in Equation 4.2.2 results in classification of a potential fire pixel, and failing the conditions in Equation 4.2.2 results in classification as a non-fire pixel.

$$T_4 > 310K \text{ (305K at night)} \text{ and } T_4 - T_{11} > 10K \text{ and } \rho_{0.86} < 0.3 \quad (4.2.2)$$

For all potential fire pixels, there are two paths that can lead to fire characterization – an absolute threshold test and a contextual test. The absolute threshold test in Equation

4.2.3 is a simple test that says if the 4 μm observed brightness temperature is hot enough it is due to fire.

$$T_4 > 360K \text{ (320 K at night)} \quad (4.2.3)$$

Regardless of the outcome of 4.2.3, background characterization is necessary before the contextual tests are run. The background test is run for every potential fire pixel where a window is centered on a potential fire pixel and includes valid neighboring pixels. For the pixel to be valid, it must be a land pixel, not a cloud or water pixel, and it cannot be a background fire pixel. Equation 4.2.4 defines background fire pixels where these hot-spots are identified to avoid contamination when calculating the background temperature.

$$T_4 > 325K \text{ (310 K at night)} \text{ and } T_4 - T_{11} > 20K \text{ (10 K at night)} \quad (4.2.4)$$

Using the valid, non-background fire pixels, a 3 by 3 window surrounding the potential fire pixel and is allowed to expand up to a maximum of 21 by 21 pixels until 25% of the pixels in the window are valid and there are at least 8 valid pixels in the window. From this background window, many values are calculated that are necessary in the contextual test. \bar{T}_4 and \bar{T}_{11} are the mean 4 μm and 11 μm temperatures of the valid neighboring pixels while δ_4 and δ_{11} are the mean absolute deviation of the 4 μm and 11 μm temperatures of the valid neighboring pixels. $\overline{\Delta T}$ and $\delta_{\Delta T}$ are defined as the mean and mean absolute deviation of $T_4 - T_{11}$ for the valid neighboring pixels. Lastly, \bar{T}'_4 and δ_4 are defined as the mean and absolute deviation of the non-valid neighboring pixels.

After establishing the background the contextual tests can begin. There are 5 equations to the contextual test.

$$T_4 - T_{11} > \overline{\Delta T} + 3.5 \delta_{\Delta T} \quad (4.2.5)$$

$$T_4 - T_{11} > \overline{\Delta T} + 6K \quad (4.2.6)$$

$$T_4 > \overline{T}_4 + 3\delta_4 \quad (4.2.7)$$

$$T_{11} > \overline{T}_{11} + 3\delta_{11} - 4K \quad (4.2.8)$$

$$\delta'_4 > 5K \quad (4.2.9)$$

To tentatively be classified as a fire pixel during the daytime Equation 4.2.3 must be true or Equations 4.2.5, 4.2.6, and 4.2.7 must be true and also either 4.2.8 or 4.2.9 must also be true. Similarly, for a nighttime pixel, Equation 4.2.3 must be true or Equations 4.2.5, 4.2.6, and 4.2.7 must be true. If a pixel fails these tests, it is classified as non-fire. If not enough background pixels are established, the pixel is classified as unknown. The pixels that pass as potential fire pixels then must pass a sun glint test, a boundary test to help eliminate false fire detections that can occur along sharp transitions between land types (usually a transition into to desert regions), and also there is a test to help eliminate coastal false alarms that can be caused by errors in the water mask.

Acquiring MODIS fire data is a non-trivial processes. At the time this project was undertaken, there were two different versions of the collection 4 MODIS fire algorithm running. The MODAPS (MODIS Adaptive Processing Systems) LP-DAAC (Land Processes Distributed Active Archive Center) version 4 of the fire product available in 5-minute granules had an error in switching between the low and high saturation 4 μm channels [Giglio, 2004]. This data set is examined for one case study in this project. In all other instances the MODIS fire data comes from the version of the MODIS algorithm run at the University of Maryland (UMD) where there is no known error in switching between the 4 μm channels. The UMD data is available in ASCII

format where fire pixels for the whole day are placed in one file. Although there is a loss in information since all non-fire pixels are excluded, the file size is much smaller which makes long terms studies much more practical.

MODIS fire characterization relies on a system of equations that calculates fire confidence [Giglio et. al, 2003]. The confidence categories are shown in Table 4.2.1 where a low confidence fire as any fire with a confidence between 0 and 19%, a nominal confidence is between 20 and 79% and a high confidence fire is between 80 and 100% [Giglio, 2005]. Instead of solving the Dozier equation to characterize sub-pixel instantaneous fire temperature and size, the strategy employed for MODIS is to solve for the rate of emission of fire radiative energy (FRE). Although the term FRE is common in literature it is almost always referring to the rate of emission of FRE. Since power is the rate of emission of energy, the rate of emission of fire radiative energy should be more simply stated as fire radiative power (FRP). Energy is the time integral of power, so as shown in Equation 4.2.10, the only way to have a true FRE measurement would be to integrate a time series of FRP measurements.

$$\text{FRE} = \int \text{FRP} \, dt \quad (4.2.10)$$

$$\text{FRP}_{\text{TRUE}} = A_{\text{sample}} \varepsilon \sigma \sum_{i=1}^n A_n T_n^4 \quad (4.2.11)$$

Equation 4.2.11 defines fire radiative power. A_{sample} is the ground sampling area (m^2), σ is the Stefan-Boltzman constant ($5.67 \times 10^{-8} \text{ J s}^{-1} \text{ m}^{-2} \text{ K}^{-4}$), A_n is the fractional area of the n^{th} surface thermal component within the individual ground pixel, T_n is the temperature of the n^{th} thermal component (K), and ε is the emissivity. Studies have been done to relate radiative properties of active fires to emissions. For example, instantaneous FRP

measurements can be correlated to emission rates (with success usually only on a regional basis) and when integrated over time and space, total emissions can be calculated [Giglio et al., 2006; Ichoku and Kaufman, 2005; Roberts et al., 2005; Wooster et al., 2003; Wooster et al., 2005; Wooster, 2002; Brunner et al., 2006]. Using the example fire from section 4.2.1, for a 16 km^2 pixel (A_{sample}), and assuming the fire temperature (T_n) of 613 K over the specified 0.0028 proportion of the pixel (A_n), the FRP would be 486 MW (assuming emissivity = 1). The energy released by combustion, known in chemistry as heat of combustion, is directly related to the amount of fuel (biomass) consumed. FRE may seem to be more attractive than fire temperature because FRE is in the same units as heat of combustion and the time integral of FRE would be an indication of the total fuel consumed; however, it would be just as valid to convert fire temperature to energy.

MODIS Fire Confidence Categories	
Confidence	Category
0%-19%	low confidence fire pixel
20%-79%	nominal confidence fire pixel
80%-100%	high confidence fire pixel

Table 4.2.1

MODIS fire confidence categories where confidence categories correspond to a confidence category.

4.3 Characterization comparison

The main difference between the GOES and MODIS fire product characterization is that the GOES fire product estimates fire size and temperature while the MODIS fire product estimates the fire radiative power. There are also some differences in terms of fire classification. GOES flags fires in discrete categories whereas MODIS uses a

continuous a confidence percentage. The GOES WF_ABBA also issues a filtered product where a fire that appears in only one observation over the past 12 hours is removed due to a higher likelihood of false detection; this is only possible with frequent temporal coverage that is not available with MODIS.

After identifying the fire location, an additional step is to estimate the fire emissions. Determining the amount of available biomass fuel is one of the biggest challenges and uncertainties in estimating emissions. Experiments such as that done by Wooster relate the amount of available fuel to smoke emissions [Wooster, 2002]. Ichoku and Kaufman relate satellite detected fire characteristics to smoke emissions [Ichoku and Kaufman, 2005]. Different land types and regions are known to have different emission characteristics and are also considered when defining an emission factor. For example, the relationship between the mass of vegetation, M ; area burned, A ; biomass density, b ; and c , the completeness of combustion are combined into Equation 4.3.1 [Seiler and Crutzen, 1980].

$$M=Abc \quad (4.3.1)$$

5 Comparison of the GOES and MODIS fire product data

To quantify the differences between the characteristics of fire pixels that GOES and MODIS both detect compared to characteristics of fire pixels detected by only one product a fire pixel, it is necessary but challenging to determine when both satellites are detecting the same fire. To solve this problem, multiple combinations of spatial and temporal parameters are tested. For two fire pixels to be considered the same fire, many different definitions are tested which allow the fire pixels to be located anywhere from

within 5 km (and within $\pm 0.05^\circ$) up to within 25 km (and within $\pm 0.25^\circ$) and at the same time, the fires must occur within ± 15 minutes of each other up to within ± 12 hours of each other. A further complication is that one GOES fire pixel might have a single matching MODIS fire pixel, or one GOES fire pixel might have multiple MODIS fire pixels that are within the criteria to be considered matching fire pixels. Multiple GOES fire pixels might have a single MODIS fire pixel that fits the matching criteria, or multiple GOES fire pixels might have multiple MODIS fire pixels that all fit the matching criteria. Additionally, comparisons treat each fire pixel as a different fire; a fire occurring at the same location (or nearly the same location) as another fire pixel from the same satellite at a different time are treated as two separate fires. This is done because it is unknown if the fire pixel represents a stationary fire that burned continuously between the two time periods, or perhaps the sub-pixel fire activity has numerous fires being ignited and extinguished between observation times. Furthermore, a continuously burning fire might migrate from one pixel location to another position in sequential observations that would be difficult to account for, so instead of tracking individual fire events, statistics are generated by looking at a large number of fire pixel detections.

After establishing the similarities and differences in the satellite instrumentation and characteristics as well as the algorithm similarities and differences, it is not surprising that the GOES and MODIS fire products show some similarities and differences. Such comparisons are not validation studies. Each fire pixel from either product could be a false detection as a result of sun glint, noise, land or cloud misclassification, or a surface thermal anomaly. If both fire products detect a fire at the same location, it remains possible that they are both false detections. Also, if a fire is detected in one satellite

product, that could be a result of a false detection, or one satellite might have been obscured by clouds, sun-glint, and land-type mapping, navigational errors, coverage gaps, or the fire signature might not have been identifiable by the different fire algorithms. Despite all the factors that can cause differences between the fire products, there is value added by analyzing the fire pixels that are collocated in time and space and compare their characteristics against the fires that are only detected by one product. The products are examined using both annual statistics that show some statistically significant trends and also some case studies for particular days and regions to show examples with a small data set typical of a regular day.

For this study, data from 2004 and 2005 are used from GOES-12 (GOES-East) and MODIS (AQUA and TERRA). These years were chosen because there is nearly complete coverage from all platforms for both years; 2003 was not selected because GOES-8 began the year as the GOES-East satellite and combining GOES-8 and GOES-12 fire products would introduce inconsistencies. MODIS AQUA data became available in the middle of 2002 but 2002 does not have complete data coverage from AQUA and in 2000 and 2001 MODIS TERRA was the only provider of the MODIS fire product.

5.1 Case studies

Case studies help explain the similarities and differences between the GOES and MODIS fire products for particular days and in particular regions. Annual statistics give a general idea of how well GOES and MODIS fire products agree with each other, but case studies generate a picture of typical scenes that combine to form the annual trends.

5.1.1 North America

April 4, 2004 was a day with particularly high fire activity in North America. Figure 5.1.1.1 shows that for fire pixels with a match within 10 km and +/- 12 hours, 224 GOES fire pixels had a matching MODIS fire pixel and 233 GOES fire pixels did not have a MODIS matching fire pixel, while 334 MODIS fire pixels had a matching GOES fire pixel and 498 MODIS fire pixels did not have a matching GOES fire pixel. There is however more agreement between the products, and visually there is less noise when removing low possibility fire pixels from consideration as shown in Figure 5.1.1.2. The difference made by removing low possibility fire pixels decreases the number of unmatched GOES fire pixels from 233 to 125 while only 28 of the original 224 GOES fire pixels with a MODIS match are low confidence fire pixels. In this case study very few MODIS fire pixels are low confidence fire pixels and so there is little difference between Figure 5.1.1.1 and Figure 5.1.1.2 with respect to MODIS fire pixels with a GOES fire pixel match. Considering GOES filtered fire pixels as in Figure 5.1.1.3, a much higher ratio of GOES filtered fire pixels have a MODIS match compared to the unfiltered fire pixels in Figure 5.1.1.1. However, there are fewer MODIS fire pixels with a match in Figure 5.1.1.1 compared to Figure 5.1.1.3 because some of the fires detected by GOES that did not pass the temporal filter are collocated with MODIS fires. Furthermore, Figure 5.1.1.4 shows GOES filtered fire pixels and MODIS fire pixels both excluding low confidence fire pixels. Of the original 233 GOES fire pixels without a matching MODIS fire pixel, removing low confidence fire pixels and filtering the GOES fire product eliminates all but 48 of the unmatched fire pixels. With this reduction however, the original 224 GOES fire pixels with a match from Figure 5.1.1.1 are reduced

to 116 GOES filtered fire pixels with low confidence fire pixels excluded as shown in Figure 5.1.1.4. Reducing the number of GOES fire pixels through filtering eliminates some fire pixels that would match with MODIS and removing low confidence fire pixels removes more GOES fire pixels than MODIS fire pixels (which also has fewer collocated fire pixels after low confidence fire pixels are removed). To illustrate this, 334 MODIS fire pixels had a matching GOES fire pixel in Figure 5.1.1.1 but only 198 MODIS fire pixels with low confidence fire pixels excluded matched with a GOES filtered fire pixel with low confidence fire pixels excluded. Another aspect to consider is the size of the temporal window. For example, Figure 5.1.1.5 requires fires to occur within ± 0.25 hours such that MODIS fires must be found by the GOES image that is closest to the time the MODIS fire was detected. Furthermore, all GOES fire pixels that occurred in areas not covered by MODIS within ± 0.25 hours of the fire detection are excluded from consideration because it was not possible for MODIS to detect these fire pixels. A much higher percentage of the GOES fire pixels have a matching MODIS fire pixel within ± 0.25 hours, 67% (35 out of 52), than at ± 12 hours, 49% (224 out of 457). However only 14% of MODIS fire pixels (118 out of 832) have a matching GOES fire pixel within ± 0.25 hours compared to 40% of MODIS fire pixels (334 out of 832) that have a GOES match within ± 12 hours. Figure 5.1.1.6 reveals that when excluding low confidence GOES filtered fire pixels, only 1 fire pixel is found that does not have a matching MODIS fire pixel within ± 0.25 hours, while 16 GOES filtered fire pixels have a MODIS match. But again while the ratio of GOES fire pixels with a match increases, the ratio of MODIS fire pixels with a match decreases. Increasing the temporal window expands the area by MODIS swaths, however the area covered by GOES

remains constant. Increasing the temporal window will increase the number of MODIS fire pixels that match with a GOES fire pixel because MODIS fires that did not have a matching GOES fire pixel in the nearest possible GOES product might have a match as more time is allowed to pass. For GOES, increasing the temporal window does increase the number of collocated fire pixels, but more fire detections are unique to GOES because MODIS can not detect the fires that if they are not burning during the MODIS overpass.

4 April 2004 GOES and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

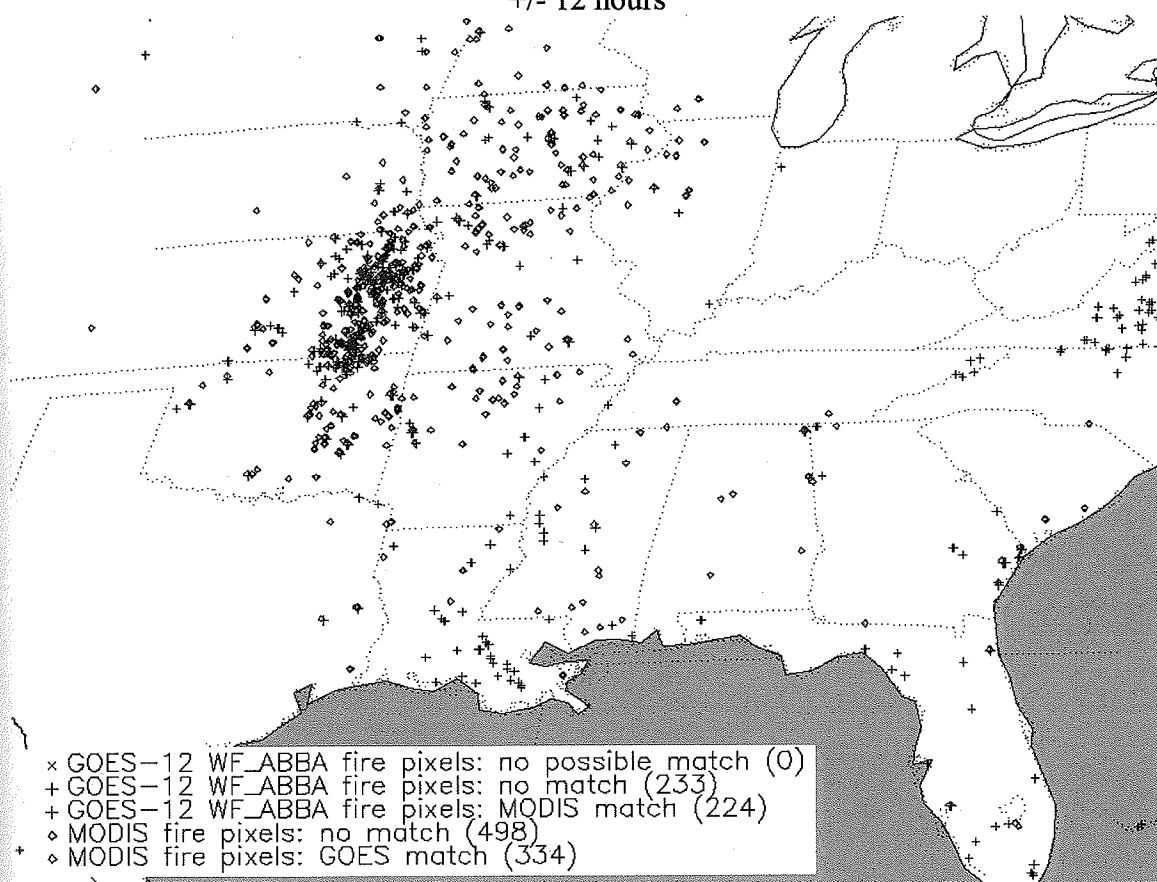


Figure 5.1.1.1

GOES and MODIS fire pixels for 4 April 2004 with and without a match within 10 km and +/- 12 hours in the Central and Southeastern United States. A large number of fire pixels agree in Oklahoma and Kansas. MODIS fire pixels are more numerous in Iowa, Missouri and Arkansas than GOES fire pixels. Many GOES fire pixels are found in Louisiana and Virginia, many of which are likely false detections that do not correspond with MODIS fire detections.

4 April 2004 GOES and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

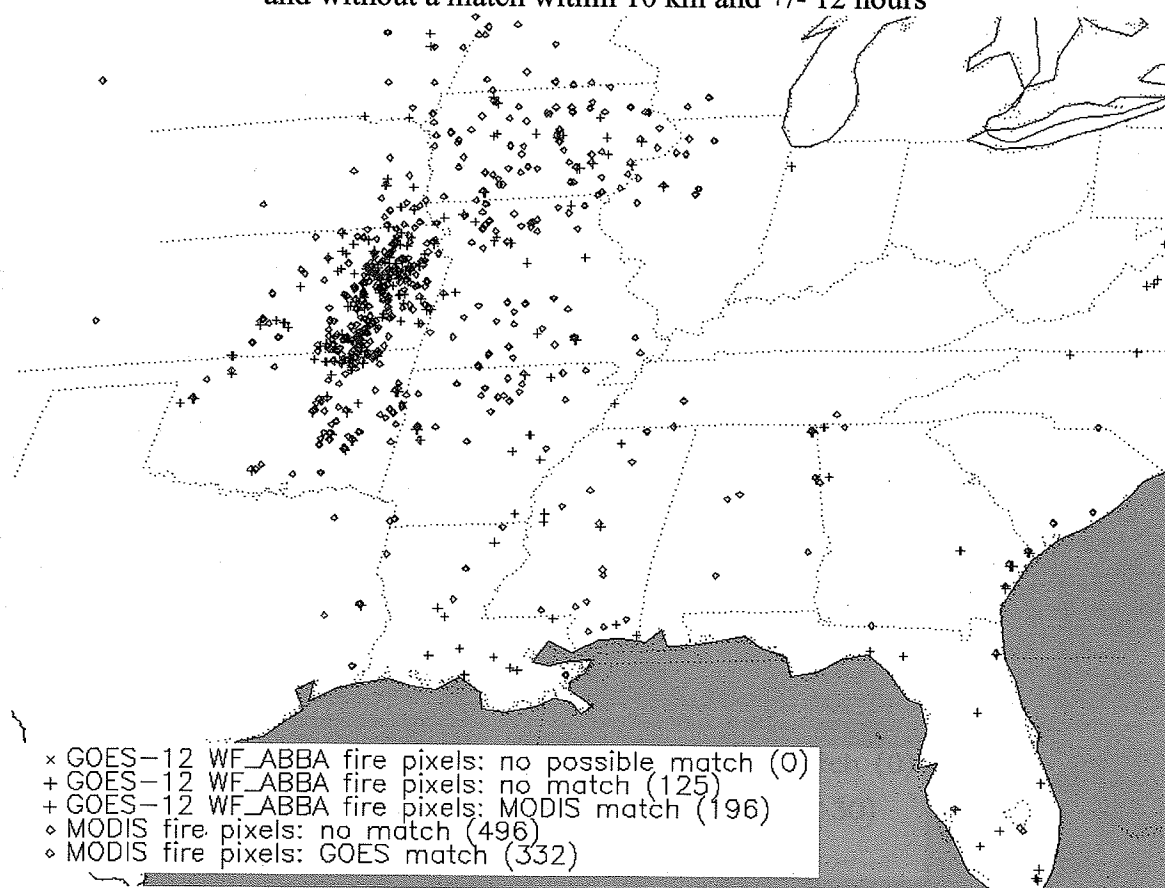


Figure 5.1.1.2

GOES and MODIS fire pixels with low confidence fire pixels excluded on 4 April 2004 with and without a match within 10 km and +/- 12 hours in the Central and Southeastern United States. While excluding low confidence fire pixels reduces the number of fire pixels with a match, the number of fire pixels with no match is reduced more.

4 April 2004 GOES filtered and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

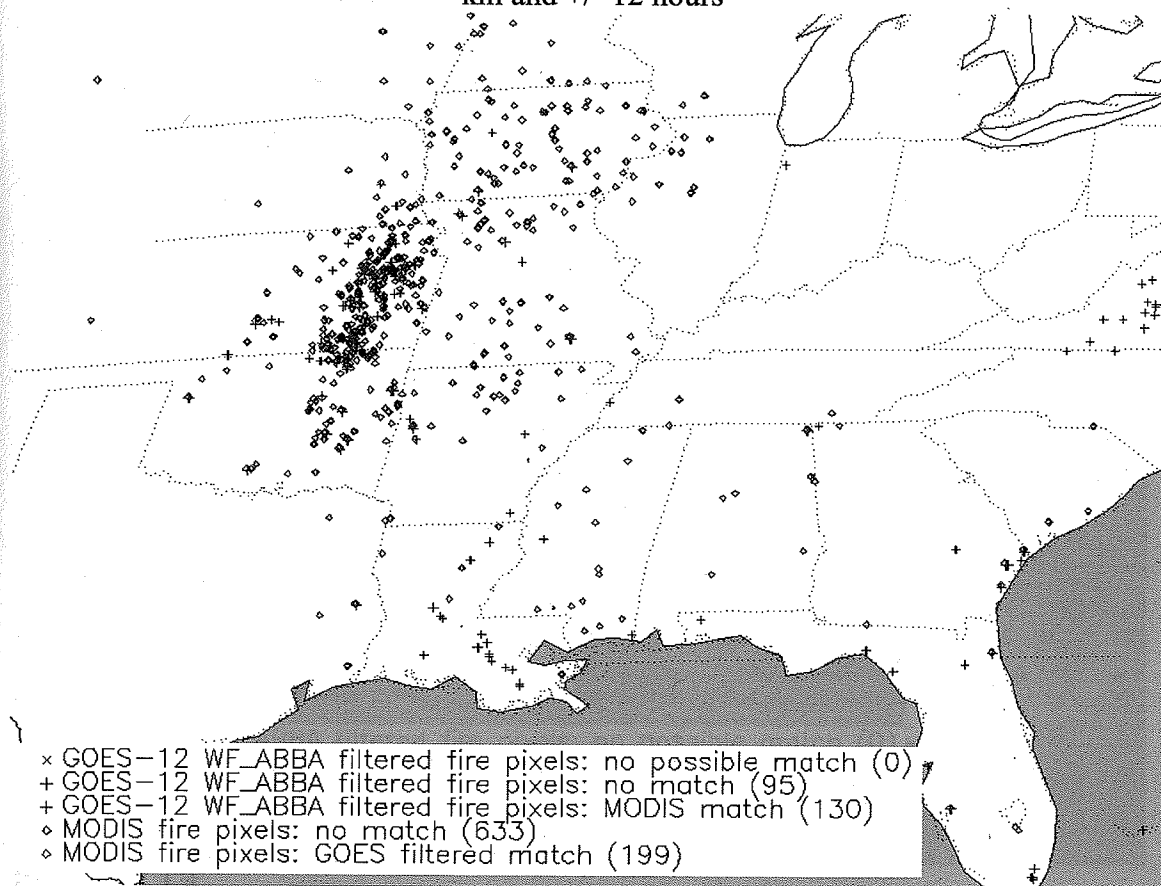


Figure 5.1.1.3

GOES filtered and MODIS fire pixels for 4 April 2004 with and without a match within 10 km and +/- 12 hours in the Central and Southeastern United States. With the GOES filtered product, less MODIS fire pixels have a match than with the unfiltered product and the unfiltered product with low confidence fire pixels excluded, however, there is a higher proportion of GOES fire pixels with a match than found with the unfiltered GOES products.

4 April 2004 GOES filtered and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

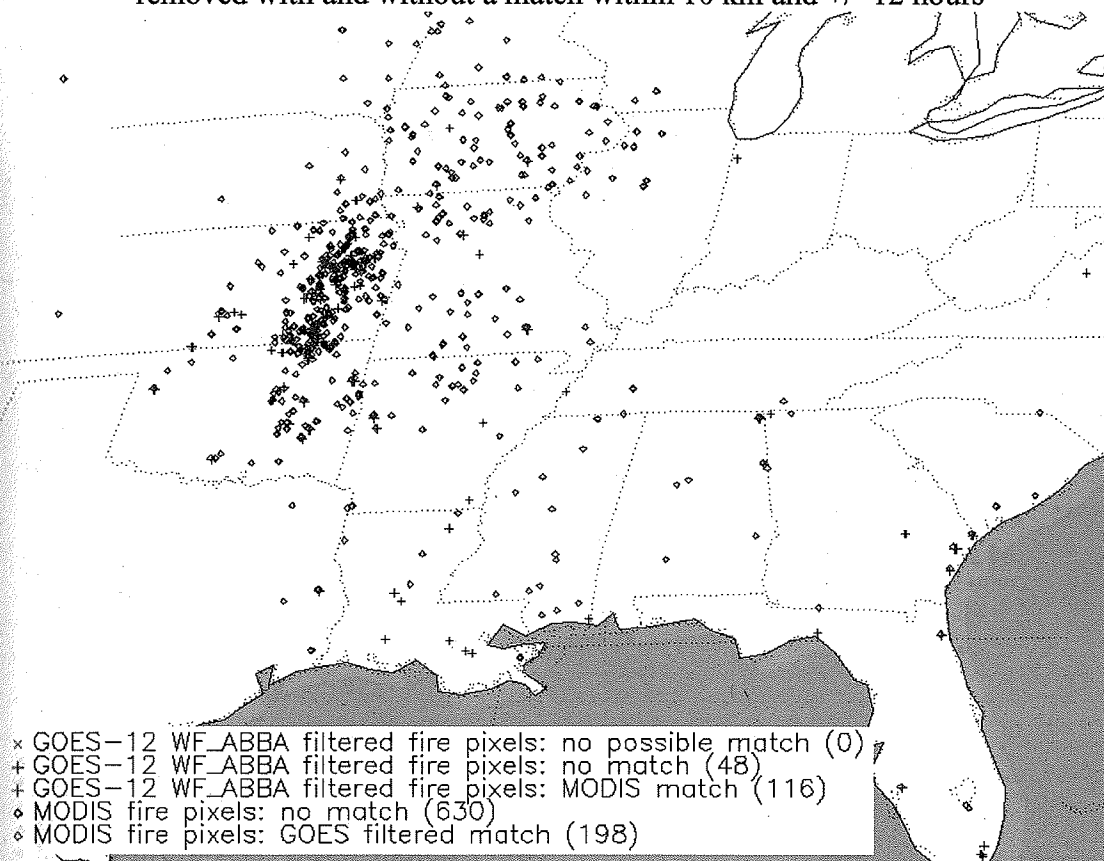


Figure 5.1.1.4

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded for 4 April 2004 with and without a match within 10 km and +/- 12 hours in the Central and Southeastern United States. The proportion of GOES filtered fire pixels with a match compared to no match is highest when low confidence fire pixels are excluded, however the proportion of MODIS fire pixels with a match is lowest under these conditions. Notice that the cluster of GOES fire pixels in Virginia that did not have a MODIS match has been reduced to only one fire pixel location as rest of the fire pixels in the region are eliminated in the filtered product and by excluding low confidence fire pixels.

4 April 2004 GOES and MODIS fire pixels with and without a match within 10 km and
 ± 0.25 hours

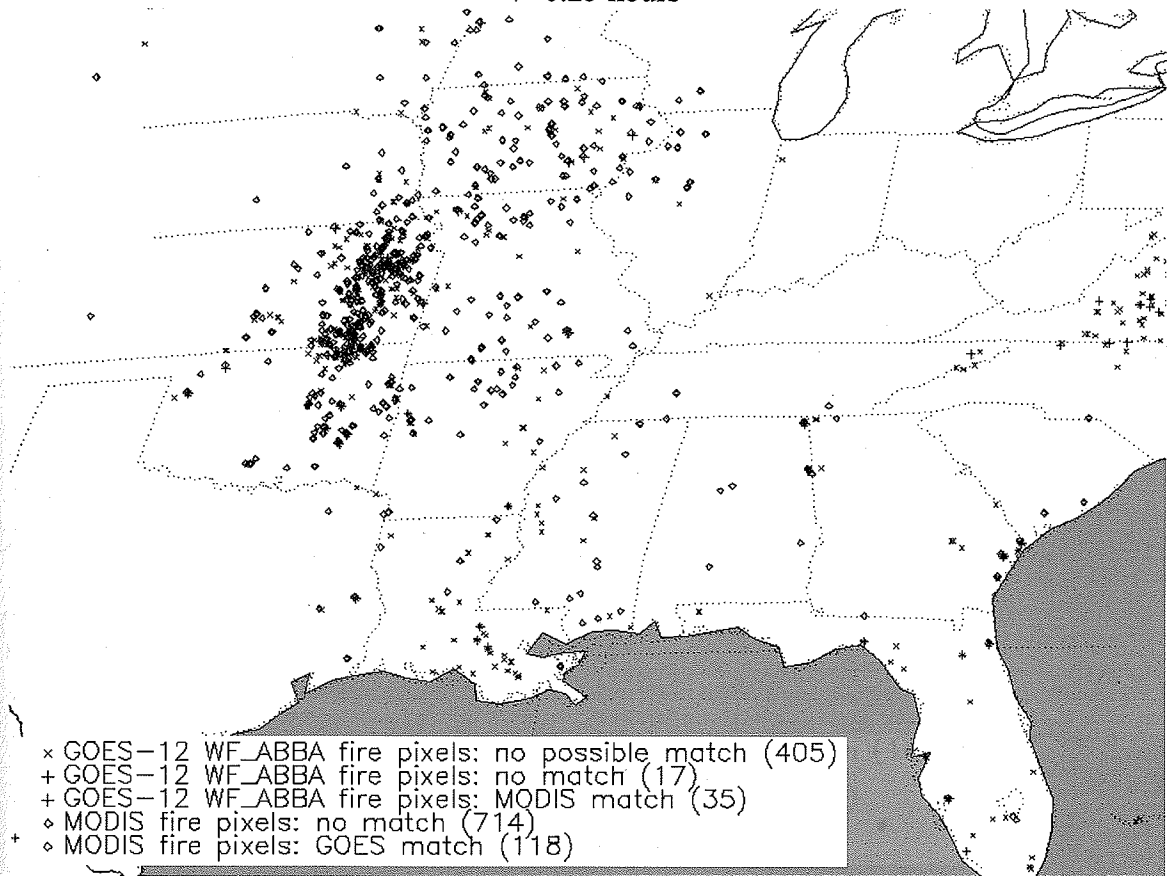


Figure 5.1.1.5

GOES and MODIS fire pixels for 4 April 2004 with and without a match within 10 km and ± 0.25 hours in the Central and Southeastern United States. A large number of fire pixels agree in Oklahoma and Kansas and most of the GOES fire pixels that do not match with a MODIS fire pixel are green which are GOES fire pixels occurring in areas not covered within ± 0.25 hours of the GOES fire detection.

4 April 2004 GOES filtered and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 0.25 hours

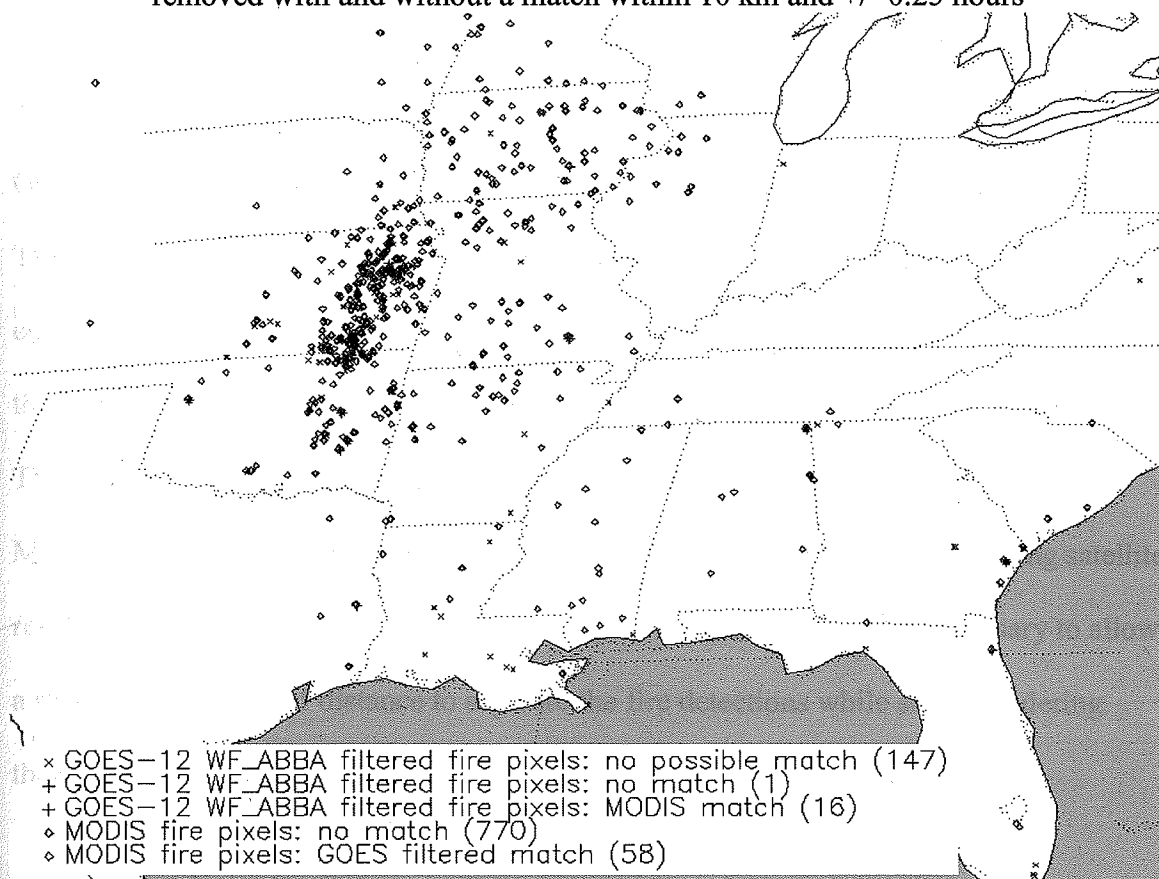


Figure 5.1.1.6

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded for 4 April 2004 with and without a match within 10 km and +/- 0.25 hours in the Central and Southeastern United States. When low confidence fire pixels are excluded only one GOES filtered fire pixel that is in an area covered by MODIS within +/- 0.25 hours of the fire pixel detection does not have a matching MODIS fire pixel. With such a narrow constraint on time, a very low ratio of MODIS fire pixels have a match with a GOES fire pixel; more MODIS fire pixels match with GOES when the temporal criteria is extended.

Another case in North America comes from 24 May 2004. From this day, Figure 5.1.1.7 shows the derived GOES and MODIS fire pixels for this day. Notice that there are many unmatched GOES fire pixels, however almost all of them disappear when GOES filtered fires are used and low confidence fire pixels are removed (Figure 5.1.1.8). This case illustrates two important concepts where it is very clear that removing low confidence fire pixels and using the filtered GOES fire product eliminates almost all of the fires that both satellites do not detect because they are most likely false detections. The second important concept illustrated is that while it is quite apparent GOES and MODIS are detecting the same fire, the fire pixels, due in a large part to differing satellite resolutions, are not precisely collocated on top of one another and it is necessary to allow a reasonable amount of distance to separate the fire detections while still considering them collocated fires.

24 May 2004 GOES and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

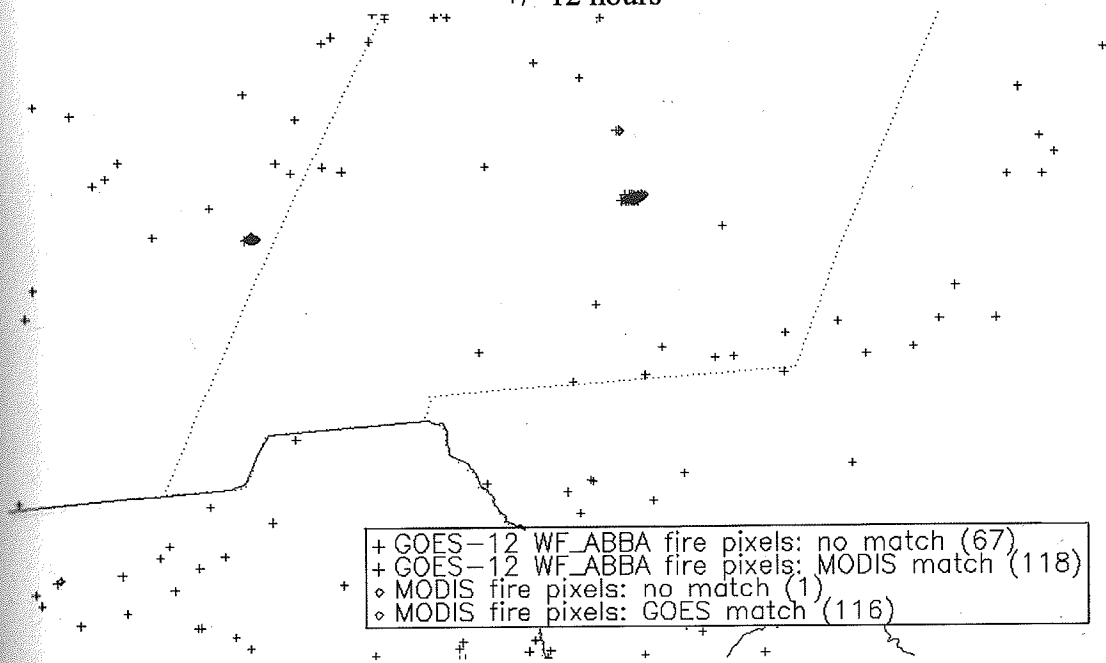


Figure 5.1.1.7

GOES and MODIS fire pixels for 24 May 2004 with and without a match within 10 km and +/- 12 hours in the Southwestern United States. A large cluster of fire pixels agree in New Mexico and in far eastern Arizona while the rest of the region shows scattered GOES fire detections that are undetected by MODIS.

24 May 2004 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

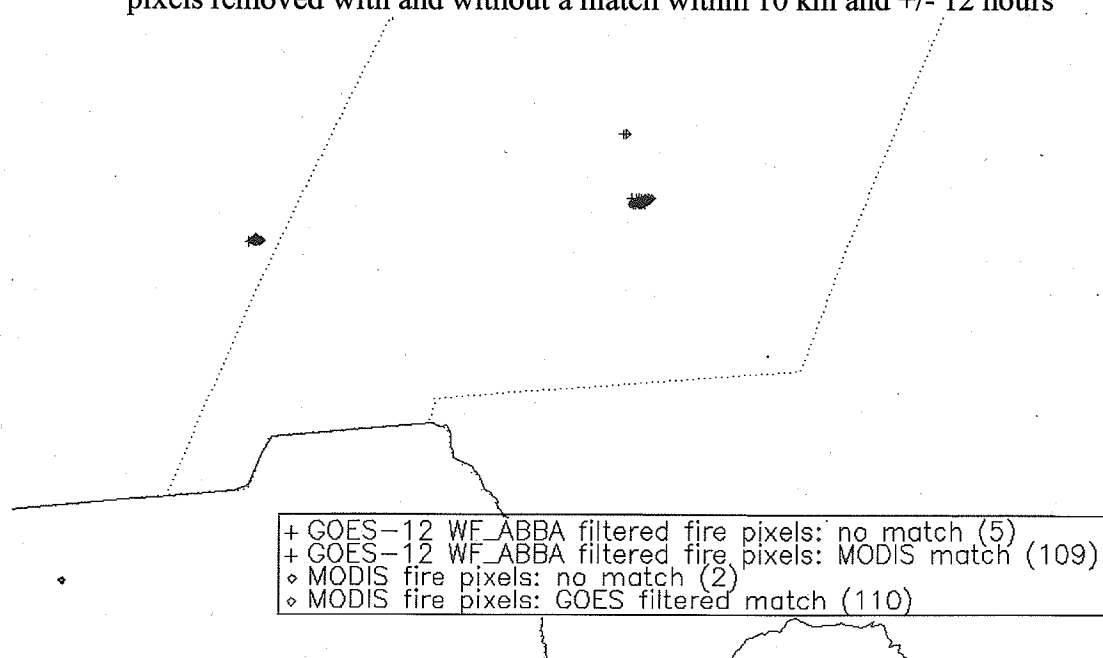


Figure 5.1.1.8

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded from 24 May 2004 with and without a match within 10 km and +/- 12 hours in the Southwestern United States. The large cluster of fire pixels continue to agree in New Mexico and in far eastern Arizona remain while the GOES fire detections that were scattered throughout the rest of the region have been removed by excluding low confidence detections and by including only the GOES filtered product. There is a MODIS fire detection in northern Mexico that had corresponded to a GOES fire detection that is now unmatched with the filtered GOES product with low confidence fires excluded.

Another North American case study is focused on 11 October 2004 in North Dakota, Minnesota, and Southern Manitoba where MODIS fire detections outnumber GOES fire detections. Figure 5.1.1.9 shows GOES and MODIS fire pixels with and without a match within 10 km and +/- 12 hours. There are a few examples especially just south of Lake Winnipeg where some GOES fire pixels are found near a MODIS fire pixel but are beyond 10 km and are not considered a match. At such high latitudes, GOES resolution becomes increasingly coarse such that fire detection becomes increasingly

difficult and with such large pixels allowing the distance between the centers of pixels to expand becomes more reasonable than at lower latitudes.

11 October 2004 GOES and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

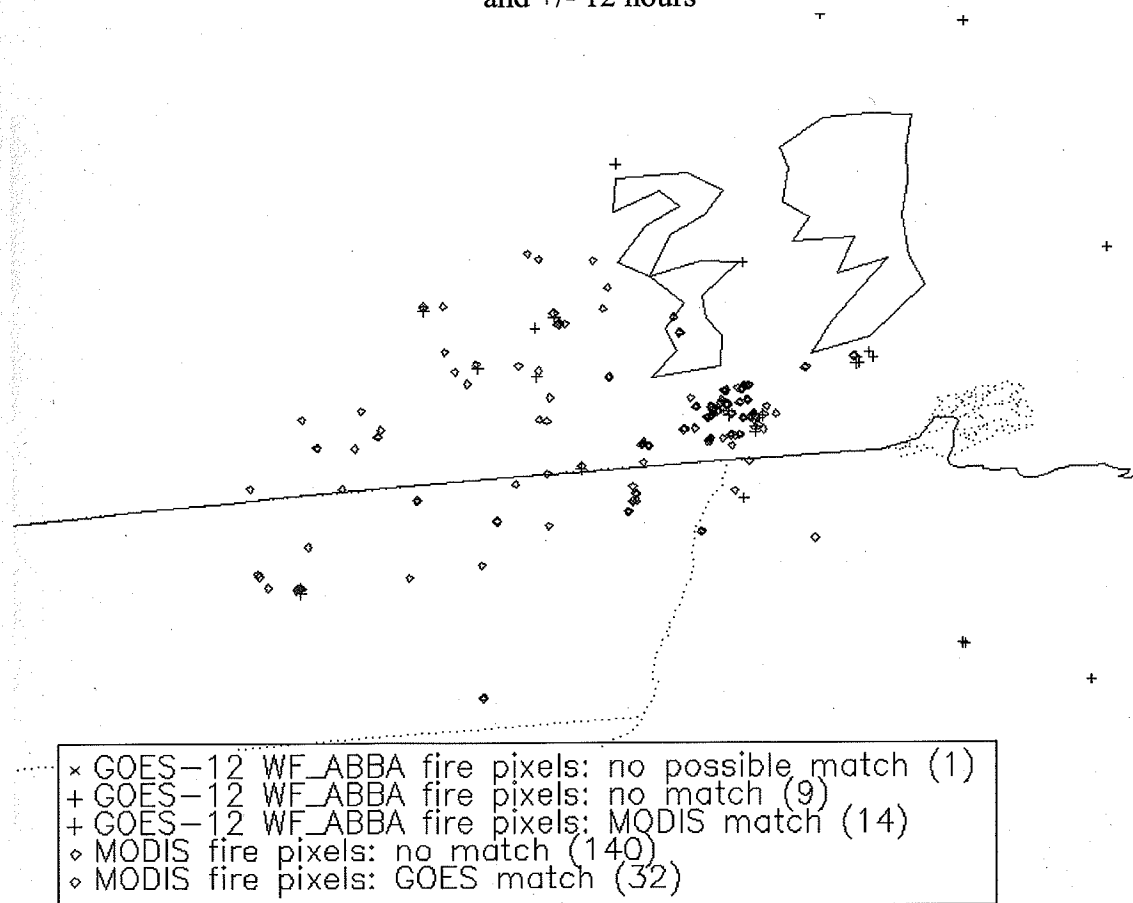


Figure 5.1.1.9

GOES and MODIS fire pixels for 11 October 2004 with and without a match within 10 km and +/- 12 hours in North Dakota, Minnesota, and southern Manitoba, Canada. A cluster of fire pixels near Winnipeg contains matching fire pixels. In this case MODIS fire pixels outnumber GOES fire pixels and most MODIS fire pixels do not have a GOES match. South of Lake Winnipeg there is a cluster of GOES and MODIS fire pixels that might be detecting the same fire but perhaps due to the coarse GOES resolution at this latitude the GOES and MODIS pixels are beyond 10 km apart.

June 30, 2005 is an example of an active fire day in the Western United States in Figure 5.1.1.10. Once again, removing low probability fire pixels and using filtered GOES fire pixels provides a much more clear picture of fire activity as shown in Figure 5.1.1.11.

30 June 2005 GOES and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

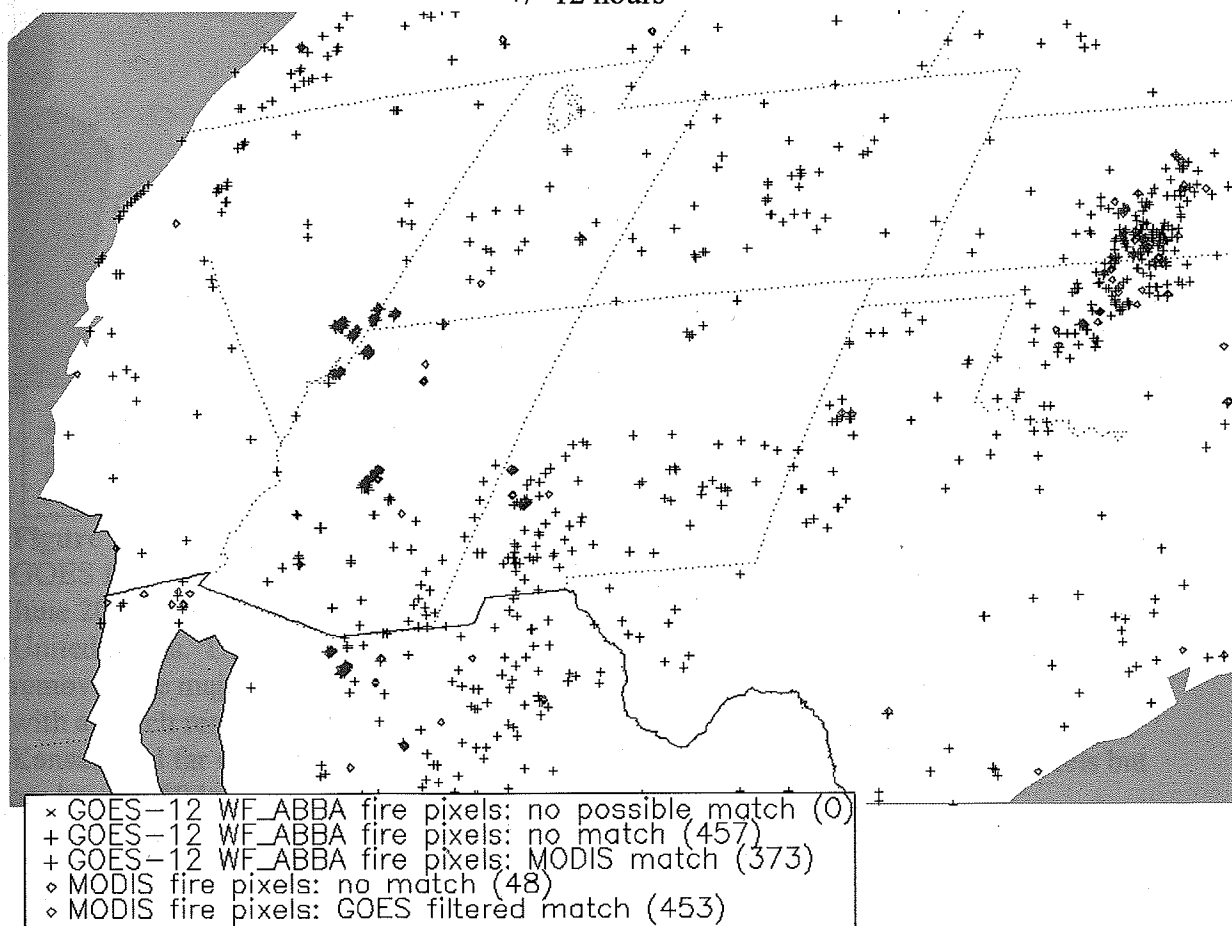


Figure 5.1.1.10

GOES and MODIS fire pixels for 30 June 2005 with and without a match within 10 km and +/- 12 hours in the southwestern United States. Groups of fire detections in Arizona, Nevada, Utah, New Mexico, Mexico, Oklahoma, and Kansas show collocated GOES and MODIS fire pixels. Scattered throughout the rest of the area are numerous unmatched GOES fire pixels and relatively few unmatched MODIS fire pixels.

30 June 2005 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

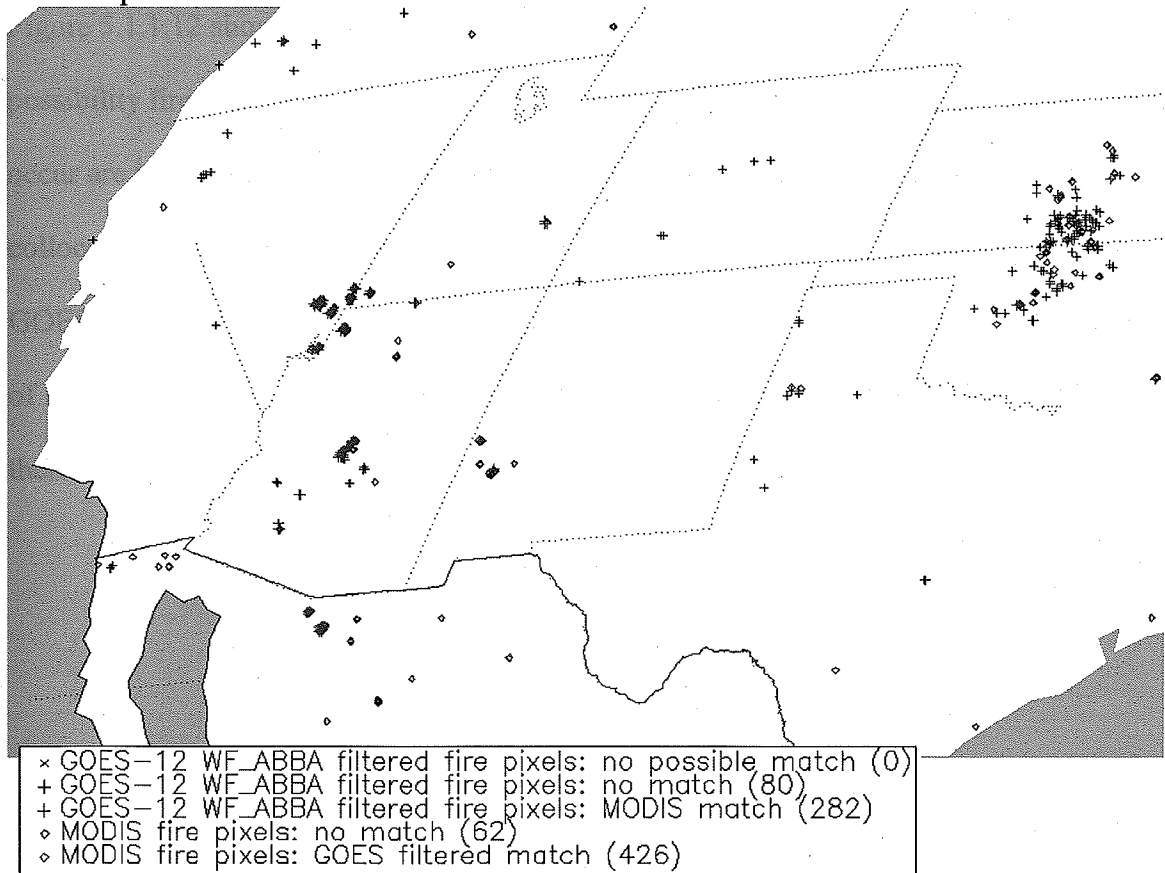


Figure 5.1.1.11

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 30 June 2005 with and without a match within 10 km and +/- 12 hours in the southwestern United States. Using the GOES filtered product and removing low confidence fire pixels removed the majority of unmatched GOES fire pixels while the majority of fire pixels with a match remain. There also remain clusters of fire pixels in Oklahoma, Texas, Kansas, and far western Mexico where GOES fire pixels are near MODIS fire pixels but are beyond 10 km.

A final example of fires in North America is in Quebec on 12 October 2005.

Figure 5.1.1.12 shows the filtered GOES fire pixels and MODIS fire pixels with low possibility fire pixels removed and while there are only a few fire pixels, the fires that do occur are in good agreement. With a zoomed in view, the eastern cluster of fires are collocated. The western cluster of fire detections are close together but only one of the GOES and MODIS fire pixel locations are within 10 km. The rest of the western cluster of fire pixels seem to be part of the same fire event they fail to be within 10 km and therefore are counted as unmatched fire pixels.

12 October 2005 GOES filtered fire pixels and MODIS fire pixels with low possibility
fire pixels removed with and without a match within 10 km and +/- 12 hours

- + GOES-12 WF_ABBA filtered fire pixels: no match (2)
- + GOES-12 WF_ABBA filtered fire pixels: MODIS match (11)
- ◇ MODIS fire pixels: no match (6)
- ◇ MODIS fire pixels: GOES filtered match (6)

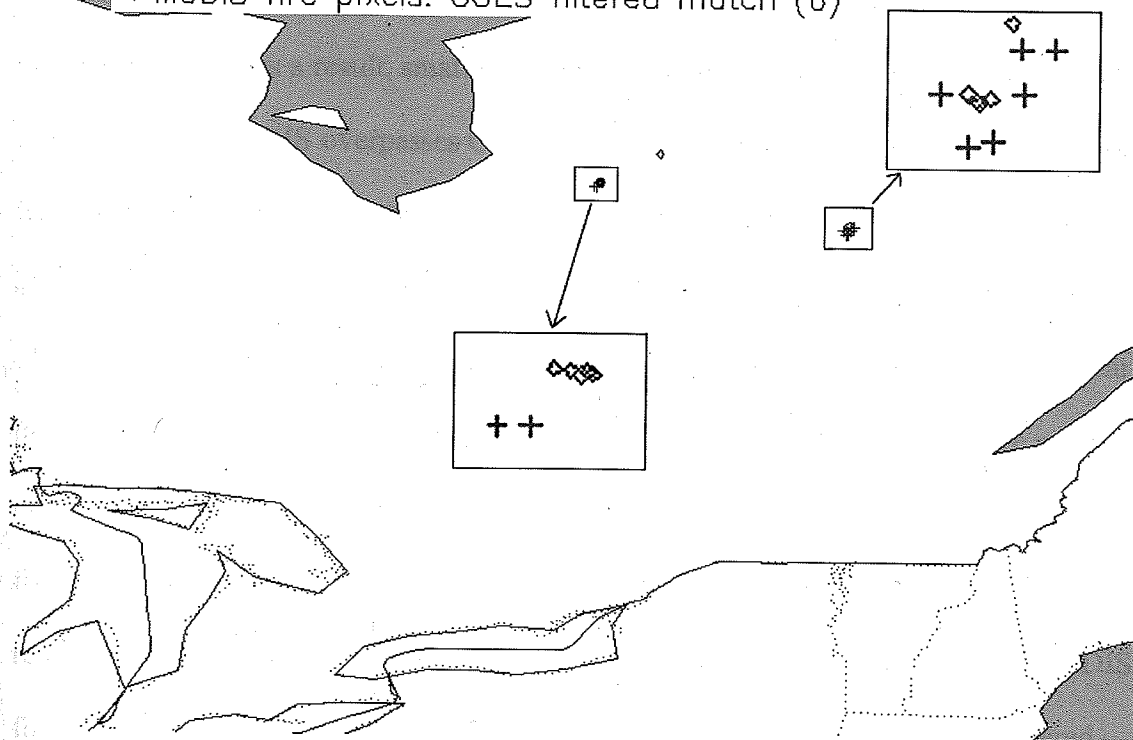


Figure 5.1.1.12

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded, with and without a match within 10 km and +/- 12 hours in Quebec, Canada on 12 October 2005. The MODIS and GOES fire pixels in the east are within 10 km of each other and are considered matching. There is only one MODIS fire pixel and one GOES fire pixel location that is within 10 km of each other in the west, while there is a nearby GOES fire pixel location and a few nearby MODIS fire pixels that are close but fail to be within 10 km, so they are not considered matching fire pixels.

5.1.2 Central America

Central American fires detections have different characteristics than the rest of North America for a number of reasons. At lower latitudes, the GOES spatial resolution is much finer, and as a result, smaller or less intense fire activity within a pixel triggers fire detection. MODIS overpasses Central America closer to the mid-day diurnal peak in fire activity compared to the overpass times at higher North American latitudes. The climate, land type, and agricultural practices are all in general more conducive to consistent and widespread fire activity in Central and South America from year to year than at the higher latitudes in North America. Figure 5.1.2.1 illustrates the fire activity on an active spring day on 24 April 2004 in Central America. With well over a thousand fire pixels, this region is much more active than a typical northern North American region. Of the GOES fire pixels, 47% have a MODIS match while 74% of the MODIS fire pixels have a match with GOES. As was the case in North America, the filtered GOES fire product reduces the number of false detections as does removing low confidence fire pixels and Figure 5.1.2.2 shows the fire pixels in the same region as in Figure 5.1.2.1 but with the low confidence fire pixels removed and using the GOES filtered product. As high as 61% of the GOES filtered fire pixels that exclude low confidence fire pixels have a MODIS match and in this case 61% of the MODIS fire pixels have a GOES match. Considering only the GOES filtered fire pixels and removing low confidence fire pixels improves the ratio of GOES fire pixels with a match but decreases the ratio of MODIS fire pixels with a GOES match. The timing of the fire and the MODIS overpass is important in Central America. Figure 5.1.2.3 shows that 43% of the MODIS fire pixels have a GOES match within +/-0.25 hours of MODIS detecting a

fire pixel, compared to only 28% of the MODIS fire pixels with low confidence fire pixels excluded that have a GOES filtered match as shown in Figure 5.1.2.4.

24 April 2004 GOES fire pixels and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

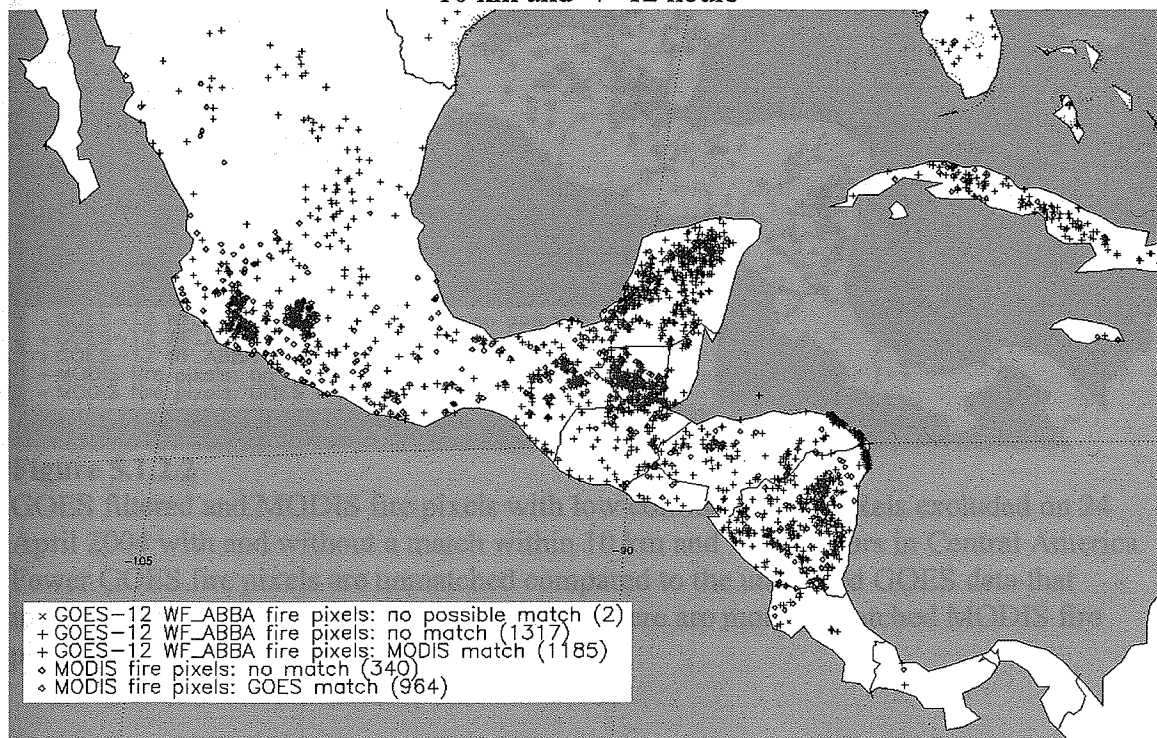


Figure 5.1.2.1

GOES and MODIS fire pixels on 24 April 2004 with and without a match within 10 km and +/- 12 hours in Central America.

24 April 2004 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

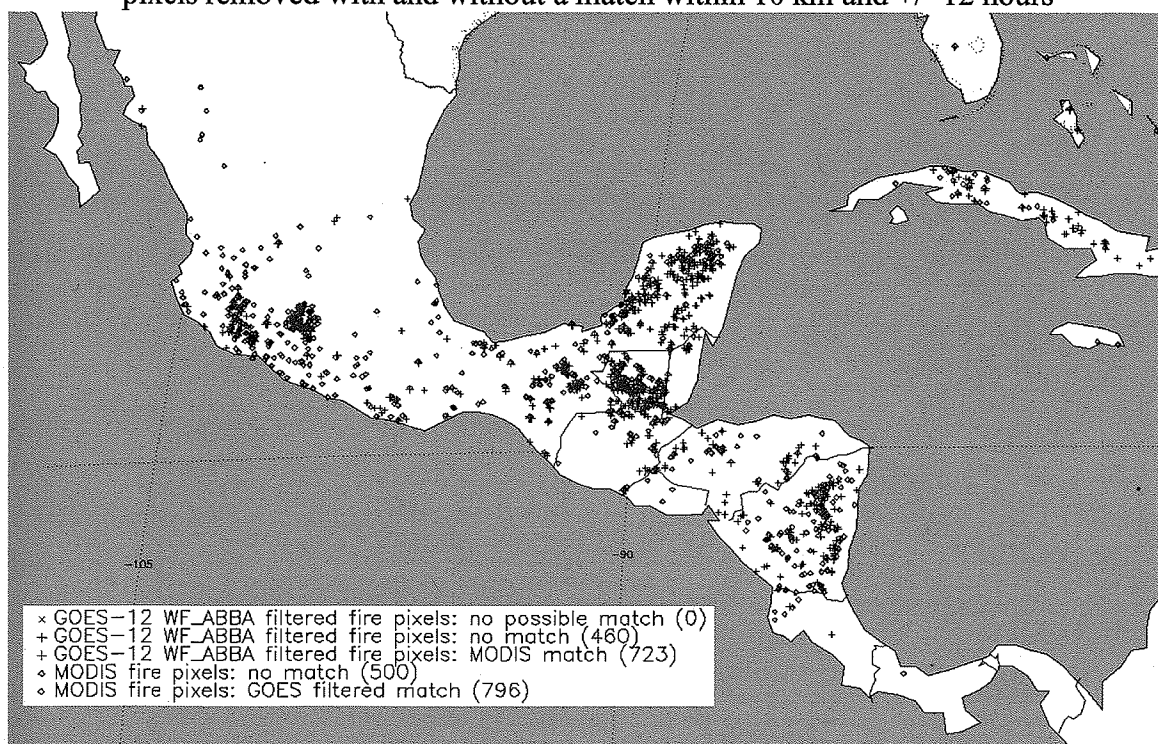


Figure 5.1.2.2

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 24 April 2004 with and without a match within 10 km and +/- 12 hours in Central America. Fewer GOES fire pixels are unmatched compared to the unfiltered GOES data that includes low confidence fire pixels, however, there are more unmatched MODIS fire pixels.

24 April 2004 GOES fire pixels and MODIS fire pixels with and without a match within 10 km and +/- 0.25 hours

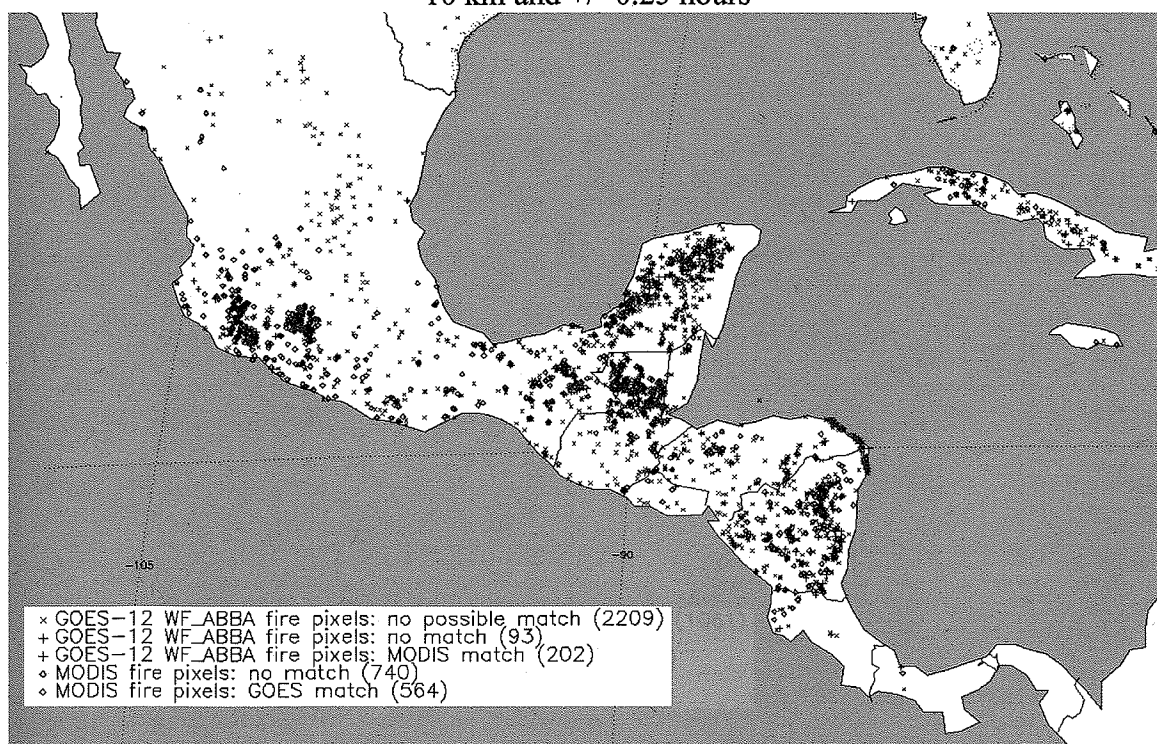


Figure 5.1.2.3

GOES and MODIS fire pixels on 24 April 2004 with and without a match within 10 km and +/- 0.25 hours in Central America. An order of magnitude more GOES fire pixels occur more than +/- 0.25 hours from a MODIS overpass. However, the ratio of GOES fire pixels that match with MODIS fire pixels is higher than when +/- 12 hours are considered.

24 April 2004 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 0.25 hours

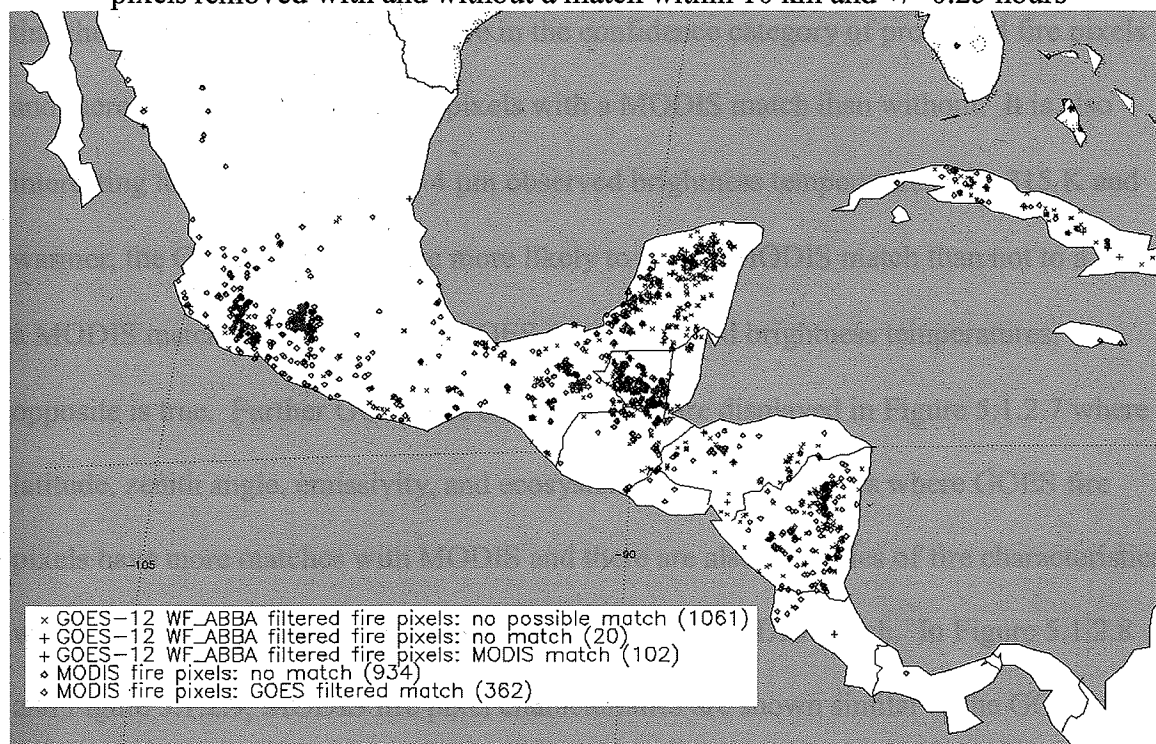


Figure 5.1.2.4

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 24 April 2004 with and without a match within 10 km and +/- 0.25 hours in Central America. The ratio of GOES filtered fire pixels with low confidence fire pixels excluded that have a MODIS fire pixel match is even higher than the unfiltered GOES data with low confidence fire pixels included. There is however the highest ratio of MODIS fire pixels with no GOES match recorded for this scenario.

Instead of using the daily ASCII MODIS data set, the 5 minute granule HDF files are used analyze the 24 April 2004 case more closely. Figure 5.1.2.5 uses the new data set in Central America for GOES filtered and MODIS fire pixels with low confidence fire pixels excluded. There are 6 fewer fire pixel matches using this version of the MODIS data however there are nearly 300 more MODIS fire pixels with no GOES match while over 500 more MODIS fire pixels have a GOES match compared to the daily ASCII data in Figure 5.1.2.2. Note that these differences are due to different versions of the MODIS

algorithm. Looking at the characteristics of the GOES fire pixels, Figure 5.1.2.6 shows that the majority of the fire pixels are in the confidence category of processed fire pixels and there are more processed fire pixels with a MODIS match than without. It is also interesting to see that for GOES 4 μm observed brightness temperatures of ~ 315 K and warmer, the GOES fire pixels are more likely to have a MODIS match than not to have a MODIS match, while for cooler GOES 4 μm observed brightness temperatures, the opposite is true. Further GOES fire characteristics are displayed in Figure 5.1.2.7 where latitude, zenith angle, emissivity, and ecosystem all show examples where GOES fire pixels have more matches with MODIS and there are also examples of fire characteristics where GOES fire pixels are more likely to not have a MODIS match. In Figure 5.1.2.8 and Figure 5.1.2.9, MODIS fire pixel characteristics are shown similar to the GOES fire pixels in Figure 5.1.2.6 and Figure 5.1.2.7. For MODIS fire pixels there are more MODIS fire pixels with a match as confidence increases. Again, warmer 4 μm observed brightness temperatures tend to have more fire pixels with a match than with no match. There are also different latitudes, emissivities and ecosystems that have more matches than other categories just as there are other characteristics that yield fewer matches than would be expected. Table 5.1.2.1 conveys similar information in a table format. There are differences in the GOES product compared to the GOES filtered product and also using or excluding low confidence fire pixels alters the overall data set. The mean value of the fire characteristics indicates that fire pixels with a match tend to have a higher confidence value and tend to have a warmer 4 μm observed brightness temperature. In general, the standard deviations are large for both matched and unmatched fire pixels, but unmatched fire pixels tend to have a larger standard deviation for all of the categories and

characteristics. Further analysis of the differences between the characteristics of fire pixels with a match compared to the characteristics of fire pixels with no match is in section 5.2.3 where a statistical tool, discriminant analysis, is applied to exploit the differences in the characteristics of fire pixels with a match compared to the fire pixels without a match. A predictive forecast is generated that has skill in determining if a fire pixel will have a match from another satellite based only on the characteristics of the fire pixel.

24 April 2004 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

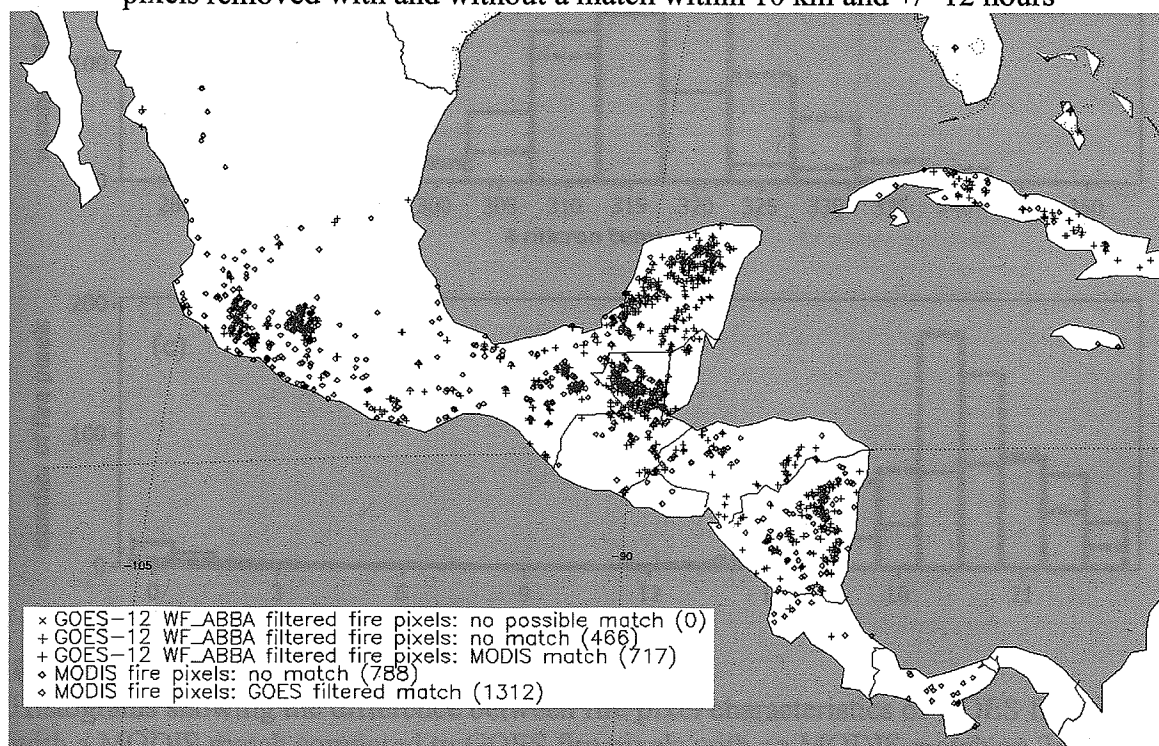


Figure 5.1.2.5

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 24 April 2004 with and without a match within 10 km and +/- 12 hours in Central America. Fewer GOES fire pixels are unmatched compared to the unfiltered GOES data that includes low confidence fire pixels, however, there are more unmatched MODIS fire pixels.

24 April 2004 GOES filtered fire pixels, excluding low confidence fire pixels, compared with MODIS fire pixels within +/- 12 hours and within 10 km

□ matched fire pixels
 □ unmatched fire pixels

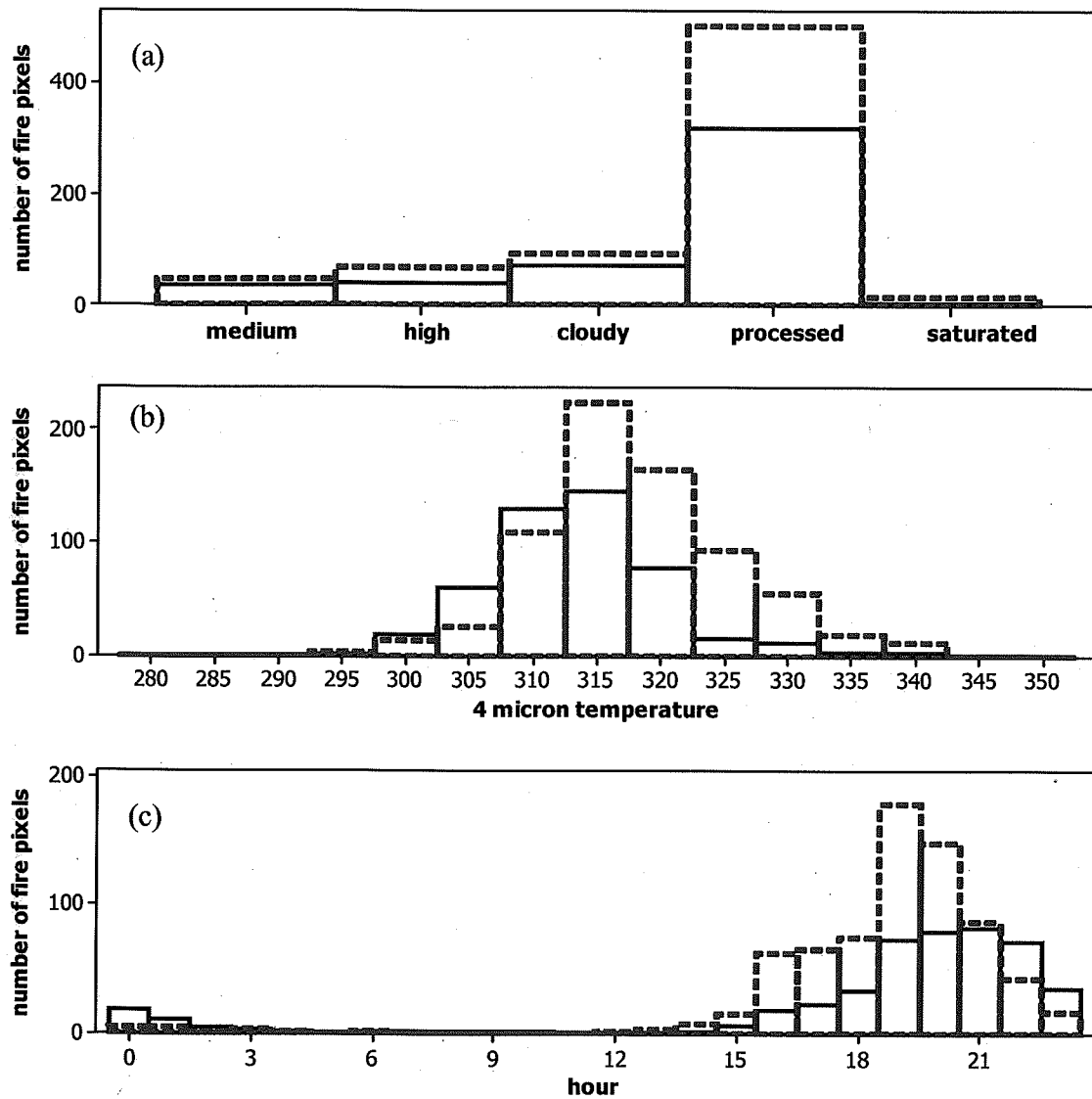


Figure 5.1.2.6

Histograms showing the difference between fire pixel characteristics of GOES fire pixels with a MODIS match compared to GOES fire pixels with no MODIS match on 24 April 2004; (a) shows confidence category, (b) 4 μm observed brightness temperature (K), and (c) hour (UTC) of the fire detection.

24 April 2004 GOES filtered fire pixels, excluding low confidence fire pixels, compared with MODIS fire pixels within +/- 12 hours and within 10 km

□ matched fire pixels
 □ unmatched fire pixels

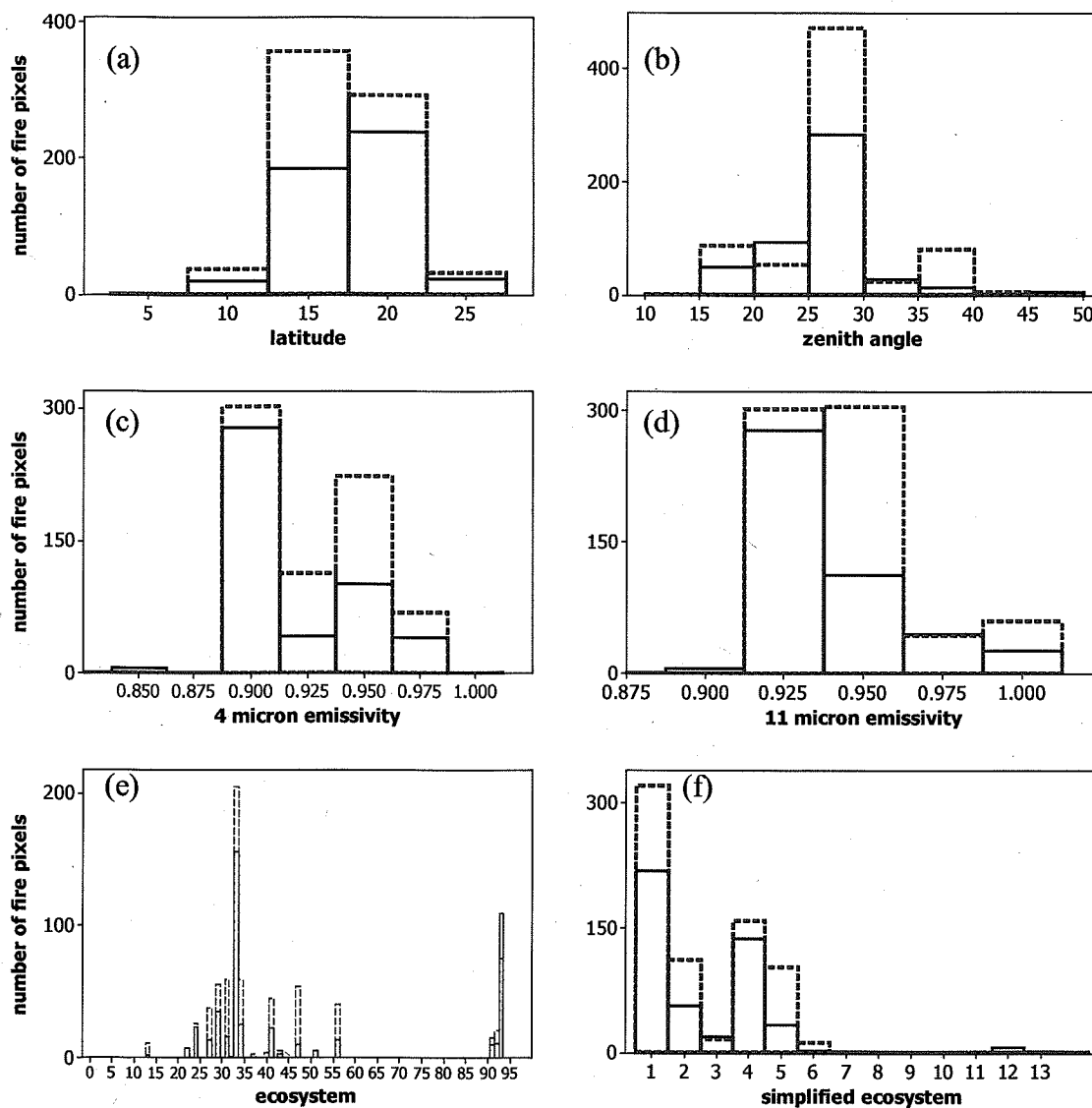


Figure 5.1.2.7

Histograms showing the difference between fire pixel characteristics of GOES fire pixels with a MODIS match compared to GOES fire pixels with no MODIS match on 24 April 2004; (a) shows latitude, the zenith angle is shown in (b), 4 μm emissivity (c) and 11 μm emissivity (d) are shown, the ecosystem (e) of the fire pixel on the, and a simplified ecosystem classification (f).

24 April 2004 MODIS fire pixels, excluding low confidence fire pixels, compared with GOES filtered fire pixels within +/- 12 hours and within 10 km

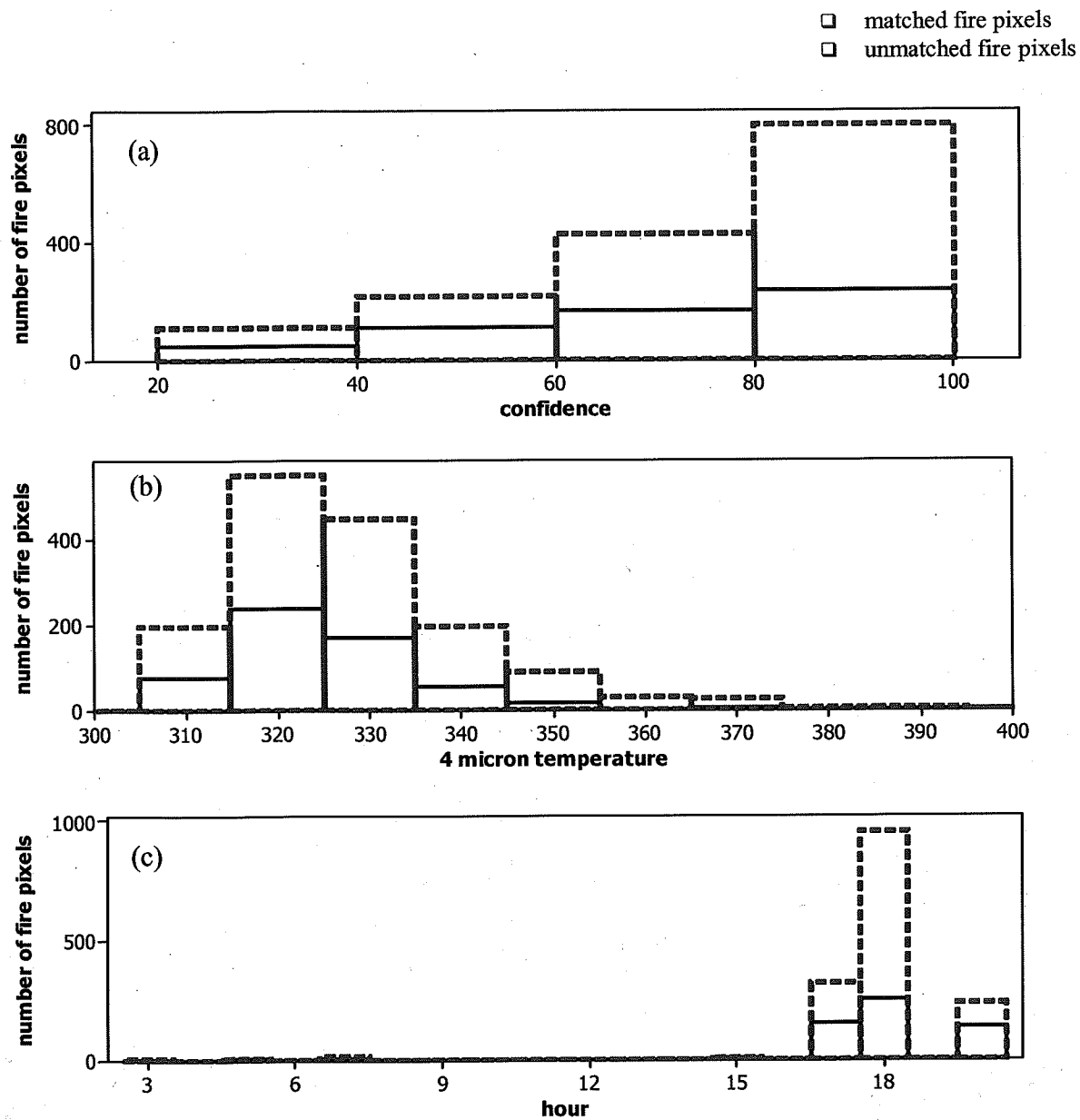


Figure 5.1.2.8

Histograms showing the difference between fire pixel characteristics of MODIS fire pixels with a GOES match compared to MODIS fire pixels with no GOES match on 24 April 2004; (a) shows confidence category, (b) 4 μm observed brightness temperature (K), and (c) hour (UTC) of fire detection.

24 April 2004 MODIS fire pixels, excluding low confidence fire pixels, compared with GOES filtered fire pixels within +/- 12 hours and within 10 km

□ matched fire pixels
 □ unmatched fire pixels

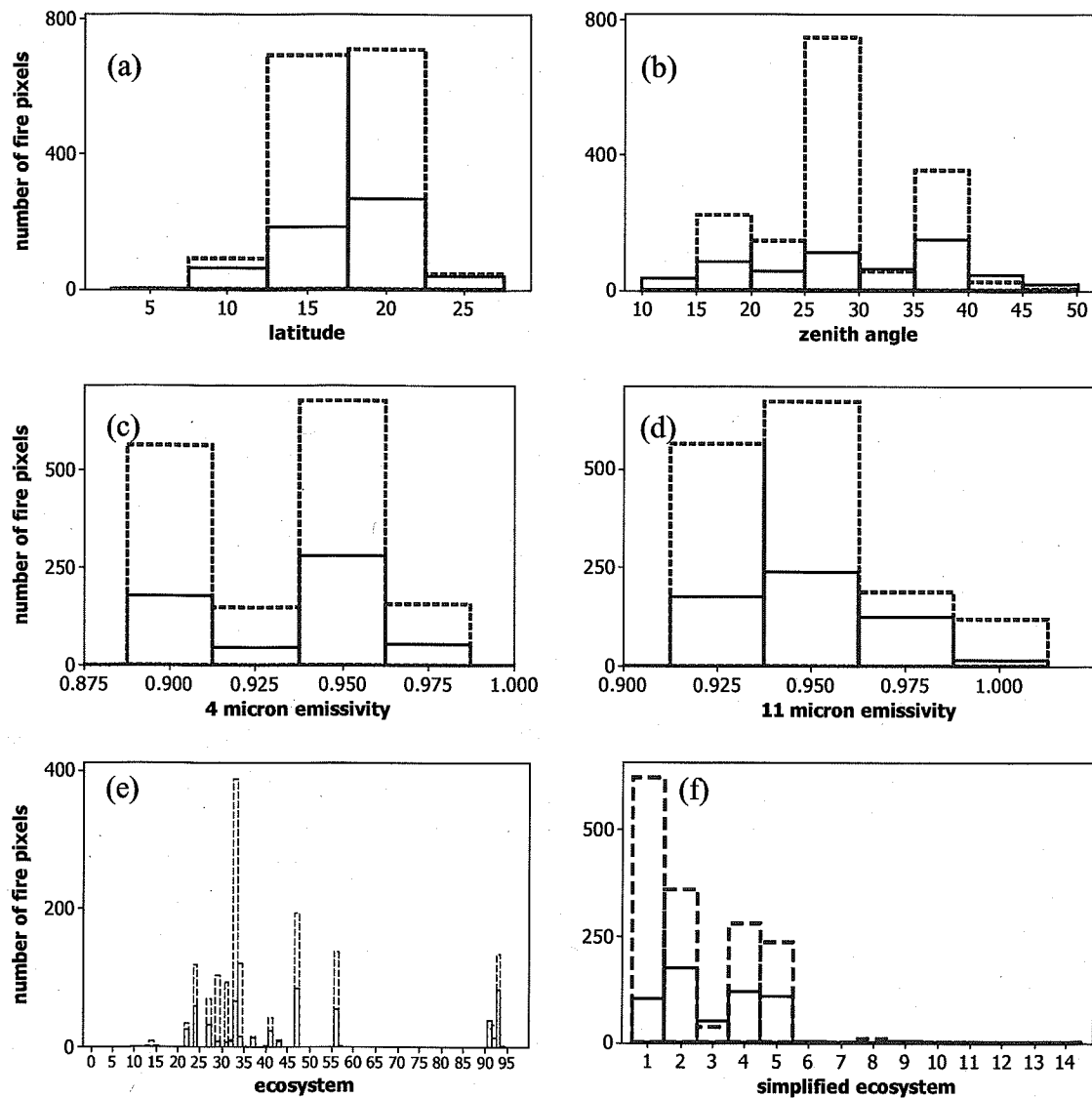


Figure 5.1.2.9

Histograms showing the difference between fire pixels characteristics of MODIS fire pixels with a GOES match compared to MODIS fire pixels with no GOES match on 24 April 2004; (a) shows latitude, the zenith angle is shown in (b), 4 μ m emissivity (c) and 11 μ m emissivity (d) are shown, the ecosystem (e) of the fire pixel on the, and a simplified ecosystem classification (f). The ecosystem key is in Appendix IV.

		Central America Case Study 24 April 2004		hour	latitude	T ₄	zenith angle	confidence	4 μm emissivity	11 μm emissivity
GOES	μ	matched	18.2	17.41	317.0	27.7	77.7	0.913	0.927	
		unmatched	17.0	17.54	312.1	26.7	70.6	0.917	0.933	
	σ	matched	3.23	2.83	7.38	5.6	16.48	0.204	0.205	
		unmatched	5.60	3.51	8.79	6.3	18.42	0.151	0.152	
GOES filtered	μ	matched	18.6	17.50	317.3	27.7	78.4	0.908	0.922	
		unmatched	17.5	17.36	311.9	25.9	73.7	0.916	0.932	
	σ	matched	3.32	2.78	7.62	5.3	16.20	0.224	0.226	
		unmatched	5.92	3.11	8.52	5.0	17.91	0.149	0.150	
GOES no low	μ	matched	18.2	17.47	317.7	27.6	85.0	0.908	0.923	
		unmatched	18.0	17.68	314.0	26.6	84.5	0.921	0.937	
	σ	matched	3.17	2.84	7.50	5.4	9.36	0.220	0.221	
		unmatched	5.18	3.24	6.60	5.2	9.33	0.121	0.121	
GOES filtered no low	μ	matched	18.6	17.52	318.0	27.5	85.2	0.903	0.917	
		unmatched	18.3	17.78	313.5	26.3	84.6	0.918	0.934	
	σ	matched	3.24	2.79	7.71	5.2	9.25	0.239	0.240	
		unmatched	5.66	2.99	6.73	27.5	9.43	0.128	0.129	
MODIS	μ	matched	17.9	17.33	328.0	28.5	75.8	0.936	0.950	
		unmatched	17.9	17.18	325.2	29.7	70.9	0.925	0.939	
	σ	matched	1.88	2.71	13.82	6.5	21.24	0.054	0.053	
		unmatched	2.10	3.99	9.87	9.0	21.27	0.164	0.165	
MODIS filtered	μ	matched	17.9	17.52	328.4	28.6	76.8	0.936	0.950	
		unmatched	17.9	16.90	325.5	29.1	70.7	0.929	0.942	
	σ	matched	1.85	2.61	14.19	6.2	20.58	0.058	0.057	
		unmatched	2.08	3.76	10.35	8.7	22.07	0.139	0.139	
MODIS no low	μ	matched	17.9	17.35	328.1	28.6	76.3	0.936	0.950	
		unmatched	17.9	17.25	325.3	29.8	71.4	0.925	0.939	
	σ	matched	1.88	2.70	13.82	6.5	20.57	0.055	0.053	
		unmatched	2.11	3.96	9.85	8.9	20.62	0.165	0.166	
MODIS filtered no low	μ	matched	17.9	17.53	328.5	28.7	77.0	0.936	0.949	
		unmatched	17.9	16.98	325.6	29.3	71.5	0.929	0.942	
	σ	matched	1.86	2.61	14.17	6.2	20.21	0.058	0.057	
		unmatched	2.09	3.73	10.34	8.7	21.02	0.140	0.140	

Table 5.1.2.1

Mean (μ) and standard deviation (σ) of GOES, GOES filtered and MODIS fire pixel with and without a match.

An example of off-season fire activity is presented for 31 October 2004 and is shown in Figure 5.1.2.10. There are relatively few GOES and MODIS fire detections in the region compared the previous example from April. Interestingly, it appears that on less active days there appears to be a trend where the ratio of fires with a match is lower than on days with more fire activity. As in previous examples, using the GOES filtered product and removing low confidence fire pixels does improve the ratio of GOES fire pixels with a match and the scene in general has much less noise as seen in Figure 5.1.2.11. Again it is important to consider how much time passes between the collocated GOES and MODIS fire detections. The ± 0.25 hours comparison is the minimum amount of time needed to match a MODIS overpass with the closest possible GOES image (since most areas are covered by a GOES image every 30 minutes). The ± 12 hours comparison is the maximum amount of time needed to match (almost) every location covered by GOES with a MODIS overpass (since MODIS has nearly complete global coverage every 24 hours). The GOES fire detections that do not have a corresponding MODIS overpass within the defined temporal window are put into a separate category (MODIS fire detections that occurred in areas of GOES coverage gaps were not accounted for). Figure 5.1.2.12 demonstrates that the overwhelming majority of GOES fire pixels occurred when there was no corresponding MODIS coverage but that compared to Figure 5.1.2.10 there is a slightly higher ratio of GOES fire pixels with a match within ± 0.25 hours of a MODIS fire pixel, 15.4%, compared to 14.5% of the GOES fire pixels that have a match within ± 12 hours of a MODIS fire pixel. For the ± 0.25 hours comparison, 5 MODIS fire pixels had a match and only 4 GOES fire pixels had a match (which is reasonable because the resolution of MODIS is fine enough

for multiple MODIS pixels to fall within the footprint of a single GOES pixel). When looking at +/- 12 hours, only 3 additional MODIS fire pixels had a match compared to +/- 0.25 hours, while there are an additional 28 GOES fire pixels that did not have a MODIS match within +/- 0.25 hours, but do have a MODIS match within +/- 12 hours. Similarly, comparing Figure 5.1.2.11 with Figure 5.1.2.13, both showing GOES filtered fire pixels and MODIS fire pixels with low confidence fire pixels excluded, and only 1 MODIS fire pixel has a GOES match within +/- 12 hours that did not have a GOES match within +/- 0.25 hours but 18 more GOES fire pixels have a MODIS match at +/- 12 hours than within +/- 0.25 hours.

31 October 2004 GOES fire pixels and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

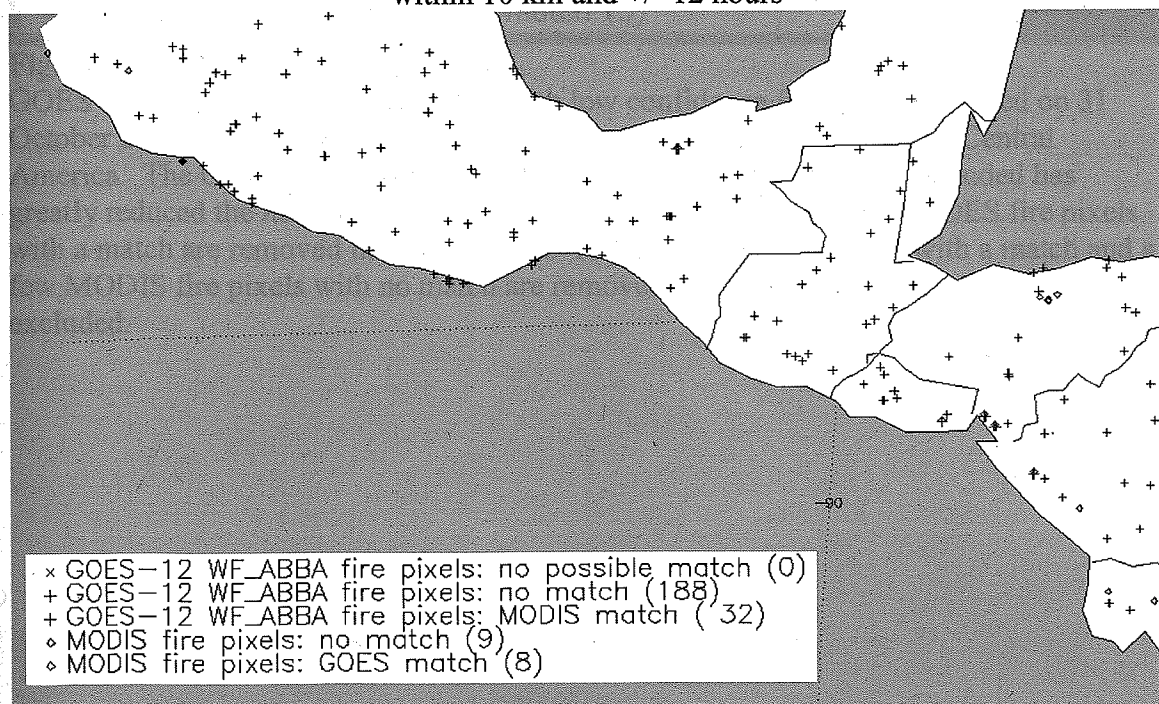


Figure 5.1.2.10

GOES and MODIS fire pixels on 31 October 2004 with and without a match within 10 km and +/- 12 hours in Central America. This case has numerous GOES fire pixels and relatively few MODIS fire pixels.

31 October 2004 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

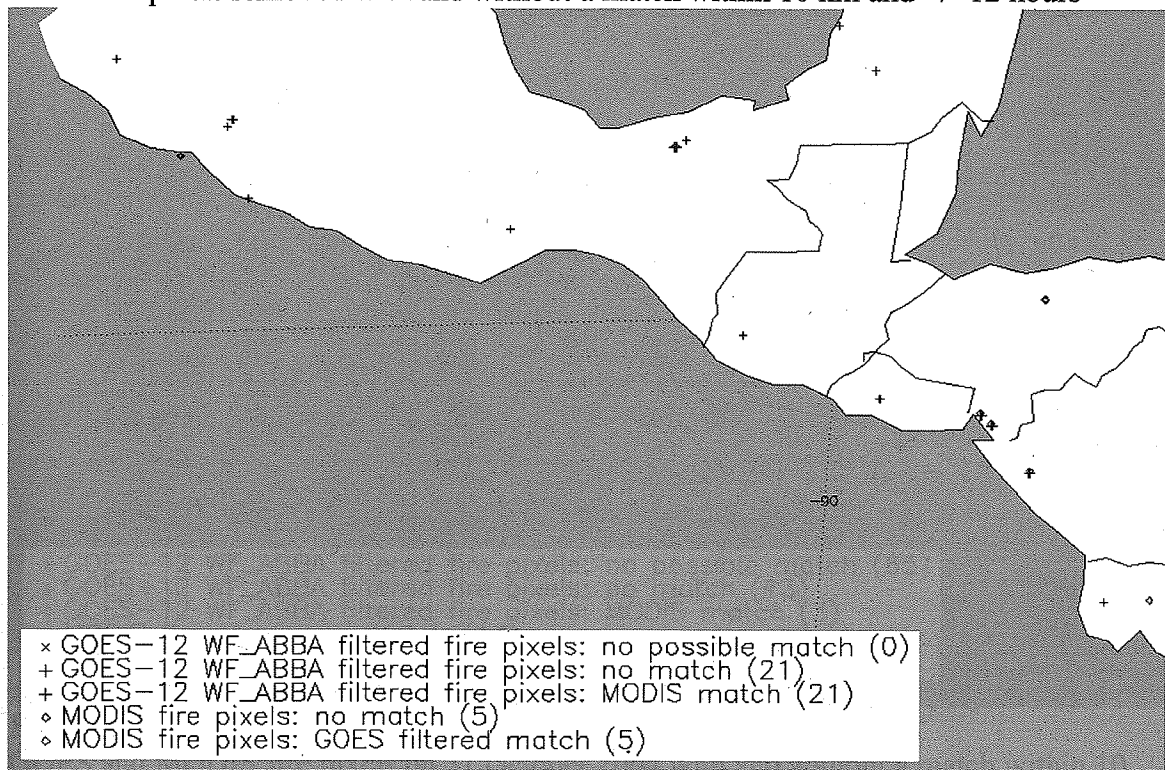


Figure 5.1.2.11

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 31 October 2004 with and without a match within 10 km and +/- 12 hours in Central America. The GOES filtered product with low confidence fire pixels excluded has greatly reduced the number of unmatched GOES fire pixels, yet a few GOES fire pixels with a match are removed in the reduction. A few MODIS fire pixels with a match and a few MODIS fire pixels with no match are removed when low confidence fire pixels are excluded.

31 October 2004 GOES fire pixels and MODIS fire pixels with and without a match within 10 km and +/- 0.25 hours

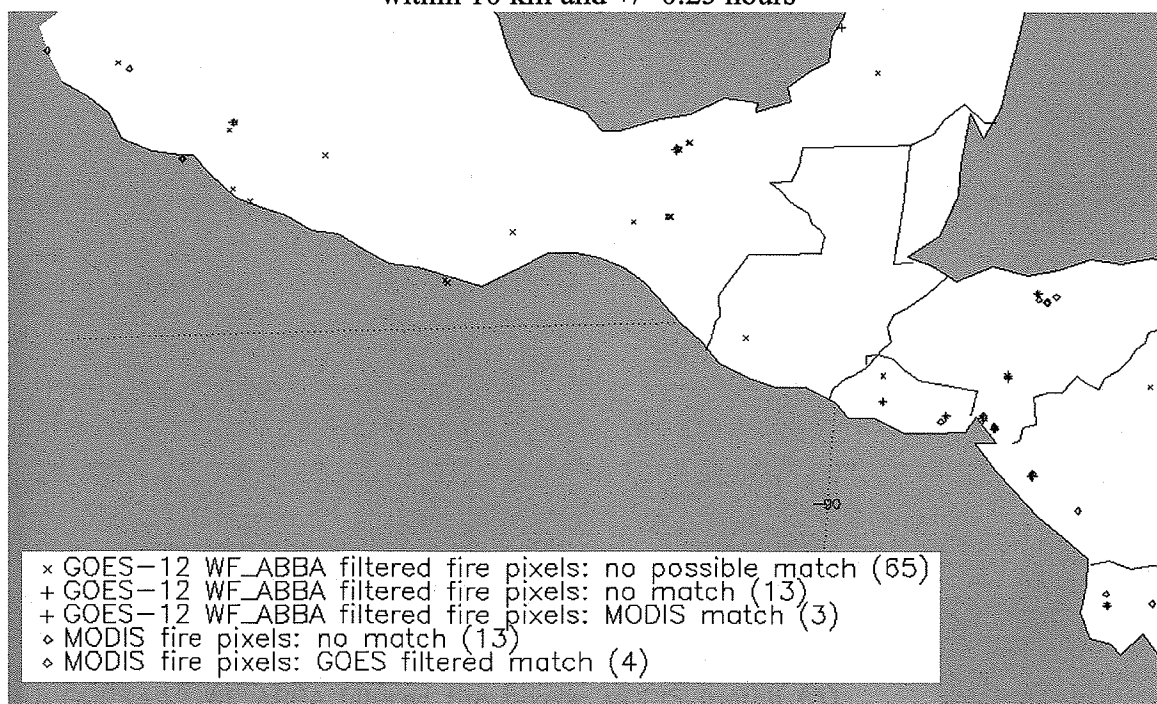


Figure 5.1.2.12

GOES and MODIS fire pixels on 31 October 2004 with and without a match within 10 km and +/- 0.25 hours in Central America. The majority of the GOES fire pixels beyond +/- 0.25 hours of a MODIS overpass do not match with a MODIS fire pixel, however, only 4 GOES fire pixels match with a MODIS fire pixel within +/- 0.25 hours compared to 32 within +/- 12 hours. However, most of the additional matching GOES fire pixels are a result of fire detections at the same or nearly same location over an extended period of time as evident by an addition of only 3 MODIS fire pixels that have a match within +/- 12 hours of a GOES fire pixel compared to +/- 0.25 hours.

31 October 2004 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 0.25 hours

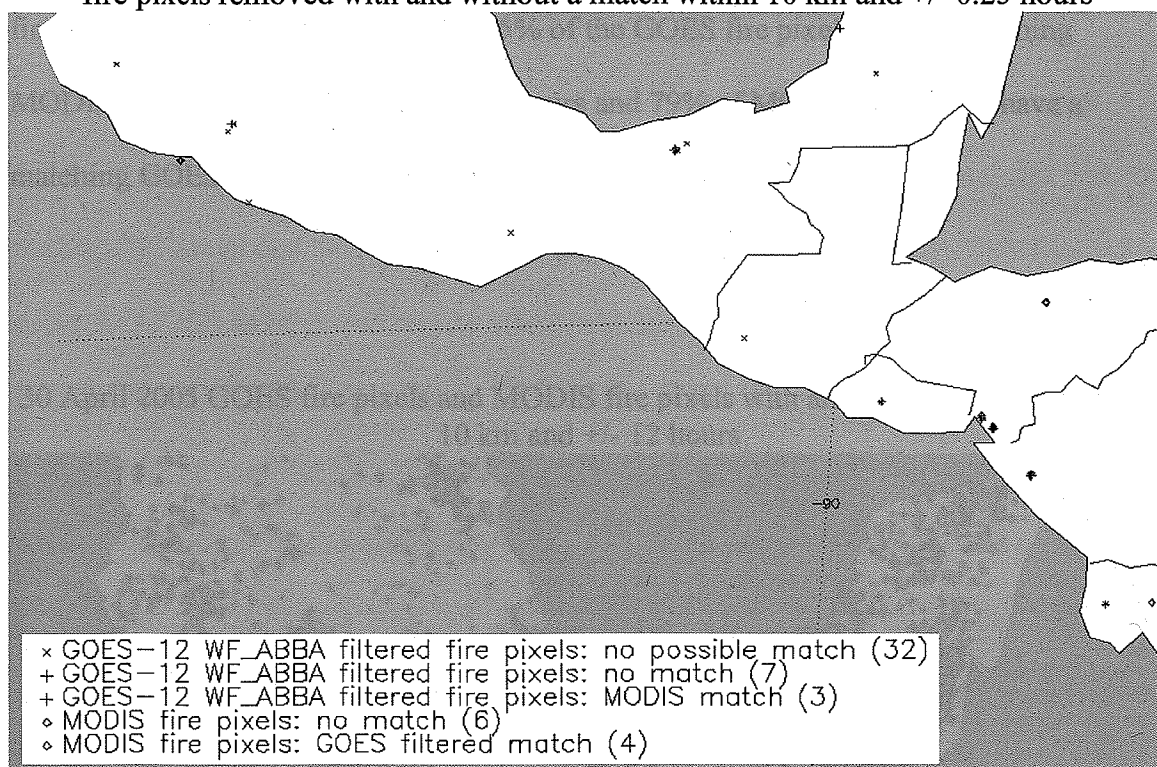


Figure 5.1.2.13

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 31 October 2004 with and without a match within 10 km and +/- 0.25 hours in Central America. There are more MODIS fire pixels with a match than GOES filtered fire pixels with a match which indicates that this is a case where multiple MODIS fire pixels are within 10 km of a single GOES fire pixel. There is 1 MODIS fire pixel that does not have a GOES match within +/- 0.25 hours that does have a match within +/- 12 hours of a GOES fire pixel's occurrence, while 18 GOES fire pixels are within 10 km and +/- 12 hours of a MODIS fire pixel but not within 10 km and +/- 0.25 hours of a MODIS fire pixel.

Another Central American fire example from the spring of 2005 shows an active fire day. Figure 5.1.2.14 shows that 75% of the GOES fire pixels have a matching MODIS pixel within 10 km and +/- 12 hours and 79% of MODIS fire pixels have a matching GOES fire pixel within 10 km and +/- 12 hours.

30 April 2005 GOES fire pixels and MODIS fire pixels with and without a match within 10 km and +/- 12 hours

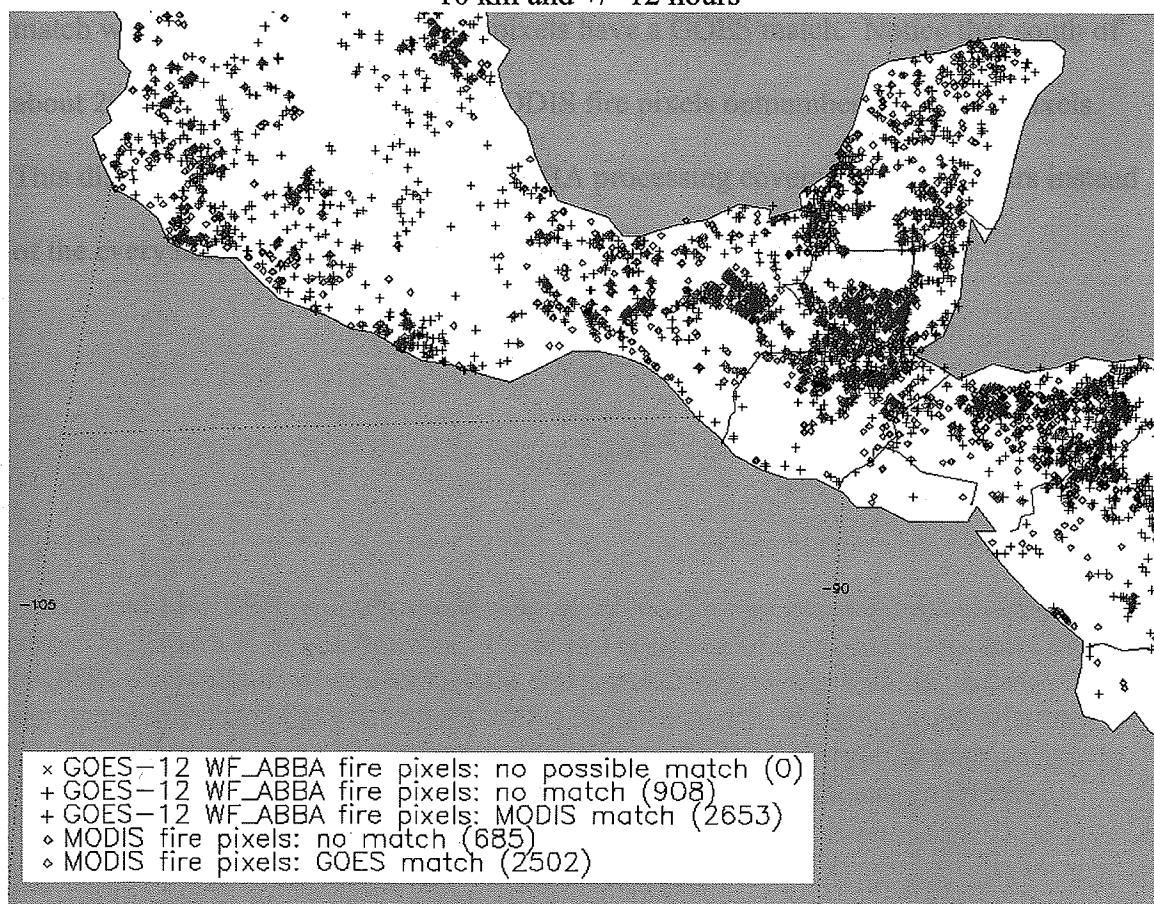


Figure 5.1.2.14
GOES and MODIS fire pixels on 30 April 2005 with and without a match within 10 km and +/- 12 hours in Central America. This is an active fire day and more than 2 out of every 3 fire pixels are collocated.

5.1.3 South America

South American case studies show that fires in the Amazon Basin are more numerous than in Central America. Figure 5.1.3.1 depicts fire activity on 24 August 2004 and shows that 46% of the GOES fire pixels have a MODIS match and that 74% of the MODIS fire pixels have a GOES fire pixel match within +/- 12 hours. Alternatively, using the GOES filtered data set and also excluding the low possibility fire pixels from GOES and MODIS shows, in Figure 5.1.3.2, that 55% of the GOES fire pixels have a match while 65% of the MODIS fire pixels have a GOES match. Notice that south of about 20°S latitude, the unmatched MODIS fire pixels outnumber GOES fire pixels. This disparity likely arises from WF_ABBA processing coverage every 3 hours instead of the every half hour that north of 20°S receives during normal operation.

24 August 2004 GOES fire pixels and MODIS fire pixels with and without a match
within 10 km and +/- 12 hours

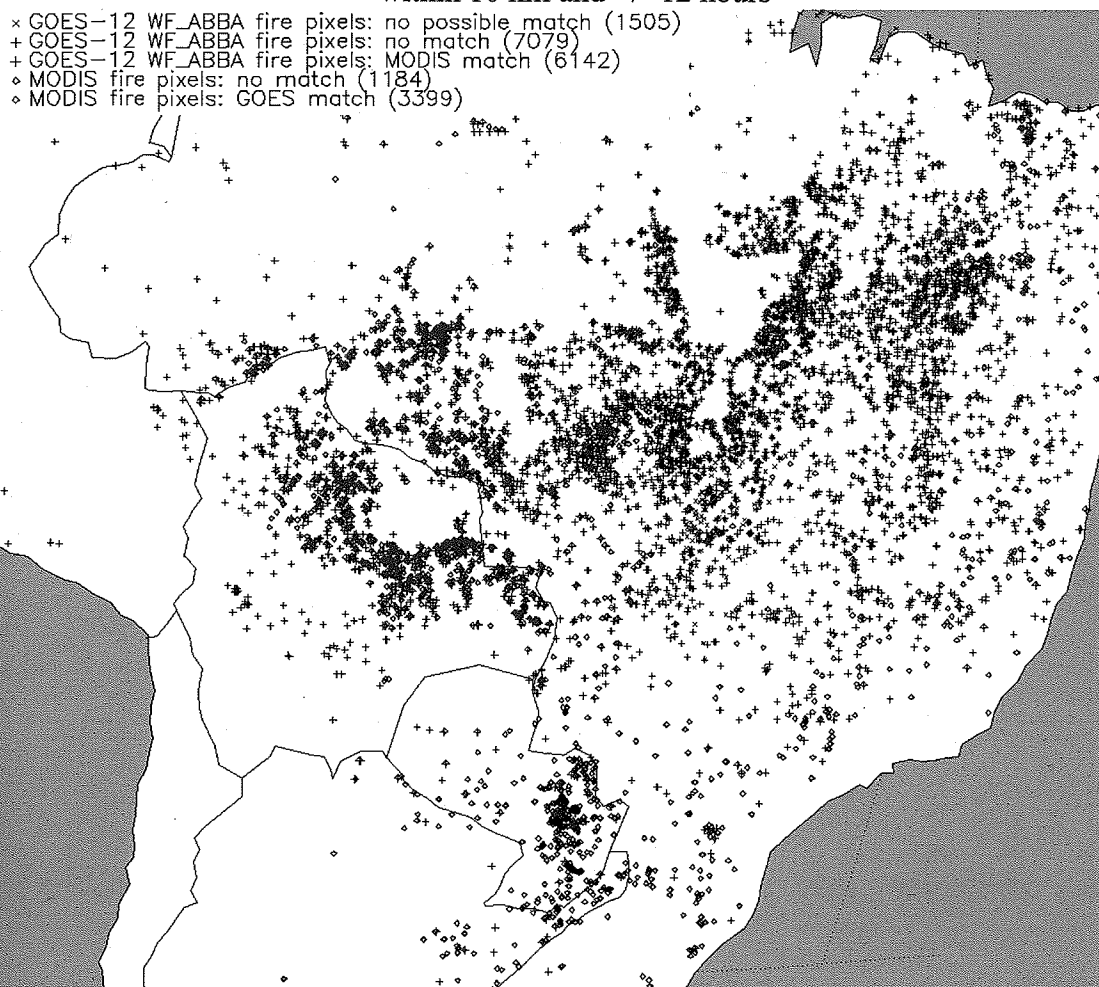


Figure 5.1.3.1

GOES and MODIS fire pixels on 24 August 2004 with and without a match within 10 km and +/- 12 hours in South America. There is a high rate of agreement between GOES and MODIS fire products in eastern Bolivia and western Brazil near Bolivia. Eastern Brazil seems to have less GOES fire pixels with a MODIS match. South of ~ 20°S latitude there are relatively few GOES fire pixels and many MODIS fire pixels with no match, which is likely a result of reduced GOES WF_ABBA fire monitoring in this area.

24 August 2004 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

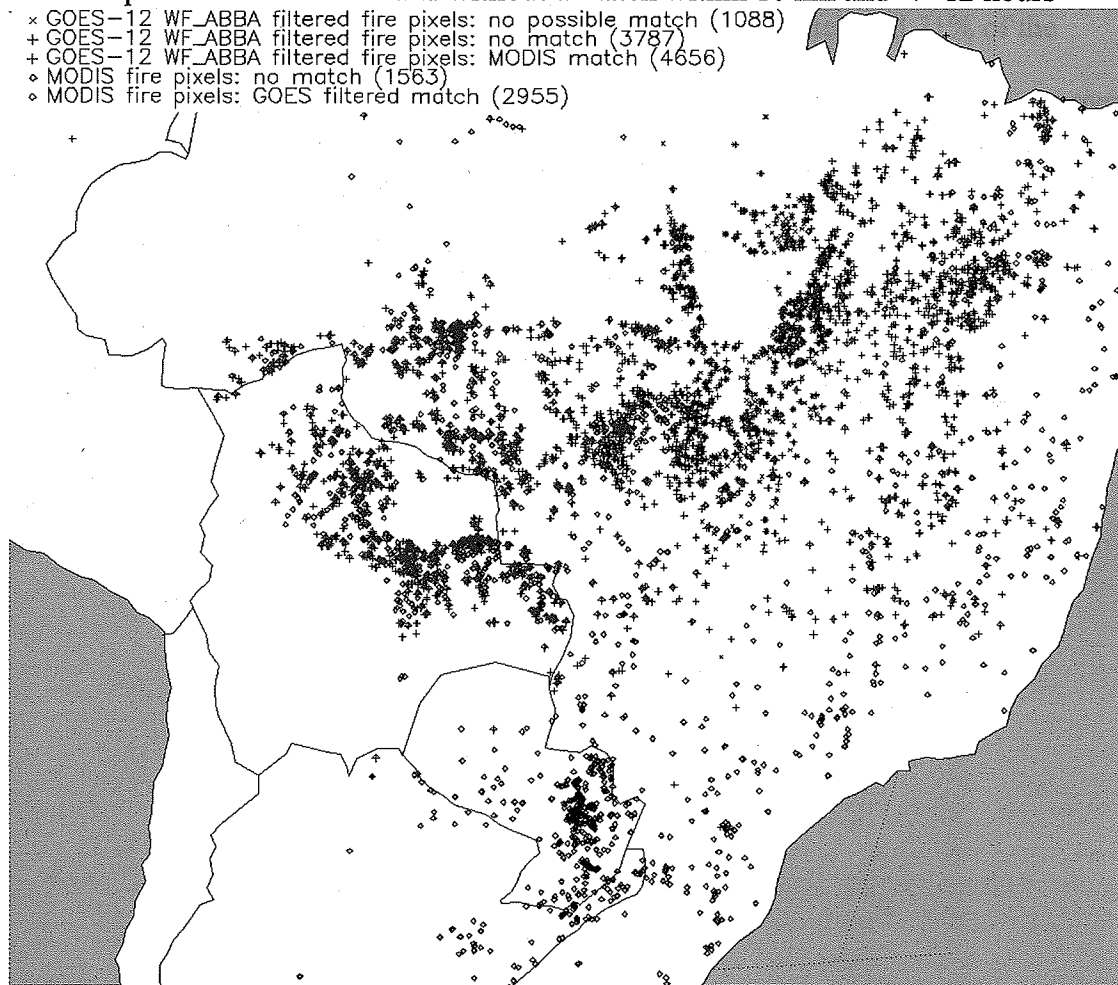


Figure 5.1.3.2

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 24 August 2004 with and without a match within 10 km and +/- 12 hours in South America. There remains a high rate of agreement between GOES and MODIS fire products in eastern Bolivia and western Brazil near Bolivia. South of ~20°S latitude there are even fewer GOES fire pixels and still many MODIS fire pixels with no match.

Another example taken from 15 April 2005 in South America is shown in Figure 5.1.3.3 where 22% of the GOES fire pixels have a MODIS match and 71% of the MODIS fire pixels have a GOES match. When low confidence fire pixels are removed and only GOES filtered fire pixels are included, 32% of the GOES fire pixels have a MODIS match while 66% of the MODIS fire pixels have a GOES match. This is a case where fire activity is less than what is seen during the peak fire season, and it is another example where there seems to be less agreement between GOES and MODIS fire products on days when there is less fire activity and more agreement between the fire products during the peak burning seasons.

15 April 2005 GOES fire pixels and MODIS fire pixels with and without a match within
10 km and +/- 12 hours

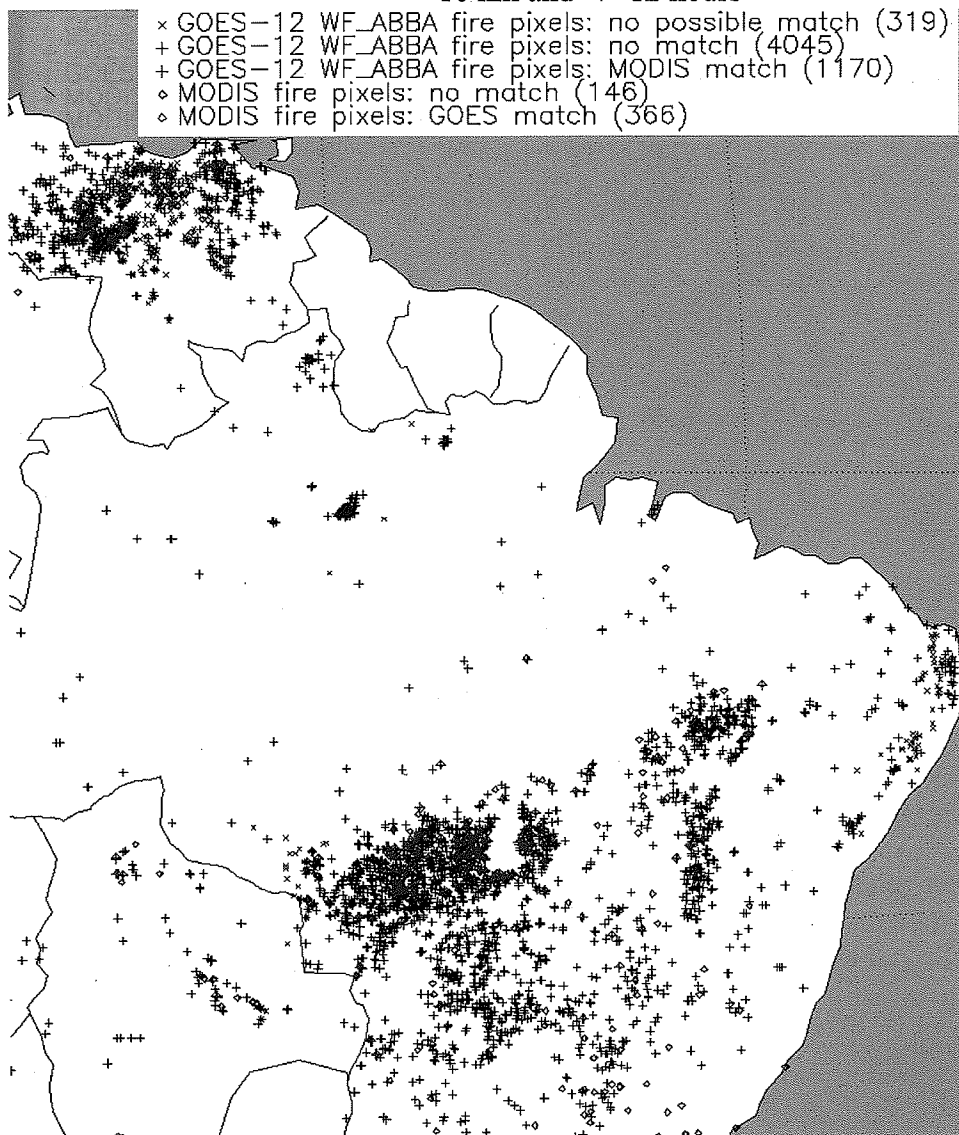


Figure 5.1.3.3

GOES and MODIS fire pixels on 15 April 2005 with and without a match within 10 km and +/- 12 hours in South America. There is a cluster of matching fire pixels in western Brazil. Also, many fire pixels in Venezuela are collocated.

15 April 2005 GOES filtered fire pixels and MODIS fire pixels with low possibility fire pixels removed with and without a match within 10 km and +/- 12 hours

- × GOES-12 WF_ABBA filtered fire pixels: no possible match (128)
- + GOES-12 WF_ABBA filtered fire pixels: no match (1592)
- + GOES-12 WF_ABBA filtered fire pixels: MODIS match (745)
- ◇ MODIS fire pixels: no match (89)
- ◇ MODIS fire pixels: GOES filtered match (170)



Figure 5.1.3.4

GOES filtered and MODIS fire pixels with low confidence fire pixels excluded on 15 April 2005 with and without a match within 10 km and +/- 12 hours in South America. Fewer GOES fire pixels are found in northern Brazil with the filtered product and low confidence fire pixels removed.

5.2 Annual comparisons

Case studies can provide interesting snapshots and examples of fire activity, but it is also important to consider fire activity over a long period of time to establish trends.

There are many things to consider when looking at the annual data sets. The first thing of interest is to identify the fires pixels that are collocated in time and space. Defining how close the fires should be in time and space is not trivial. Tests were run that required the fires to be temporally collocated from within +/- 15 minutes all the way up to +/- 12 hours, and also spatially collocated within +/- 5 km (and within +/- 0.05° latitude and longitude) up to +/- 25 km (and within +/- 0.25° latitude and longitude). Different applications might dictate which criteria are most suitable. More stringent collocation requirements provide the best opportunity to compare the radiative properties of the active fires. As more time passes between fires detections, the more likely it becomes that the fire's radiative output changes to the point that while individual detections may be the same fire, the detections are at different stages in the fire life-cycle such that radiatively they are different fires despite being detected in the same location.

Characteristics such as time of day, brightness temperature, and the confidence parameter will become meaningless when trying to compare fires detected by different satellites if the fires are dissimilar in time and radiative properties. It is possible that numerous small fires can trigger fire detection at one time and location, but a different set of fires, with different radiative properties at the same location but at a different time could also result in a fire detection. Similarly, if numerous small fires in a region are being detected as one fire pixel by one satellite fire product, another instrument might detect these as separate fires and the distance between the fires is a function of the instrument resolution at the location of the fire as well as the differences in navigation systems that define the

center of the pixel as the location of the fire for each satellite product. Furthermore, even a fire occurring at one location will not be detected at the same location by different satellites because the fire location is recorded at the center of the pixel and with different navigation systems and different resolution, the coordinates of the fire will rarely be exactly the same. For all of these reasons it is necessary to allow for some time and spatial distance to exist between fire detections from different satellites. This is a different process than using a grid to sort fire data into bins to compare the frequency of fire occurrences at different locations. Grids suffer from the subjectivity necessary to determine the grid size and a time window, and then averaging fire activity within each bin loses some information that comes from comparing individual fire pixels instead of fire activity in a bin. In addition to investigating the properties of fires that occur at the same location in time and space, it is necessary to also consider the fire detections that went undetected by a second fire product.

There are many reasons for a fire to be detected by one satellite but not the other. The major challenge when creating a merged fire product is deciding what fire detections should be used when a fire detection is only found in one of the two fire products. Many factors could cause a positive detection in one fire product to go undetected by another product. The fire might have occurred in an area not covered by both satellites; even if inside a swath of a satellite, topography, agriculture, surface characteristics, atmospheric conditions or cloud cover, and satellite noise or missing data could all explain why another satellite product did not detect the same fire. It is also possible that the fire signature did not pass detection in both fire algorithms possibly because the fire was too small or too cool to be detected.

5.2.1 Statistics

The number of fire pixels from one fire product that have a match in another fire product can provide some important information. Studying statistics of the frequency of collocated versus unique fire pixels from various spatial and temporal criteria provides evidence to which categories are better than others. Some users, for example, might be interested in when a product has the highest percentage of collocated fire pixels while other users might seek the most collocated (or fewest unique) fire pixels. In addition to calculating the frequency of collocated fire pixels for the entire Western Hemisphere, different regions are investigated because of the variability in the satellite coverage patterns as well as differences due to different types of fires being found in different regions. Lastly, the frequency of collocated fire pixels is shown as a function of various fire characteristics.

For GOES fire pixels, after checking for a MODIS fire pixel match an attempt was made to remove GOES fire pixels from consideration that occurred beyond the MODIS coverage area by estimating the AQUA and TERRA orbits. Increasing the temporal window increases the number of GOES fire pixels that fall in an area of MODIS coverage. Appendix I contains tables that show how changing the temporal window impacts the number of GOES fire pixels with a matching MODIS fire pixel.

Approximately 62.8% of the GOES filtered fire pixels (when low confidence fire pixels are excluded) have a MODIS match in 2004 (59.7% in 2005). At +/- 12 hours, the GOES fire product has the most matches with MODIS, however the percentage of fire pixels with a match is lower than at +/- 1 hour for a number of reasons. The half-hourly GOES WF_ABBA fire product may have detected a fire that had not yet ignited at the time of

the MODIS overpass, had already extinguished, or had been obstructed from MODIS field of view during its overpass. When considering the GOES filtered product, and when removing the GOES low confidence fire pixels, the total number of matches with MODIS fire pixels decreases; however, this is because the total number of GOES fire pixels is decreasing, and the proportion of GOES fire pixels with a match compared to GOES fire pixels with no match actually increases. The GOES product has the highest percentage of fire pixels that are collocated with MODIS when considering fires within +/- 1 hour. While expanding the time window does increase the number of matches with MODIS, the percentage of GOES fires with a match decreases with increasing time.

The number of GOES fire pixels with a MODIS fire pixel match is not the same as the number of MODIS fire pixels with a GOES fire pixel match. It is possible for numerous MODIS fire pixels to be spatially close to a single GOES fire pixel (one GOES fire pixel with numerous MODIS fire pixel matches but numerous MODIS fire pixels with a GOES fire pixel match). Similarly, numerous GOES fire pixels over a period of time might be collocated with only one MODIS fire pixel (numerous GOES fire pixels with a MODIS match but one MODIS fire pixel with a GOES fire pixel match). Unlike the comparison considering GOES pixels with MODIS matches, nearly all (due to coverage gaps) MODIS fire pixels are in areas covered by GOES within +/- 0.25 hours. Expanding the time window does not increase the number of MODIS fire pixels to consider as it does when expanding the time window for GOES fire pixels. As a result, the most MODIS fire pixels with a GOES match occurs at +/- 12 hours; even a higher percentage would be found if the time window continued to expand, however as more time passes between the fires it becomes more likely that they would be different fires

that just happened to occur at the same or nearly same location. Up to 65.6% of MODIS fire pixels (within 10km and +/- 12 hours with low confidence fire pixels are excluded) have a GOES fire pixel match in 2004 (69.1% in 2005).

In addition to allowing for different amounts of elapsed time to consider fire pixels to be collocated, it is equally valid to consider a range of spatial criteria. With a more rigid criteria it is not surprising to see fewer matches, and in fact the highest percentage of GOES fire pixels (filtered fire pixels with low confidence fires removed) with a MODIS match in 2004 is 51.4% within 5 km (and +/- 1 hour) and compared to 62.8% within 10 km (and +/- 1 hour). Similarly, in 2005, 48.6% of GOES fire pixels have a MODIS match within 5 km (and +/- 1 hour) compared to 59.7% within 10 km (and +/- 1 hour). A similar drop is seen in MODIS fire pixels with a GOES match, for example, 50.5% of MODIS fire pixels have a match within 5 km in 2004, while 53.5% have a match within 5 km in 2005 (compared to 65.6% and 69.1% within 10 km). Looking at fires with such stringent match criteria improves the likelihood that the matched fires actually represent the same fire and share similar radiative properties, but it is somewhat unrealistic to expect fires to be this close due to navigational differences, instrument resolution, and other sources of error. On the other end of the spectrum, it is also worth investigating the implications of expanding the spatial window to allow fires within 25 km to be considered matching fires. These fires are more likely to be different fires, however some applications might only be interested in how fire activity is captured in a region instead of an exact location. In this case a large spatial window tests to see how frequently fire pixels from both GOES and MODIS are detected in the same region. As expected, with relaxed criteria, 76.7% of GOES fires (filtered with low confidence

fires removed from consideration) have a MODIS match within 25 km (and +/- 1 hour) in 2004 and 74.1% in 2005. Interestingly, a higher percentage of GOES fire pixels have a match at +/- 3 hours when considering fires within 25 km instead of +/- 1 hour which had the highest percentage of matches for fires within 10 km and 5 km. MODIS fire pixels also have more matches with GOES fire pixels at 25 km compared to 10 km. Up to 79.8% of MODIS fires, with low confidence fires removed, have a match within 25 km (and +/- 12 hours) in 2004 and 82.9% have a match in 2005.

Different regions produce different collocation statistics. The fire pixels in South America tend to be detected by multiple satellites more often than in other regions, but because the majority of fire pixels are found in South America, the statistics for the entire Western Hemisphere are similar to the statistics for South America. For example, in 2004 up to 63.7% of GOES fire pixels have a match within 10 km in South America, compared to 62.8% for the entire Western Hemisphere. In 2004 South American MODIS fire pixels had a GOES match within 10 km 68.3% of the time and 70.0% in 2005. When considering only fire matches within 5 km in South America, there are fewer matches, but again there tends to be a higher percentage of fire pixels with a match in South America compared to the Western Hemisphere as a whole. In 2004, as high as 52.2% of GOES fire pixels had a MODIS match within 5 km in South America compared to 51.4% for the whole hemisphere. In 2005, 48.7% of GOES fire pixels have a MODIS match. MODIS fire pixels have a match within 5 km in South America 53.2% of the time in 2004 and 54.4% in 2005. Similarly, in South America, when allowing fire pixels within 25 km to be considered matched, there are more matches in South America than for the Western Hemisphere in general. For example, in 2004, 78.3% of GOES fire pixels have

a match in South America compared to 76.7% for the entire hemisphere. In 2005, 74.9% of GOES fire pixels have a match compared to 74.1% for the entire hemisphere. In 2004 and 2005, MODIS fire pixels occurred within 25 km of a GOES fire pixel in South America 82.1% and 83.5% of the time, respectively.

In this study, Central America is defined as land south of 25°N and north of the South American continent. Up to 50.0% of GOES fire pixels (filtered with low confidence excluded) have a MODIS match (within 10 km and +/- 3 hours) in Central America in 2004 compared with 65.3% with a match (within 10 km and +/- 3 hours) in 2005. It is unclear why there is such a discrepancy between the two years, and more years should be used to establish an expected value. MODIS fire pixels are less likely to have a match within 10 km in Central America than for the hemisphere as a whole; 55.5% of MODIS fires pixels have a GOES match in 2004 and 67.1% have a match in 2005. In 2004, Central America GOES fire pixels with a MODIS match within 5 km occurred only 40.8% of the time, but in 2005 54% of the time. So, while in 2004 GOES fires with a MODIS match were less common than for the hemisphere in general, GOES fires had a MODIS match more often in Central America than for the hemisphere in general. MODIS fire pixels however were less likely to have a GOES match within 5 km in both 2004 and 2005 in Central America compared to the whole Western Hemisphere. Considering fire pixels in Central America that have a match within 25 km also does not show a clear trend. In 2004 comparing Central America with the entire Western Hemisphere reveals that a lower percentage of GOES fire pixels in Central America have a match within 25 km (63.2%) than for the whole hemisphere (76.7%). Unlike 2004, a

higher percentage of GOES fire pixels in Central have a match within 25 km (79.3%) than the whole hemisphere (74.1%).

The final region that is considered is North America, north of 25°N and south of the arc defined by the GOES East 80° viewing angle. There is nearly an order of magnitude increase in the number of fire pixels in Central America compared to North America and there are almost twice as many fires in South America as in Central America. Fewer GOES fire pixels have a MODIS match within 10 km in North America in 2004 (61.5%) and 2005 (53.4%) compared to the entire hemisphere where as many as 62.8% and 59.7% of GOES fire pixels have a MODIS match respectively. The same trend is true for MODIS fires with a GOES match within 10 km. In 2004, up to 48.5% of MODIS fire pixels have a GOES match and in 2005 up to 63.3% of MODIS fires have a GOES match compared to 65.6% (2004) and 69.1% (2005) of MODIS fire pixels that have a match when considering fires detected in the whole hemisphere. Considering fire matches within 5 km reveals that in North America a lower percentage of fires have a match than for the hemisphere overall. In 2004, 47.8% of GOES fire pixels have a MODIS match compared to 51.4% for the entire hemisphere. In 2005, 41.4% of North American GOES fires have a match, compared to 48.6% for the entire hemisphere. Similarly, only 32.9% (2004) and 49.1% (2005) of MODIS fire pixels have a GOES match within 5 km compared to 50.5% (2004) and 53.5% (2005) for the entire hemisphere. The same trend is seen when considering fire matches within 25 km. For GOES fire pixels with a MODIS match, 65.9% (2004) and 58.0% (2005) of the GOES fire pixels have a MODIS match compared to 76.7% (2004) and 74.1% (2005) for the entire hemisphere. In 2004 and 2005, 59.7% and 71.4% of the MODIS fire have a GOES

match compared to 79.8% (2004) and 82.9% (2005) of the MODIS fires having a match for the entire hemisphere.

In addition to considering the frequency of collocated fire pixels by region, other fire characteristics display differences between the properties of fire pixels that are collocated with fire pixels from another satellite fire product and fire pixels that are not collocated with fire pixels from another fire product. GOES fire pixels, with low confidence fire pixels removed, that had a MODIS match within 10 km and +/- 1 hour, and MODIS fire pixels, with low confidence fire pixels removed, that had a GOES match within 10 km and +/- 12 hours were shown in the previous section to have the highest proportion of matched versus unmatched fires and so these were selected for further examination. Figure 5.2.1.1 through Figure 5.2.1.4 show how the Julian day of the year, hour of day (UTC), 4 μm observed brightness temperature, fire confidence, and satellite zenith angle provide clues to how likely a fire pixel will have a collocated fire pixel from another satellite. Looking at fire activity as a function of day of the year, there is a maximum occurring around August-September (day 220 - 260) which corresponds to the Southern Hemisphere spring time when agricultural burning is used to clear fields before planting, and it corresponds to late summer in the Northern Hemisphere when forest fires are most likely to occur in dry regions. Along with the peak in fire occurrence, there is a general trend for more of the fire pixels to have a collocated fire from another satellite fire product. Conversely, in the Southern Hemisphere fall fire activity is muted and there are instances where more fire pixels occur that do not have a collocated fire pixel from a second satellite fire product. In the Northern Hemisphere spring there is increased burning in the Great Plains and Southeast United States as well as in Central America,

but the overall statistics are dominated by the minimum in fires in South America.

Looking at fire occurrence as a function of time of day, it is clear that there is a diurnal signature in terms of fire detection frequency. Fire activity peaks at around 17 UTC; this corresponds to the maximum occurrence of unmatched fire pixels but it is also the time of day when there is an even larger maximum of fire pixels with a match.

2004 GOES filtered fire pixels, excluding low confidence fire pixels, compared with MODIS fire pixels within +/- 1 hour and within 10 km

□ matched fire pixels
 □ unmatched fire pixels

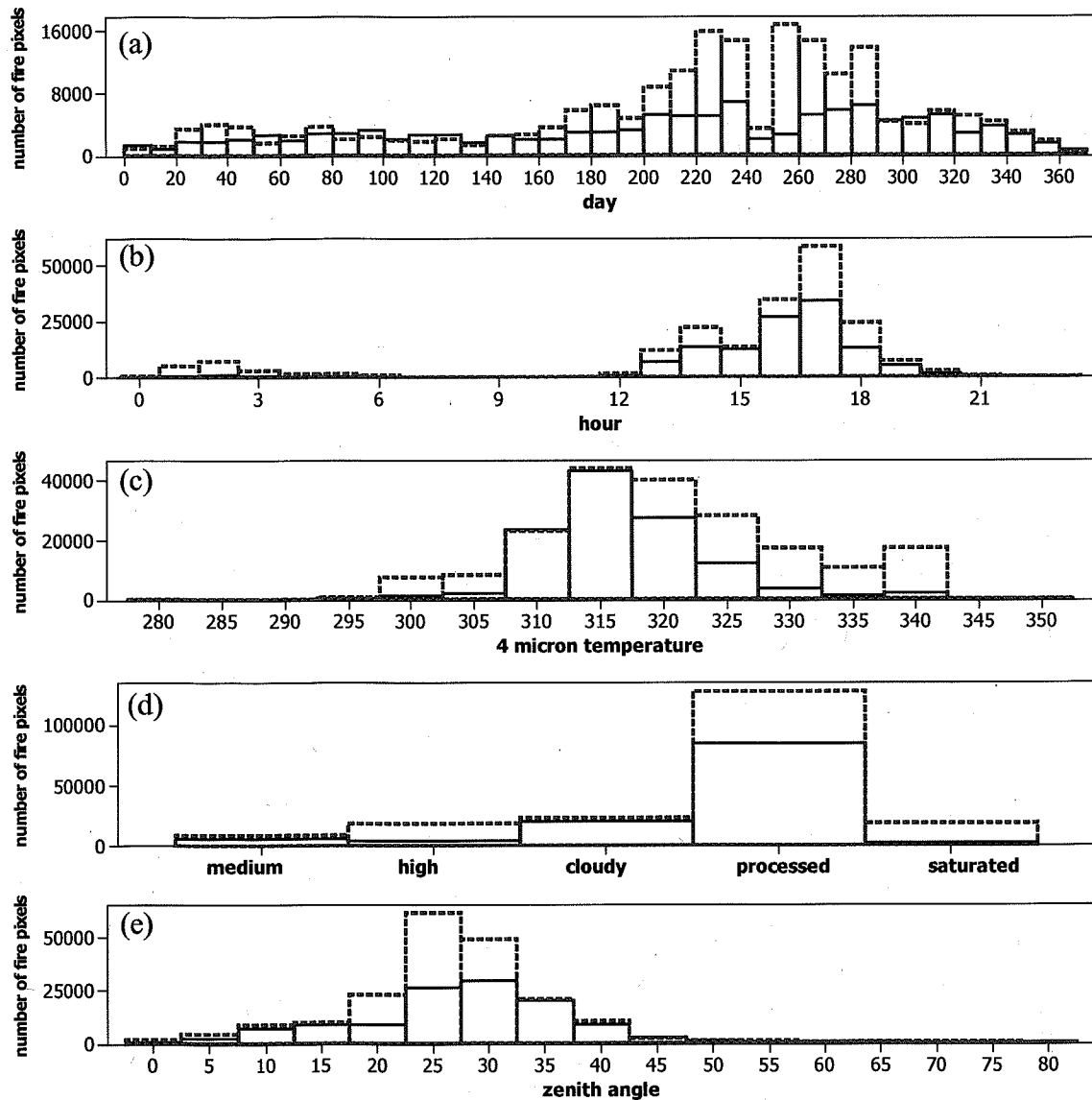


Figure 5.2.1.1

Histograms showing the difference between characteristics of GOES fire pixels with a MODIS match and GOES fire pixels with no MODIS match in 2004; (a) shows the Julian day of the year, (b) hour (UTC) of fire detection, (c) 4 μm observed brightness temperature (K), (d) confidence category, and (e) zenith angle.

2005 GOES filtered fire pixels, excluding low confidence fire pixels, compared with MODIS fire pixels within +/- 1 hour and within 10 km

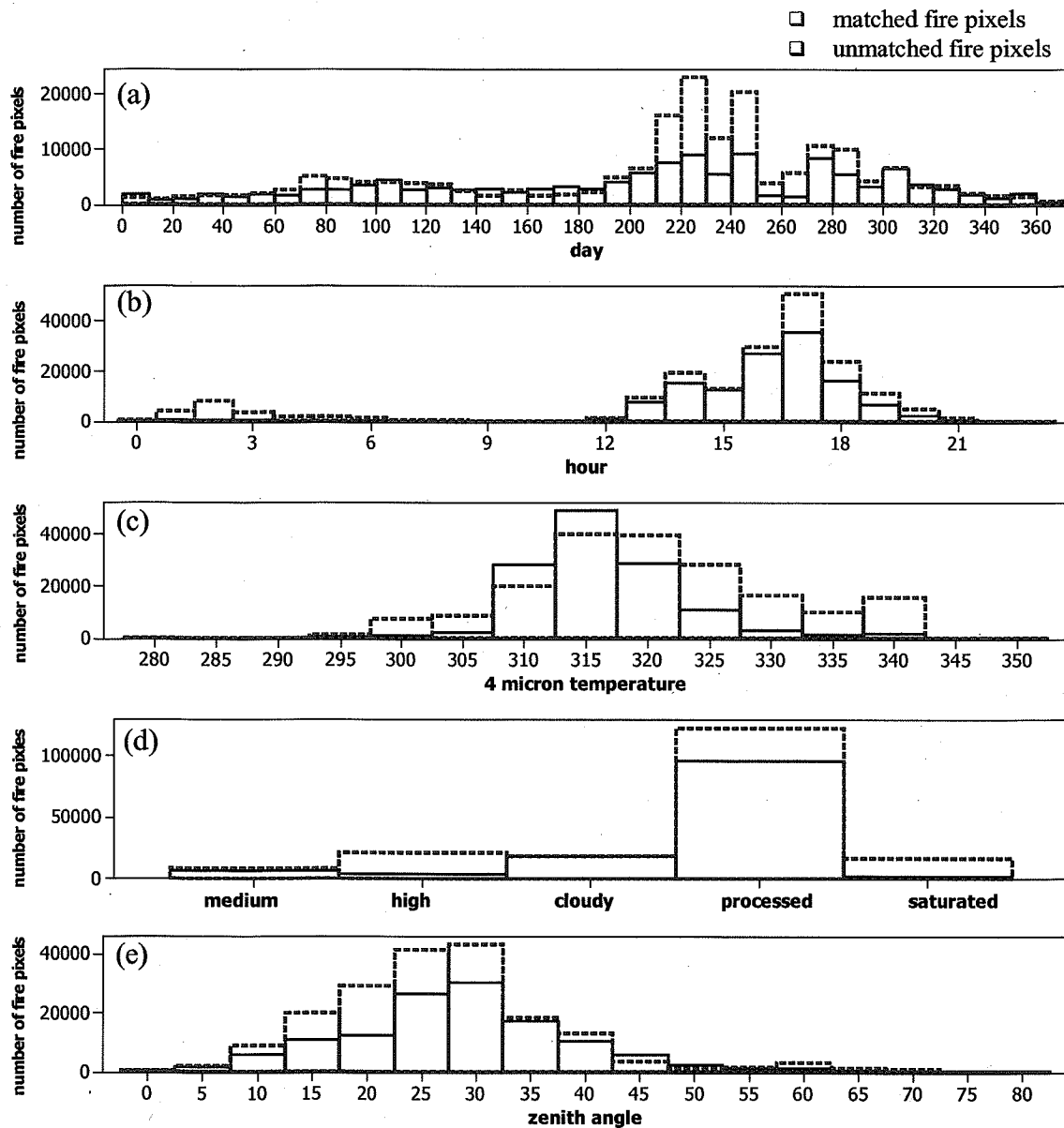


Figure 5.2.1.2

Histograms showing the difference between characteristics of GOES fire pixels with a MODIS match and GOES fire pixels with no MODIS match in 2005; (a) shows the Julian day of the year, (b) hour (UTC) of fire detection, (c) 4 μ m observed brightness temperature (K), (d) confidence category, and (e) zenith angle.

2004 MODIS fire pixels, excluding low confidence fire pixels, compared with GOES fire pixels within +/- 12 hours and within 10 km

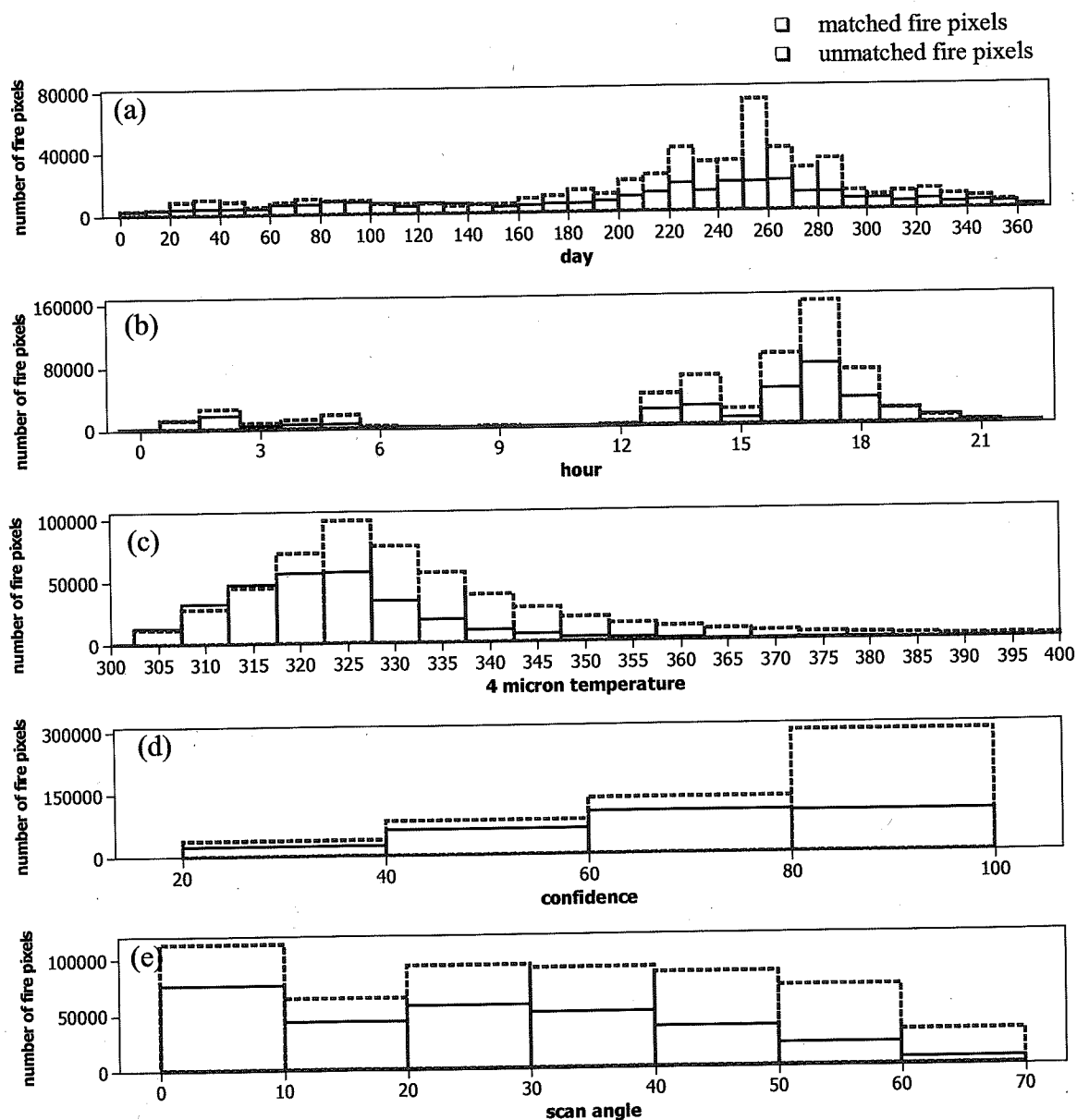


Figure 5.2.1.3

Histograms showing the difference between characteristics of MODIS fire pixels with a GOES match and MODIS fire pixels with no GOES match in 2004; (a) shows the Julian day of the year, (b) hour (UTC) of fire detection, (c) 4 μ m observed brightness temperature (K), (d) confidence category, and (e) scan angle.

2005 MODIS fire pixels, excluding low confidence fire pixels, compared with GOES fire pixels within +/- 12 hours and within 10 km

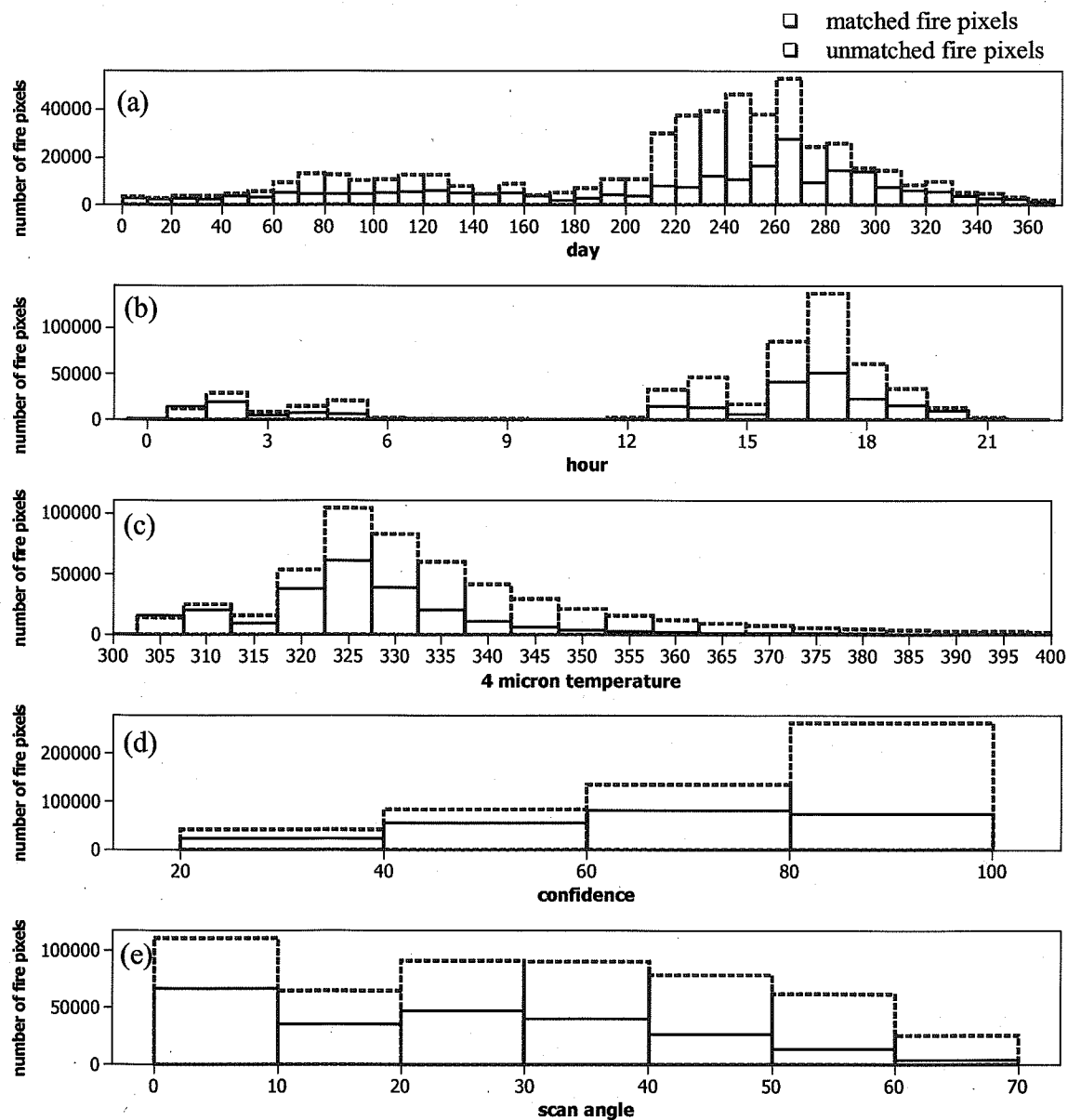


Figure 5.2.1.4

Histograms showing the difference between characteristics of MODIS fire pixels with a GOES match and MODIS fire pixels with no GOES match in 2005; (a) shows the Julian day of the year, (b) hour (UTC) of fire detection, (c) 4 μ m observed brightness temperature (K), (d) confidence category, and (e) scan angle.

Perhaps the most significant trend is shown in analyzing the 4 μm observed brightness temperature of fire pixels where the warmer pixels are far more frequently associated with fire pixels with a match than no match. While the majority of warm fire pixels have a match it is reasonable to assume that the cooler fire pixels would be more likely to be unmatched fire pixels. But, the majority of cooler fire pixels are also low confidence fire pixels and are not included on the plots. If one were to include low confidence fire pixels one would find that more fire pixels at cooler temperatures would be unmatched compared to matched, just as warmer fire pixels are more likely to have a match than to not have a match.

Fire confidence can also provide some clues to how likely it might be for a fire pixel to have a matching fire pixel from a second satellite. Again, low confidence fires are removed from consideration; however, if they were to be considered, there would be a trend for unmatched fire pixels to be more common than matched fire pixels at the lowest confidence level. Confidence levels are typically considered to be general guidelines for user applications. GOES confidence categories are assigned by various algorithm tests, and it appears that medium probability fires are approximately as likely to have a MODIS match as not have a MODIS match. High probability fire pixels are much more likely to have a MODIS match than not. Cloudy fire pixels are those pixels that the algorithm identifies as containing a fire and is likely partially obstructed by clouds. This category is about as likely to have a MODIS match as not have a match. Processed fire pixels and saturated fire pixels are the most confident categories and are also the most likely categories where GOES fire pixels have a collocated MODIS fire. The MODIS algorithm assigns fire confidence differently than GOES, and while it is not practical to

compare the confidence category of a GOES fire pixel with the confidence percentage of a MODIS fire pixel, it is important to note that a similar trend is seen where different confidence values for MODIS fire pixels provide clues to the likelihood of a GOES fire pixel to be collocated with a MODIS fire pixel. Again, low confidence fire pixels are not shown, but if they were, they would show that unmatched MODIS pixels are most common at low confidences just as at the highest confidence MODIS pixels are the most likely to have a collocated GOES fire pixel.

Satellite zenith angle can be an important factor. The zenith angle gives an indication of how far from nadir a fire pixel occurs; for high zenith angles the fire is farther from the sub-satellite point and the spatial resolution of the pixel is more coarse than at low zenith angles. For GOES, relatively few fire pixels are found at small zenith angles because there is relatively little land surface at low angles and much of the coverage area is ocean. For MODIS, the zenith angle is still an indicator of pixel size, however there is not a specific relationship linking zenith angles to a specific geographic location because of orbital differences on successive MODIS overpasses. For GOES fire pixels, zenith angles between 20° and 30° are much more likely to have a MODIS match than for the rest of the zenith angles. As the MODIS zenith angle increases the number of fire detections generally decreases. While zenith angles above 50° are relatively rare, these pixels approach the same size as a GOES pixel at nadir, and proportionally many more MODIS pixels have a GOES match when MODIS has a large zenith angle than the proportion of fire pixels with a match at low MODIS zenith angles.

Figure 5.2.1.5 through Figure 5.2.1.8 show histograms of fire pixels binned according to latitude, geographical region, emissivity and ecosystem type. The latitude

histogram illustrates that fire pixels are most frequently found around 10°S latitude, a similar maximum might be expected around 10°N latitude, however there is comparatively less land there and it is primarily mountainous and not tropical forest. It is apparent that in general, fire pixels in the southern hemisphere are more likely to have a collocated fire from a second satellite than in the northern hemisphere. The only exception would be south of ~30°S where MODIS fire pixels may be less likely to have a corresponding GOES fire pixel because GOES WF_ABBA processing for this region is less frequent (every 3 hours). Emissivity at 4 μm and 11 μm are shown to illustrate that different land surfaces with different emissivities can provide clues towards the likelihood of a fire pixel being collocated with another fire pixel. Emissivities are assigned based on the values given by the WF_ABBA where each ecosystem is assigned an emissivity value. Emissivities and ecosystem do not have a one-to-one relationship; different ecosystems can have the same emissivity. Emissivity is used in an attempt to organize ecosystems into a continuous variable that are easier to work with statistically. The main point to observe regarding ecosystem is that the most common fire pixel ecosystem types tend to have a high proportion of matched fire pixels compared to unmatched fire pixels.

2004 GOES filtered fire pixels, excluding low confidence fire pixels, compared with MODIS fire pixels within +/- 1 hour and within 10 km

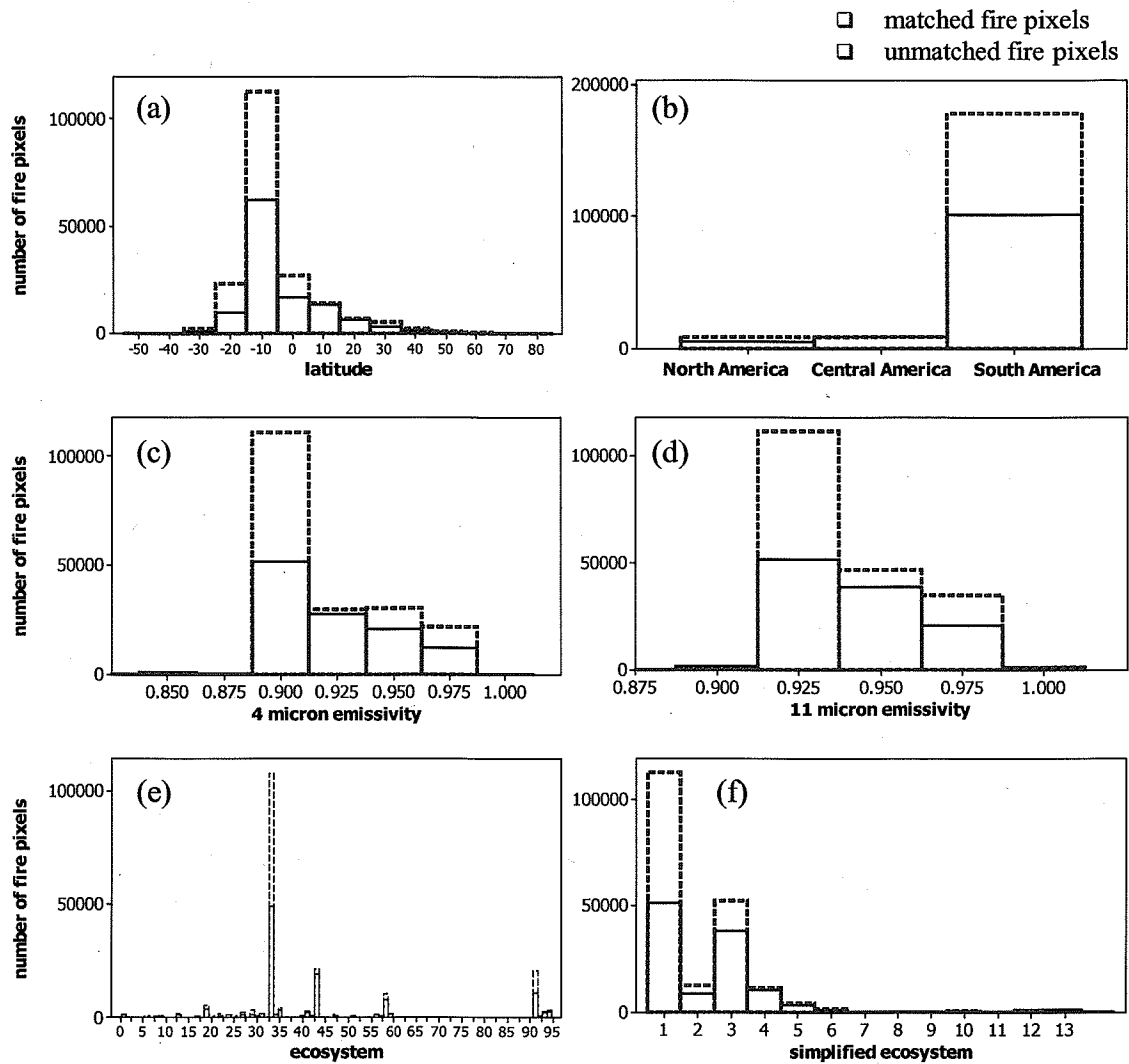


Figure 5.2.1.5

Histograms showing the difference between characteristics of GOES fire pixels with a MODIS match and GOES fire pixels with no MODIS match in 2004; (a) shows latitude, (b) the geographical region, (c) 4 μ m emissivity, (d) 11 μ m emissivity, (e) the ecosystem of the fire pixel, and (f) a simplified ecosystem classification. The ecosystem key is shown in Appendix IV.

2005 GOES filtered fire pixels, excluding low confidence fire pixels, compared with MODIS fire pixels within +/- 1 hour and within 10 km

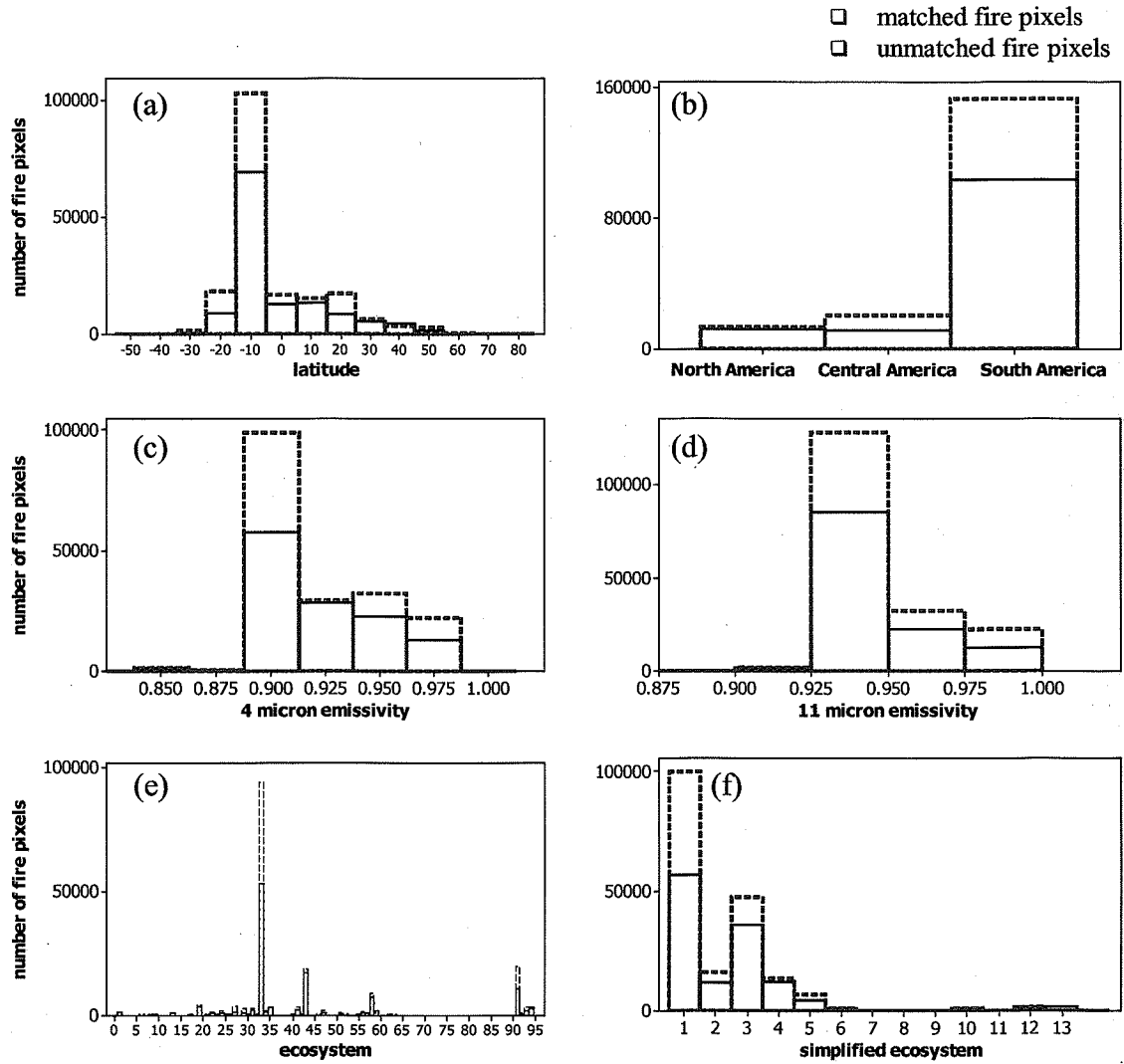


Figure 5.2.1.6

Histograms showing the difference between characteristics of GOES fire pixels with a MODIS match and GOES fire pixels with no MODIS match in 2005; (a) shows latitude, (b) the geographical region, (c) 4 μ m emissivity, (d) 11 μ m emissivity, (e) the ecosystem of the fire pixel, and (f) a simplified ecosystem classification. The ecosystem key is shown in Appendix IV.

2004 MODIS fire pixels, excluding low confidence fire pixels, compared with GOES fire pixels within +/- 12 hours and within 10 km

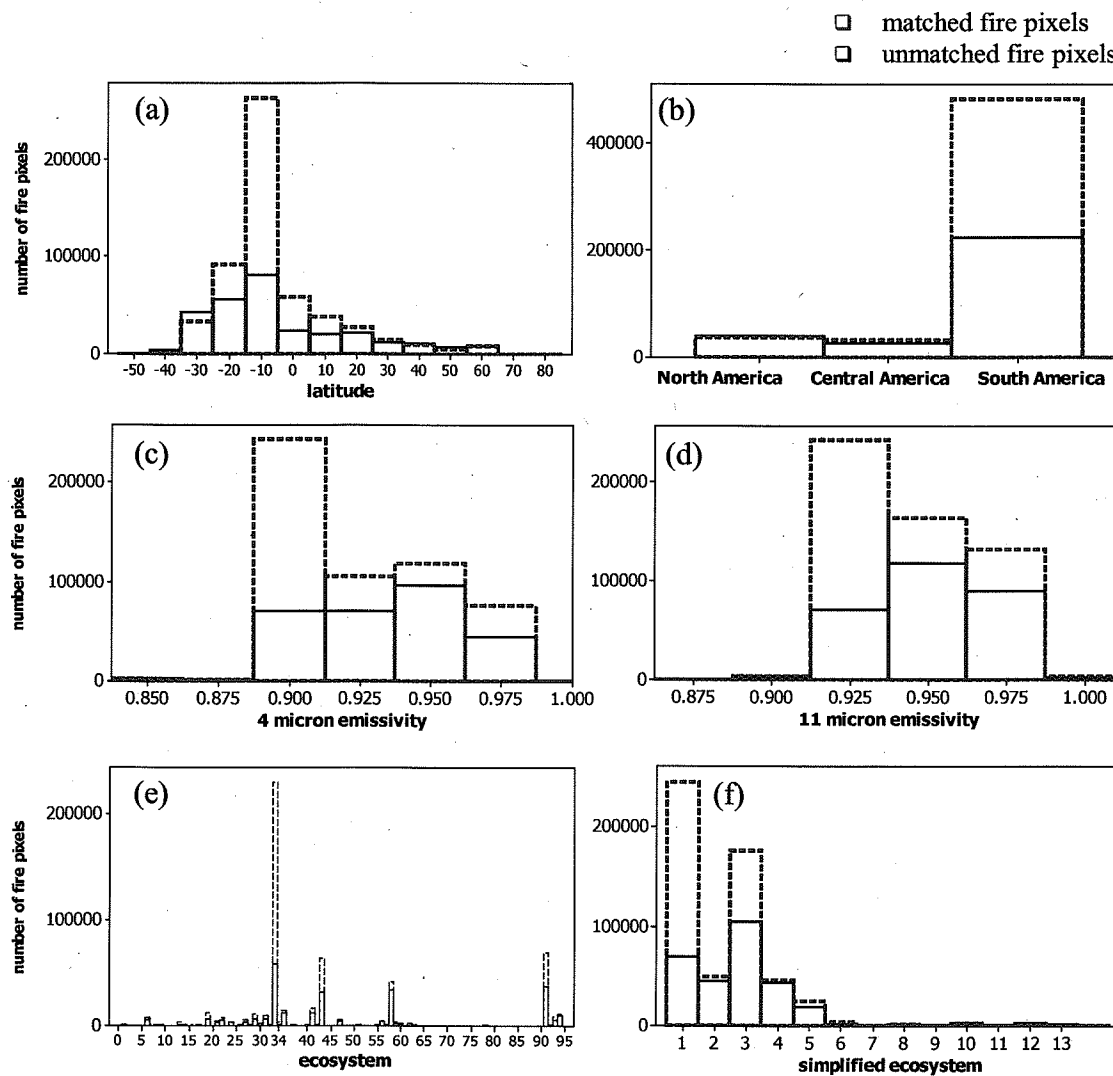


Figure 5.2.1.7

Histograms showing the difference between characteristics of MODIS fire pixels with a GOES match and MODIS fire pixels with no GOES match in 2004; (a) shows latitude, (b) the geographical region, (c) 4 μ m emissivity, (d) 11 μ m emissivity, (e) the ecosystem of the fire pixel, and (f) a simplified ecosystem classification. The ecosystem key is shown in Appendix IV.

2005 MODIS fire pixels, excluding low confidence fire pixels, compared with GOES fire pixels within +/- 12 hours and within 10 km

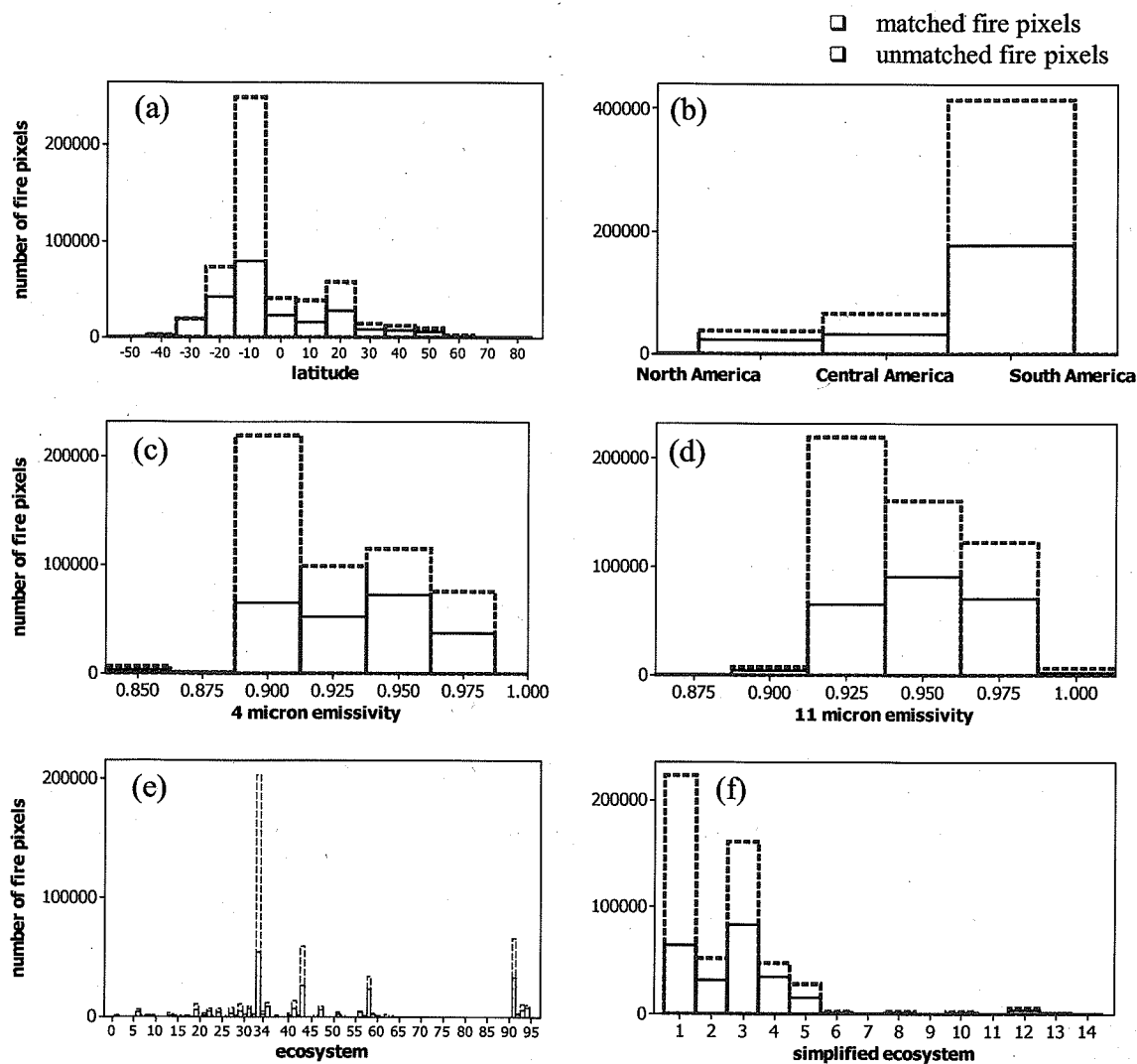


Figure 5.2.1.8

Histograms showing the difference between characteristics of MODIS fire pixels with a GOES match and MODIS fire pixels with no GOES match in 2005; (a) shows latitude, (b) the geographical region, (c) 4 μ m emissivity, (d) 11 μ m emissivity, (e) the ecosystem of the fire pixel, and (f) a simplified ecosystem classification. The ecosystem key is shown in Appendix IV.

The ratio of fire pixels with a match compared to fire pixels without a match is just the first step in trying to understand the differences between GOES and MODIS fire pixels. The next step is to examine the characteristics of the fire pixels, and notice how fire pixels with a match have different bulk characteristics than fire pixels without a match. The mean and standard deviation of the Julian day of the year, hour (UTC), latitude, 4 μm observed brightness temperature, zenith angle, confidence, 4 μm emissivity, and 11 μm emissivity for the GOES fire pixels and GOES filtered fire pixels with a match MODIS match and without a MODIS match for 2004 and 2005 are included in Appendix II. On average, fire pixels with a match, have a higher 4 μm observed brightness temperature, occur with higher confidence, and are found in regions with higher 4 and 11 μm emissivity. It is also apparent that fires with a match tend to occur later in the year, corresponding to the Southern Hemisphere springtime fire season, and tend to be found further south than unmatched fire pixels. Fire pixels with a match tend to have a smaller zenith angle than fire pixels without a match. In general, the standard deviation for all of the fire characteristics is larger for unmatched fire pixels than for matched fire pixels. For the filtered fire pixels, there is a trend for unmatched fire pixels to occur at a later hour of day than the matched fire pixels. The mean and standard deviation of MODIS fire pixel characteristics with and without a GOES filtered or unfiltered fire pixel match are also shown in Appendix II. Most of the same trends are seen with MODIS fire pixels as seen with GOES fire pixels. With differences and limitations in instruments, comparing GOES and MODIS 4 μm observed brightness temperature is not a useful comparison. Also comparing confidence values of GOES fire pixels and MODIS fire pixels is not appropriate due to algorithm differences. Similarly,

the zenith angle for MODIS is not directly related to the latitude and longitude of a fire pixel as it is for GOES so MODIS and GOES zenith angle values should not be directly compared. The trends are important to notice such as the fact that MODIS fire pixels tend to occur later in the year than GOES fire pixels. Also, the latitude of MODIS fire pixels tend to be more southern than GOES fire pixels, but just as with GOES fire pixels, MODIS fire pixels with a match tend to be found further south than MODIS fire pixels with no match. MODIS fire pixels with a match are also warmer on average than unmatched MODIS fire pixels and MODIS fire pixels with a match tend to have a higher confidence than unmatched MODIS fire pixels; the same trend is seen with GOES fire pixels. Also, as with GOES fire pixels, the zenith angle for MODIS fire pixels with a match tends to be smaller than unmatched MODIS fire pixels. The 4 μm and 11 μm emissivity values are derived from GOES emissivities as a function of land type for the location of the fire pixel, so the absolute values of emissivity are likely not valid for MODIS. Emissivity is a surrogate value for land type of a fire pixel and it is evident that MODIS fire pixels with a match occur in land types that have higher emissivities than unmatched fire pixels.

5.2.2 Analysis

As shown in the previous section, there are differences in the characteristics of fire pixels that are collocated with fire pixels from another satellite fire product and fire pixels that are not collocated. It is possible to use statistical tools that use fire pixel characteristics to predict if a particular fire pixel should have a matching fire pixel from

another satellite product based only on the characteristics of the particular fire pixel without referring to the other satellite fire product.

The first step in the analysis involves applying a binary indicator to the GOES and MODIS fire products to indicate if each fire pixel does or does not have a collocated fire pixel from the other fire product. The statistical method, discriminant analysis, can forecast if a given fire pixel should or should not have a matching fire pixel based on fire pixel characteristics. Because there is a difference in the characteristics of fire pixels with a match and fire pixels with no match, discriminant analysis can utilize characteristics such as the 4 μm observed brightness temperature, latitude, and fire confidence to forecast whether or not a match will occur. The analysis produces a 2 by 2 contingency table, Table 5.2.2.1, where for each fire pixel one of four possible outcomes can occur: a fire pixel with a match is correctly forecast by discriminant analysis to have a match when it actually has a collocated fire pixel from another fire product, a fire pixel with a match is incorrectly forecast by discriminant analysis to have no match when the other fire product does have a collocated fire pixel, a fire pixel with no match from the other fire product is incorrectly forecast by discriminant analysis to have a match, and the last outcome is a fire pixel with no match from the other fire product is correctly forecast by discriminant analysis to have no match. This is not a validation exercise since discriminant analysis might identify a fire pixel that has the characteristics of a fire pixel that suggest it should have a collocated fire pixel but the fire pixel was not found by the other satellite fire algorithm. There is a difference between collocated fire pixels and validated fire pixels. However, the results from discriminant analysis are encouraging because they do show that there are characteristics of fire pixels that provide clues about

the likelihood for a fire pixel to be detected by another satellite fire product and that these fire pixels are most likely to be true fire detections. These fire detections are most likely cases where each fire product provides unique information about the same fire on the ground. The success of discriminant analysis is dependent on what predictors are used. The combination of predictors that yields the best results can depend on the temporal window considered as well as other variables. There are cases where using every available predictor does not necessarily provide the best forecast; there are cases when adding an additional predictor will decrease the skill of the forecast. Notice that discriminant analysis is not being used in place of a fire detection algorithm, it is conceivable to use statistical methods based on fire characteristics to examine all pixels – fire pixels and non-fire pixels – to identify the most likely to be fire pixels.

	Fire pixel with an observed match	Fire pixel with no observed match
Fire pixel with a forecasted match	a	b
fire pixel with no forecasted match	c	d

Table 5.2.2.1

2 by 2 contingency table showing the possible discriminant analysis outcomes.

Often in weather forecasting statistics such as probability of detection or hit rate, probability of false detection or false alarm rate, and threat score or critical success index are used to describe the skill of a forecast. These statistics are most applicable when analyzing the skill of a forecast for an event that is rare compared to a common non-event. For example, considering tornado forecasts, by far the most common forecast will be for no tornado and the most frequent outcome will be for no tornado to occur, but the

most interesting outcomes are for when a tornado occurs when there was no tornado forecast or when no tornado occurs but there was a tornado forecast to occur. In the case of fire pixel analysis it is equally important to recognize when a fire pixel is forecast to have a collocated fire pixel and did have a match as well as when a fire pixel is forecast not to have a match and in fact it did not have a match (whereas a forecast for no tornado when no tornado occurs is not as significant as a forecast for a tornado and a tornado occurs). Statistics that are important for fire pixel analysis include accuracy or proportion correctly forecast shown in Equation 5.2.2.1, the Heidke Skill Score as in Equation 5.2.2.1, and Peirce Skill Score as in Equation 5.2.2.3 [Wilks, 2005].

$$PC = \frac{a + d}{n} \quad (5.2.2.1)$$

$$HSS = \frac{2(ad - bc)}{(a + c)(c + d) + (a + b)(b + d)} \quad (5.2.2.2)$$

$$PSS = \frac{ad - bc}{(a + c)(b + d)} \quad (5.2.2.3)$$

$$\text{Random Skill} = PC^2 + (1 - PC)^2 \quad (5.2.2.4)$$

There are 'n' number of total fire pixels. A fire pixel with a match is correctly forecast by discriminant analysis to have a match when it actually does have a collocated fire pixel from another fire product and is labeled 'a', a fire pixel with a match is incorrectly forecast by discriminant analysis to have no match when the other fire product does have a collocated fire pixel is labeled 'b', a fire pixel with no match from the other fire product is incorrectly forecast by discriminant analysis to have a match is labeled 'c', and a fire

pixel with no match from the other fire product is correctly forecast by discriminant analysis to have no match is labeled 'd'.

PC is a good measure for accuracy where the number of fire pixels that discriminant analysis is able to correctly identify is compared to the total number of fire pixels, however it is not enough to completely capture the skill of the forecast. For example, a forecast that predicted every fire pixel had a match would have a PC score as high as the proportion of fire pixels that were observed to have a match. Therefore, a score such as the Heidke Skill Score is used because it accounts for the number of fire pixels as identified by discriminant analysis compared to the amount that would be identified by a random forecast. The Peirce Skill Score is an important score to consider because it is a measure of the fire pixels that discriminant analysis correctly forecasts minus the fire pixels discriminant analysis misclassified. Also, random skill, Equation 5.2.2.4 is calculated to show the skill of a forecast that is based only on the ratio of matched and unmatched fire pixels. The difference between the PC and random skill is another indicator of the skill of the discriminant analysis forecast compared to a random forecast.

The results from discriminant analysis are shown in Appendix III. The appendix shows the combination of predictors that give the highest PC score in the Western Hemisphere fire pixels for 2004 and 2005 where a fire pixel match criteria requires fire pixels to be within 10 km to be considered collocated. For GOES, the highest PC score occurs for GOES fire pixels, both filtered and unfiltered, that have a MODIS fire pixel match within 10 km and within +/- 1 hour. This is also the same time period where the difference between a random forecast and the discriminant analysis forecast is largest.

Notice however that for GOES, fires with a match within ± 12 hours, for example, yields the highest HSS which may be important for some applications. For MODIS fire pixels, as the time window increases the proportion of fires with a match also increases, however the success of discriminant analysis does not show as clear of a relationship. For MODIS fire pixels with or without a GOES fire pixel match within 10 km, discriminant analysis provides the best forecast for fire pixels that are collocated within ± 3 hours. However, for MODIS fire pixels with or without a GOES filtered fire pixel match within 10 km, discriminant analysis provides the best forecast for fire pixels that are collocated within ± 6 hours. Considering fire pixels that have low confidence fires removed, discriminant analysis provides the best forecast for GOES fire pixels, both filtered and unfiltered, that either did or did not have a MODIS fire pixel match within 10 km and within ± 1 hour. Notice however, that while the proportion of fire pixels with a match increases when excluding low confidence fires the PC, HSS, and PSS skill scores in general decrease compared to when low confidence fire pixels are not excluded. This suggests that while low confidence fire pixels are more prone to be unmatched fire pixels, removing them from consideration, while it might be appropriate to eliminate false detections, can decrease the skill of discriminant analysis by decreasing the diversity of the sample population. For the MODIS fire pixels, when excluding low confidence fire pixels, the same trend is found as with low confidence fire pixels included where at ± 3 hours discriminant analysis does best for MODIS fire pixels with or without a GOES fire pixel match compared to at ± 6 hours for MODIS fire pixels with or without a GOES filtered fire pixel match. For 2005 GOES fire pixels, discriminant analysis provides the most skill for GOES fire pixels that consider a MODIS match within 10 km and within

+/- 1 hour; the only exception is that for GOES filtered fire pixels with low confidence fire pixels excluded, discriminant analysis performs slightly better at +/- 0.25 hours than at +/- 1 hour. Also, as in 2004, 2005 MODIS fire pixels that consider a matching GOES fire pixel within 10 km and +/- 3 hours shows the most skill for discriminant analysis while MODIS fire pixels that consider a matching GOES filtered fire pixel within 10 km and +/- 6 hours shows the most skill for discriminant analysis.

Along with the skill scores, it is also important to consider what predictors provide the most skill in predicting if a fire that has been detected will or will not have a collocated fire pixel in another fire product. Appendix III also includes tables that list the predictors that were used to obtain the skill scores shown earlier in the same appendix. For GOES fire pixels, confidence, day of year, and 4 μm observed brightness temperature are used every time discriminant analysis yields the highest skill, however frequently ecosystem type, hour of day, simplified ecosystem, and latitude are also used; even zenith angle, simplified ecosystem, 11 μm emissivity, and 4 μm emissivity are used when the best discriminant analysis skill is found. Emissivity tends to be used more often as a predictor only with data sets where low confidence is excluded (and the forecast skill is typically lower when low confidence fires are excluded). There is more consistency for MODIS fire pixels where every available variable is used when discriminant analysis yields the most skill with the exception of 11 μm emissivity and 4 μm emissivity which are only used in some of the cases. There are cases where adding more predictors yield less skill than with fewer predictors. One explanation for this phenomenon is that by allowing the temporal match criteria to expand, the properties of fire pixels with a match changes such that different characteristics become more or less important as a function of

the temporal match criteria. Another thing to consider is that changing the temporal match criteria changes the ratio of matched and unmatched fire pixels which changes the success rate of a random forecast and accordingly the need for discriminant analysis to use a different combination of predictors to provide the best forecast. For MODIS, the smallest temporal windows have the lowest match ratio and the skill of a random forecast is highest. In these cases, fewer predictors tend to be necessary; often only observed 4 μm temperature and satellite zenith are the only two predictors used when the skill of a random forecast is so high.

In addition to the annual statistics in Appendix III it is also worth considering a case study such as the 24 April 2004 case in Central America that was investigated in Section 5.1.2. Discriminant analysis is able to correctly classify up to 67.6% of GOES filtered fire pixels and up to 76.9 % of MODIS fire pixels as shown in Table 5.2.2.2. The set of predictors used to obtain the results in Table 5.2.2.2 is shown in Table 5.2.2.3. There are differences between the case study and the annual comparison. Some of these differences could be attributed to the differences in sample size where the case study has on the order of a thousand fire pixels compared to annual comparisons where the sample size is several million. There is also less range in attitude, zenith, and ecosystem when only considering a case in a small region. Furthermore, when only considering a single day, day of year can no longer be used as a predictor. Discriminant analysis can correctly identify fire pixels from one fire product that have (or do not have) a matching fire pixel from another product with more success than a random forecast that is only based on the proportion of fire pixels with and without a match and does not account for any fire pixel characteristics.

Central America Case Study 24 April 2004	PC	HSS	PSS	match proportion	random skill	PC - random
GOES	0.657	0.371	0.328	0.468	0.502	0.155
GOES filtered	0.676	0.380	0.322	0.566	0.509	0.167
GOES no low	0.661	0.365	0.306	0.539	0.503	0.158
GOES filtered no low	0.669	0.365	0.308	0.606	0.523	0.146
MODIS	0.769	0.227	0.164	0.734	0.609	0.159
MODIS filtered	0.709	0.381	0.320	0.622	0.530	0.179
MOIDS no low	0.768	0.221	0.159	0.734	0.610	0.158
MODIS filtered no low	0.707	0.375	0.313	0.625	0.531	0.176

Table 5.2.2.2

Discriminant analysis for fire pixels, excluding low confidence fire pixels, in Central America from 24 April 2004 for fire pixels with or without a match within 10 km and +/- 12 hours. PC indicates the proportion correctly forecast by discriminant analysis, HSS is the Hiedke Skill Score, and PSS is the Peirce Skill Score. Match proportion is the number of fire pixels with a match compared to the total number of fire pixels. Random skill indicates the proportion of fire pixels that would be correctly forecast from a forecast based only on the proportion of fire pixels with a match and proportion of fire pixels with no match.

Central America Case Study 24 April 2004	Predictors
GOES	confidence, T ₄ , latitude, hour, ecosystem, simplified ecosystem, zenith angle, 11 μm emissivity
GOES filtered	confidence, T ₄ , latitude, hour, ecosystem, simplified ecosystem, zenith angle, 11 μm emissivity, 4 μm emissivity
GOES no low	confidence, T ₄ , hour, ecosystem, zenith angle, 11 μm emissivity, 4 μm emissivity
GOES filtered no low	confidence, T ₄ , hour, ecosystem, zenith angle, 4 μm emissivity
MODIS	T ₄ , latitude, zenith angle, 11 μm emissivity, 4 μm emissivity
MODIS filtered	confidence, T ₄ , latitude, hour, ecosystem, simplified ecosystem, zenith angle
MOIDS no low	T ₄ , latitude, zenith angle, 11 μm emissivity, 4 μm emissivity
MODIS filtered no low	confidence, T ₄ , latitude, hour, ecosystem, simplified ecosystem, zenith angle

Table 5.2.2.3

The predictors used for 2004 Western Hemisphere fire pixels that yield the highest proportion of fire pixels correctly identified using discriminant analysis.

6 Conclusions

The MODIS and GOES fire products each have unique strengths and limitations. Examining the satellites, algorithms, and fire pixels that are either unique to one product or collocated between the two is a starting point in developing a merged fire product.

6.1 Differences between GOES and MODIS fire products

Often fires are detected by one satellite in areas not immediately covered by another satellite, and by the time the other satellite scans the area the fire may have extinguished, moved, or otherwise significantly changed radiative properties. The orbit of polar orbiting satellites as well as the coverage schedule of geostationary satellites is important to consider in fire studies. Geostationary satellite instruments have the advantage of high temporal resolution, but do not provide global coverage from a single satellite. Polar orbiting satellites have the advantage of finer spatial resolution but less spatial coverage in each swath compared to geostationary satellites. Polar orbiting satellites are able to cover the entire world, but a polar orbiting satellite cannot provide frequent temporal coverage over fire prone regions.

Upon examination of the collocated and unique GOES and MODIS fire pixels in each product, important trends appear. Fire pixels that are collocated tend to be warmer, have a higher confidence value, and tend to occur at lower satellite zenith angles than fire pixels that are not collocated. Furthermore, statistical methods, such as discriminant analysis, can identify differences in fire pixel characteristics for fire pixels that are unmatched compared to fire pixels that do have a match. Identifying the characteristics of matched and unmatched fire pixels offers the capability to predict whether a fire pixel

will be collocated with a fire pixel from another satellite. Further development of this technique could then be applied to validate fires in areas only covered by one satellite.

Algorithm differences can contribute to product differences. Opaque clouds are screened out with GOES and MODIS using different cloud masks, which may impact the statistical results (such an analysis requires further, intensive research). Atmospheric corrections made in the WF_ABBA account for water vapor and enhance the ability to detect and characterize fires when attenuation might prevent MODIS from detecting a fire because no atmospheric corrections are made. In addition to atmospheric attenuation and cloud screening, fire detection is limited by land surface. Fire detection is difficult in transition zones between different ecosystems, near water, and in deserts. Both GOES and MODIS fire algorithms have techniques to account for these difficulties. However, the WF_ABBA has a more sophisticated technique that uses a land type database to estimate surface emissivity and correct the GOES brightness temperature measurements. The resolution of the satellite limits the effectiveness of the land type classification, for example, an urban area might not occupy a large enough portion of the pixel to be classified as an urban pixel but then an industrial source might trigger a fire detection that would be misclassified as biomass burning. In general, the spatial resolution of MODIS detects small fires that GOES cannot detect. GOES detects many fires that MODIS cannot detect because they are not burning during a MODIS overpass and also WF_ABBA detects and characterizes some fires that would go undetected or deemed as a false positive by a less robust algorithm.

6.2 Capabilities, consistency, and confidence of multi-satellite fire detections

Satellite remote sensing technology provides the only automated fire detection method that generates regional and global fire products in near real-time, and is critical for fire detection and monitoring fires in remote areas where fires might otherwise burn out of control for days before being reported on the ground. Disagreement among fire products causes confusion in the user community, and unfortunately instrument characteristics and fire algorithm differences make product differences inevitable. It is necessary to understand the fire product similarities and differences before data fusion can begin to provide a merged fire product that combines the strengths of each fire product to provide more information than a solitary fire product provides. Some product differences are expected due to differences in satellite characteristics and coverage patterns. Furthermore, using different detection and characterization algorithms, one should expect GOES and MODIS fire products to be different. Also, it has been shown that the characteristics of the fires can contribute to the differences in fire products where fire pixels with certain characteristics will be more likely to be detected in both the GOES fire product and the MODIS fire product while fire pixels with other characteristics are more likely to only be found in one fire product.

Often conditions that cause false fire detections are short lived phenomena (e.g. satellite noise or sun-glint that appears only for specific combinations of sun angle, surface reflectivity, and satellite zenith angle), and so a method of improving detection confidence is to use the WF_ABBA filtered fire product where temporal filtering eliminates fire pixels that do not occur more than once in the previous 12 hours.

Since the size of the fire is almost always smaller than the resolution of the satellite, the exact location of the fire is indeterminate. Fire locations are defined by both the GOES and MODIS algorithms as the center of a pixel that contains a fire, so the actual fire might lie anywhere within the pixel, and the pixel size is variable and depends on the resolution and view angle of the satellite. It is also possible, and not uncommon, for more than one fire to occur within a single pixel, and the multiple fires within a pixel from one satellite derived product might occur in separate pixels in another satellite product. Navigational errors are possible, so even if two fires are not recorded at the exact same coordinates, they might be the same fire where satellite navigation might have inaccurately recorded the fire location. Being unable to resolve the exact location of the fire on scales smaller than the satellite resolution also leads to uncertainty in fire emissions due to variability in the fuel load on the sub-pixel scale. Additionally, because the detected fires are smaller than the resolution of the satellite, estimating the fire size, temperature, or fire radiative power is limited by the confidence of the estimate of the background, non-burning component of the pixel.

To understand the differences between the GOES and MODIS fire products it is necessary to examine the frequency that each fire product detects a collocated fire pixel compared to how often each product detects a unique fire pixel. Unfiltered GOES WF_ABBA fire pixels contain the most matches while filtered GOES fire pixels with low confidence fire pixels excluded provide the least unmatched fire pixels. Section 5.2.1 indicated that up to 62.8% of GOES fire pixels (filtered fire pixels with low confidence fire pixels removed) have a match (within 10 km). However, upon further examination, the largest data set with matched fire pixels (303,803 GOES fire pixels with a match) and

the smallest set of unmatched fire pixels (115,820 GOES filtered fire pixels with low confidence fire pixels excluded with a match) results in 72.4% of the fire pixels with a match – up from 62.8%. Similarly, MODIS fire pixels have the most matches when considering unfiltered GOES fire pixels of any confidence while MODIS fire pixels with low confidence fire pixels excluded yield the fewest unmatched fire pixels. By excluding low confidence fire pixels only from the set of unmatched fire pixels, up to 73.3% of all MODIS fire pixels have a match (within +/- 12 hours and 10 km in the Western Hemisphere); for comparison, only 69.1% of MODIS fire pixels have a match with low confidence fire pixels excluded from the matched and unmatched fire pixels.

It is difficult to define the best spatial and temporal collocation criteria. Fire properties change over time; a fire pixel detected at the same location but separated by too much time might be too dissimilar in terms of size, emission rate, or radiative properties to be considered the same fire. Different applications dictate how stringent the temporal and spatial requirements should be in order to determine if the fire observed by different satellites should be considered the same fire. Allowing too much time to pass between fire pixel detections from different satellite products lessens the likelihood that each product is detecting the same fire – a fire that has the same radiative and emission properties. However, not allowing enough time to pass eliminates many areas from consideration due to the limited coverage by polar orbiting satellites. In most cases north of the Equator, there is complete GOES coverage every 30 minutes and so GOES fire pixels occurring within +/- 15 minutes of a MODIS overpass offer the closest possible temporal match. The results indicate that +/- 1 hour in general yields the highest proportion of GOES fire pixels with a match compared to GOES fire pixels with no

match. On the other hand, MODIS coverage is nearly complete over a period of +/- 12 hours and the results indicate that this is also the amount of time that yields the most success in terms of MODIS fire pixels with a GOES fire pixel match. Although the proportion of fires with a match are higher at +/- 12 hours, the differences between matched and unmatched fire pixel characteristics become less clear and discriminant analysis shows more skill when fire matches are close temporally. Similarly it is necessary to allow a certain amount of space to occur between the center of fire pixels because each satellite product has a different resolution. Fire pixels that occur within 10 km and +/- 0.1 degree latitude and longitude are generally thought to be close enough to be considered the same fire detected by different satellites, or at least represent fire activity in the same region that would likely have similar fire characteristics. At a spatial distance of 25 km or more there is a higher percentage of fire pixels with a match but at this distance matching fire pixels are more likely representing two distinct and unique fires; the exception would be at high latitudes where this larger spatial criteria should be considered due to the increasing coarseness of GOES spatial resolution.

The most conservative merged data product would include only collocated fire pixels using the narrowest of spatial and temporal criteria. Such criteria are likely to be overly conservative because many fire pixels that are unique to one fire product are still valid fire pixels. To capture more fires a less conservative approach would be to expand the spatial and temporal criteria. Expanding beyond +/- 12 hours starts to allow too much time between fire detections such that the characteristics of matching fire pixels are dissimilar. Also, expanding spatially beyond 10 km results in dissimilar matching fire characteristics at lower latitudes, but it might be appropriate to allow more distance at

higher latitudes where satellite resolution is more coarse. Another technique to include more fire detections in a merged product would be to include all collocated fire pixels, and only exclude the unmatched fire pixels that have a relatively low confidence or have a relatively cold brightness temperature. Various criteria must be tested to find the combination of characteristics that excluded the most unmatched fire pixels from the GOES – MODIS match forecast. The histograms in Section 5.2.1 to exclude fires that occur in particular ecosystems, areas with particular emissivities, occur at a particular time of day, or time of year. A recent validation study showed that only 2% of GOES fire detections and 2% of MODIS fire detections were false detections in North America [Schroeder, 2006a]. A low rate of false detection and higher rate of disagreement between fire products shows that many valid fires are only detected by one satellite so there is information to be gained through a merged data product. Distinguishing between false detections and fires only detected by one satellite remains a challenge but can be initially addressed by incorporating the lessons learned in this comparative analysis.

6.3 Remaining uncertainties with fire detection and characterization

Further work is needed to validate fire pixels identified by the fire algorithms. A validation study using a high resolution instrument like ASTER onboard the TERRA satellite is being used to help validate MODIS and GOES fire pixels that occur near the ASTER overpass [Schroeder et al., 2006b]. Such a technique may not be able to identify the active GOES fire pixels that do not occur near the overpass but might detect a burn scar. There is a high ratio of GOES fire pixels that match with MODIS fire pixel when considering temporally close matched fire pixels, but when the time is allowed to expand

the ratio drops off because the likelihood that the GOES fire pixels were detectable by MODIS when there was a MODIS overpass decreases. These GOES fires cannot be assumed to be false detections but are difficult to validate. In addition to validation, future work should better address where missing satellite coverage and cloud cover contributes to disagreement between GOES and MODIS fire products. This study did not explicitly account for changes in cloud cover or other forms of missing or corrupt data where it would be more correct to remove GOES fire pixels from consideration that were masked by clouds during the nearest corresponding MODIS overpass. Section 5.2.1 showed that for the cloudy fire flag category about half of the GOES fire pixels had a matching MODIS fire detection and half did not have a match. Differences in the GOES and MODIS cloud mask can explain some of the differences. An attempt was made to remove GOES fire pixels from consideration that occurred in areas not covered by MODIS within a specified amount of time, but this method is based on an estimate of the AQUA and TERRA orbit where more rigorous methods could be employed to better account for the true coverage pattern of MODIS. Furthermore, some MODIS fire pixels that occurred in areas GOES did not cover within the time period being considered (i.e. southern South America) should be removed from consideration.

There is a theoretical difference between the GOES and MODIS sub-pixel fire characterization techniques. In addition to the fire characteristics that were studied and shown to have skill in segregating collocated fire pixels from unmatched fire pixels, it would be equally valid to test to see if FRP or an estimated fire temperature is another fire pixel characteristic that has skill in segregating collocated fire pixels from unmatched fire pixels. This however was not done in the study because reliable FRP values were

unavailable in the MODIS data set and estimated fire temperatures are available for only a portion of GOES fire pixels. Future data versions will likely include more accurate FRP values at which point it would be worth considering FRP as a possible fire pixel characteristic that could help distinguish collocated fire pixels from unmatched fire pixels.

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Appendix I Fire pixel match statistics

Western Hemisphere GOES fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	A	69,842	151,265	31.6%	90,912	136,889	39.9%	127,866	113,438	53.0%
		B	50,653	78,938	39.1%	64,910	69,540	48.3%	88,194	55,007	61.6%
		C	59,950	78,627	43.3%	76,429	67,540	53.1%	100,713	52,517	65.7%
		D	44,515	44,791	49.8%	55,884	37,428	59.9%	71,561	27,942	71.9%
	+/- 1 hour	A	227,380	507,504	30.9%	303,803	453,348	40.1%	442,552	360,287	55.1%
		B	173,414	256,434	40.3%	227,026	219,822	50.8%	313,517	164,007	65.7%
		C	196,045	260,118	43.0%	256,017	218,298	54.0%	348,818	157,844	68.8%
		D	152,831	144,767	51.4%	195,877	115,820	62.8%	255,512	78,521	76.5%
	+/- 3 hours	A	422,097	1,011,922	29.4%	571,231	894,970	39.0%	704,617	802,631	46.7%
		B	339,883	516,780	39.7%	450,877	432,120	51.1%	625,769	306,269	67.1%
		C	363,199	526,202	40.8%	480,001	435,984	52.4%	563,864	381,051	59.7%
		D	298,312	309,359	49.1%	387,595	242,222	61.5%	511,621	155,253	76.7%
	+/- 6 hours	A	525,976	1,435,359	26.8%	716,737	1,270,928	36.1%	1,053,411	992,809	51.5%
		B	434,364	747,206	36.8%	580,109	623,605	48.2%	802,595	443,894	64.4%
		C	453,375	766,870	37.2%	603,868	637,875	48.6%	837,736	446,486	65.2%
		D	381,437	471,462	44.7%	499,655	371,703	57.3%	661,036	242,436	73.2%
	+/- 12 hours	A	563,757	1,722,430	24.7%	765,708	1,529,996	33.4%	1,122,960	1,195,062	48.4%
		B	469,976	905,392	34.2%	624,813	759,018	45.2%	860,411	541,171	61.4%
		C	486,497	922,006	34.5%	645,320	770,953	45.6%	892,439	540,320	62.3%
		D	413,000	563,378	42.3%	538,203	445,203	54.7%	708,487	288,338	71.1%
2005	+/- 0.25 hours	A	68,682	158,968	30.2%	90,086	144,738	38.4%	128,088	120,253	51.6%
		B	48,338	79,373	37.8%	62,511	70,613	47.0%	85,091	55,769	60.4%
		C	58,446	85,184	40.7%	75,130	74,334	50.3%	100,701	58,391	63.3%
		D	42,261	47,229	47.2%	53,564	40,342	57.0%	69,224	30,380	69.5%
	+/- 1 hour	A	223,520	528,632	29.7%	299,455	472,972	38.8%	439,306	377,189	53.8%
		B	165,159	257,251	39.1%	216,353	221,924	49.4%	299,336	167,115	64.2%
		C	191,335	283,736	40.3%	250,834	241,048	51.0%	346,128	177,379	66.1%
		D	144,951	153,320	48.6%	186,104	125,459	59.7%	244,553	87,851	73.6%
	+/- 3 hours	A	413,510	1,066,689	27.9%	559,839	951,781	37.0%	825,239	751,225	52.3%
		B	325,901	522,881	38.4%	430,163	443,420	49.2%	594,063	324,166	64.7%
		C	353,623	561,731	38.6%	468,072	473,175	49.7%	651,601	337,413	65.9%
		D	284,900	317,488	47.3%	368,817	254,422	59.2%	486,881	170,472	74.1%
	+/- 6 hours	A	524,844	1,506,200	25.8%	712,778	1,343,858	34.7%	1,049,780	1,063,730	49.7%
		B	425,626	749,545	36.2%	564,295	631,574	47.2%	777,652	457,905	62.9%
		C	449,565	800,026	36.0%	597,339	673,185	47.0%	834,468	478,378	63.6%
		D	372,007	472,320	44.1%	484,323	377,292	56.2%	641,452	250,889	71.9%
	+/- 12 hours	A	563,587	1,783,691	24.0%	761,902	1,593,628	32.3%	1,116,372	1,258,232	47.0%
		B	461,270	894,082	34.0%	607,841	754,570	44.6%	830,712	546,163	60.3%
		C	483,439	949,127	33.7%	639,101	800,264	44.4%	887,330	566,635	61.0%
		D	403,520	555,234	42.1%	522,107	442,538	54.1%	685,842	290,217	70.3%

Table I.i

Western Hemisphere MODIS fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	a	177,912	778,786	18.6%	276,153	680,545	28.9%	382,992	573,706	40.0%
		b	137,573	819,125	14.4%	212,446	744,252	22.2%	302,262	654,436	31.6%
		c	167,894	670,092	20.0%	257,438	580,548	30.7%	348,943	489,043	41.6%
		d	131,484	706,502	15.7%	200,767	637,219	24.0%	279,456	558,530	33.3%
	+/- 1 hour	a	317,409	639,289	33.2%	455,254	501,429	47.6%	590,485	366,213	61.7%
		b	239,479	717,219	25.0%	337,802	618,896	35.3%	449,660	507,038	47.0%
		c	296,294	541,692	35.4%	418,151	419,822	49.9%	530,245	307,741	63.3%
		d	226,731	611,255	27.1%	315,411	522,575	37.6%	411,510	426,476	49.1%
	+/- 3 hours	a	404,302	552,396	42.3%	550,844	405,839	57.6%	612,730	343,968	64.0%
		b	316,048	640,650	33.0%	424,951	531,732	44.4%	545,202	411,496	57.0%
		c	375,260	462,726	44.8%	502,960	335,026	60.0%	560,315	277,671	66.9%
		d	296,798	541,188	35.4%	393,422	444,564	46.9%	495,812	342,174	59.2%
	+/- 6 hours	a	439,606	517,092	46.0%	586,019	370,664	61.3%	726,102	230,596	75.9%
		b	355,535	601,163	37.2%	470,857	485,826	49.2%	598,726	357,972	62.6%
		c	406,118	431,868	48.5%	532,039	305,947	63.5%	647,456	190,530	77.3%
		d	331,930	506,056	39.6%	432,927	405,059	51.7%	540,928	297,058	64.6%
+/- 12 hours	a	458,196	498,501	47.9%	605,582	351,101	63.3%	748,917	207,781	78.3%	
	b	372,210	584,488	38.9%	488,256	468,427	51.0%	619,274	337,424	64.7%	
	c	423,042	414,943	50.5%	549,905	288,081	65.6%	668,502	169,484	79.8%	
	d	346,927	491,059	41.4%	448,302	389,684	53.5%	559,041	278,945	66.7%	
2005	+/- 0.25 hours	a	174,135	837,157	17.2%	270,511	740,781	26.7%	379,806	631,486	37.6%
		b	131,679	879,613	13.0%	204,362	806,475	20.2%	293,044	718,248	29.0%
		c	150,524	602,757	20.0%	229,642	523,639	30.5%	306,748	446,533	40.7%
		d	116,744	636,537	15.5%	178,137	575,713	23.6%	243,820	509,461	32.4%
	+/- 1 hour	a	319,640	691,652	31.6%	467,294	543,992	46.2%	615,374	395,918	60.9%
		b	236,985	774,307	23.4%	341,043	670,249	33.7%	463,639	547,653	45.8%
		c	271,672	481,609	36.1%	388,703	364,577	51.6%	488,122	265,159	64.8%
		d	207,404	545,877	27.5%	293,150	460,130	38.9%	382,424	370,857	50.8%
	+/- 3 hours	a	416,121	594,459	41.2%	573,606	437,680	56.7%	727,654	283,638	72.0%
		b	319,945	691,347	31.6%	434,159	577,127	42.9%	567,304	443,988	56.1%
		c	350,222	403,456	46.5%	470,898	282,382	62.5%	573,444	179,837	76.1%
		d	275,995	477,286	36.6%	366,766	386,514	48.7%	462,318	290,963	61.4%
	+/- 6 hours	a	458,409	552,883	45.3%	614,935	396,351	60.8%	766,972	244,320	75.8%
		b	366,971	644,321	36.3%	489,927	521,359	48.4%	631,412	379,880	62.4%
		c	383,073	370,208	50.9%	499,990	253,290	66.4%	600,057	153,224	79.7%
		d	313,892	439,389	41.7%	409,460	343,820	54.4%	509,030	244,251	67.6%
+/- 12 hours	a	481,322	529,970	47.6%	638,458	372,828	63.1%	795,063	216,229	78.6%	
	b	387,257	624,035	38.3%	509,327	501,959	50.4%	652,844	358,448	64.6%	
	c	402,902	350,379	53.5%	520,229	233,051	69.1%	624,594	128,687	82.9%	
	d	330,884	422,397	43.9%	424,949	328,331	56.4%	526,021	227,260	69.8%	

Table I.ii

North America GOES fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	A	3,355	18,192	15.6%	4,752	17,328	21.5%	5,386	16,886	24.2%
		B	2,199	6,211	26.1%	3,041	5,721	34.7%	3,333	5,524	37.6%
		C	2,876	5,850	33.0%	4,077	5,113	44.4%	4,511	4,817	48.4%
		D	1,908	2,082	47.8%	2,645	1,654	61.5%	2,845	1,521	65.2%
	+/- 1 hour	A	10,542	69,914	13.1%	15,154	66,650	18.5%	17,868	64,655	21.7%
		B	7,336	21,516	25.4%	10,218	19,588	34.3%	11,449	18,730	37.9%
		C	9,145	20,854	30.5%	13,077	18,080	42.0%	14,891	16,750	47.1%
		D	6,457	7,307	46.9%	8,975	5,619	61.5%	9,761	5,059	65.9%
	+/- 3 hours	A	19,178	165,130	10.4%	27,239	158,062	14.7%	33,284	152,663	17.9%
		B	14,213	43,722	24.5%	19,569	39,184	33.3%	22,424	36,679	37.9%
		C	16,598	48,253	25.6%	23,399	42,315	35.6%	27,420	38,811	41.4%
		D	12,465	16,532	43.0%	17,093	12,621	57.5%	18,940	11,063	63.1%
	+/- 6 hours	A	23,391	251,038	8.5%	33,077	241,536	12.0%	41,267	233,492	15.0%
		B	17,931	62,284	22.4%	24,542	55,826	30.5%	28,413	52,023	35.3%
		C	20,224	75,660	21.1%	28,404	67,628	29.6%	33,968	62,164	35.3%
		D	15,699	24,980	38.6%	21,433	19,373	52.5%	24,082	16,770	58.9%
	+/- 12 hours	A	24,110	255,535	8.6%	33,790	245,855	12.1%	42,655	236,990	15.3%
		B	18,545	62,645	22.8%	25,045	56,145	30.8%	29,068	52,122	35.8%
		C	20,831	76,940	21.3%	28,929	68,842	29.6%	34,734	63,037	35.5%
		D	16,235	24,948	39.4%	21,837	19,346	53.0%	24,570	16,613	59.7%
2005	+/- 0.25 hours	A	4,880	24,258	16.7%	6,817	23,007	22.9%	7,938	22,251	26.3%
		B	3,325	9,316	26.3%	4,503	8,592	34.4%	5,143	8,188	38.6%
		C	4,249	9,352	31.2%	5,876	8,308	41.4%	6,586	7,846	45.6%
		D	2,945	4,174	41.4%	3,950	3,565	52.6%	4,350	3,321	56.7%
	+/- 1 hour	A	15,357	86,301	15.1%	21,710	81,355	21.1%	25,846	78,275	24.8%
		B	10,966	32,606	25.2%	15,240	29,653	33.9%	17,360	28,168	38.1%
		C	13,331	32,104	29.3%	18,713	28,001	40.1%	21,482	25,980	45.3%
		D	9,724	14,176	40.7%	13,383	11,666	53.4%	14,761	10,702	58.0%
	+/- 3 hours	A	27,635	211,065	11.6%	39,297	200,894	16.4%	48,119	192,994	20.0%
		B	21,299	72,751	22.6%	29,321	65,941	30.8%	33,802	62,053	35.3%
		C	23,987	69,071	25.8%	33,791	60,557	35.8%	39,598	55,437	41.7%
		D	18,801	29,729	38.7%	25,631	23,954	51.7%	28,518	21,508	57.0%
	+/- 6 hours	A	34,302	323,130	9.6%	48,368	309,383	13.5%	60,276	297,659	16.8%
		B	27,144	101,071	21.2%	37,254	91,220	29.0%	43,314	85,275	33.7%
		C	29,748	101,693	22.6%	41,535	90,200	31.5%	49,303	82,576	37.4%
		D	23,898	41,100	36.8%	32,498	32,742	49.8%	36,444	28,893	55.8%
	+/- 12 hours	A	35,444	327,921	9.8%	49,692	313,672	13.7%	62,536	300,829	17.2%
		B	28,147	101,715	21.7%	38,317	91,545	29.5%	44,671	85,191	34.4%
		C	30,631	102,938	22.9%	42,490	91,078	31.8%	50,569	83,000	37.9%
		D	24,690	41,222	37.5%	33,317	32,595	50.5%	37,344	28,568	56.7%

Table I.iii

North America MODIS fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	a	10,176	74,956	12.0%	18,319	66,813	21.5%	23,660	61,472	27.8%
		b	7,462	77,670	8.8%	13,367	71,765	15.7%	17,007	68,125	20.0%
		c	9,579	65,006	12.8%	17,195	57,390	23.1%	22,042	52,543	29.6%
		d	7,074	67,511	9.5%	12,642	61,943	16.9%	15,999	58,586	21.5%
	+/- 1 hour	a	17,270	67,862	20.3%	28,283	56,849	33.2%	35,755	49,377	42.0%
		b	12,964	72,168	15.2%	20,871	64,261	24.5%	25,778	59,354	30.3%
		c	16,080	58,505	21.6%	26,159	48,426	35.1%	32,809	41,776	44.0%
		d	12,185	62,400	16.3%	19,513	55,072	26.2%	23,928	50,657	32.1%
	+/- 3 hours	a	23,495	61,637	27.6%	35,838	49,294	42.1%	45,014	40,118	52.9%
		b	18,284	66,848	21.5%	27,184	57,948	31.9%	33,427	51,705	39.3%
		c	21,749	52,836	29.2%	32,947	41,638	44.2%	41,030	33,555	55.0%
		d	17,088	57,497	22.9%	25,206	49,379	33.8%	30,739	43,846	41.2%
	+/- 6 hours	a	25,800	59,332	30.3%	38,592	46,540	45.3%	48,066	37,066	56.5%
		b	20,339	64,793	23.9%	29,572	55,560	34.7%	36,254	48,878	42.6%
		c	23,883	50,702	32.0%	35,483	39,102	47.6%	43,817	30,768	58.7%
		d	18,992	55,593	25.5%	27,393	47,192	36.7%	33,297	41,288	44.6%
	+/- 12 hours	a	26,539	58,593	31.2%	39,306	45,826	46.2%	48,825	36,307	57.4%
		b	20,958	64,174	24.6%	30,125	55,007	35.4%	36,822	48,310	43.3%
		c	24,572	50,013	32.9%	36,145	38,440	48.5%	44,506	30,079	59.7%
		d	19,575	55,010	26.2%	27,914	46,671	37.4%	33,825	40,760	45.4%
2005	+/- 0.25 hours	a	14,912	82,168	15.4%	26,225	70,854	27.0%	32,914	64,166	33.9%
		b	11,541	85,539	11.9%	20,331	76,696	21.0%	25,329	71,751	26.1%
		c	12,578	48,430	20.6%	21,919	39,089	35.9%	26,303	34,705	43.1%
		d	10,092	50,916	16.5%	17,619	43,637	28.8%	21,135	39,873	34.6%
	+/- 1 hour	a	25,320	71,760	26.1%	38,579	58,500	39.7%	46,597	50,483	48.0%
		b	19,778	77,302	20.4%	29,833	67,246	30.7%	35,599	61,481	36.7%
		c	20,403	40,605	33.4%	30,400	30,608	49.8%	34,992	26,016	57.4%
		d	16,730	44,278	27.4%	24,762	36,246	40.6%	28,306	32,702	46.4%
	+/- 3 hours	a	33,669	63,359	34.7%	47,099	49,980	48.5%	56,384	40,696	58.1%
		b	27,443	69,637	28.3%	37,397	59,682	38.5%	44,262	52,818	45.6%
		c	26,606	34,650	43.4%	35,920	25,088	58.9%	40,883	20,125	67.0%
		d	22,644	38,364	37.1%	29,928	31,080	49.1%	33,892	27,116	55.6%
	+/- 6 hours	a	36,955	60,125	38.1%	49,973	47,106	51.5%	59,449	37,631	61.2%
		b	30,535	66,545	31.5%	40,464	56,616	41.7%	47,588	49,492	49.0%
		c	29,105	31,903	47.7%	37,914	23,094	62.1%	42,831	18,177	70.2%
		d	25,095	35,913	41.1%	32,165	28,843	52.7%	36,151	24,857	59.3%
	+/- 12 hours	a	37,916	59,164	39.1%	50,772	46,307	52.3%	60,309	36,771	62.1%
		b	31,428	65,652	32.4%	41,147	55,932	42.4%	48,272	48,808	49.7%
		c	29,946	31,062	49.1%	38,605	22,403	63.3%	43,553	17,455	71.4%
		d	25,885	35,123	42.4%	32,748	28,260	53.7%	36,722	24,286	60.2%

Table I.iv

Central America GOES fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	A	4,651	14,193	24.7%	5,781	13,384	30.2%	7,610	12,115	38.6%
		B	2,667	6,151	30.2%	3,294	5,723	36.5%	4,146	5,163	44.5%
		C	3,665	6,795	35.0%	4,464	6,236	41.7%	5,548	5,533	50.1%
		D	2,163	3,236	40.1%	2,622	2,928	47.2%	3,142	2,614	54.6%
	+/- 1 hour	A	13,073	43,035	23.3%	17,002	40,120	29.8%	23,983	35,077	40.6%
		B	8,233	18,608	30.7%	10,551	16,966	38.3%	13,799	14,721	48.4%
		C	10,324	20,755	33.2%	13,201	18,671	41.4%	17,505	15,687	52.7%
		D	6,696	9,700	40.8%	8,448	8,487	49.9%	10,513	7,146	59.5%
	+/- 3 hours	A	23,914	90,676	20.9%	33,074	83,452	28.4%	49,803	70,744	41.3%
		B	16,567	39,432	29.6%	22,505	34,917	39.2%	31,123	28,585	52.1%
		C	18,954	43,094	30.5%	25,774	37,804	40.5%	36,573	29,808	55.1%
		D	13,482	21,530	38.5%	18,070	18,086	50.0%	23,912	13,921	63.2%
	+/- 6 hours	A	29,769	121,412	19.7%	42,247	110,850	27.6%	65,851	91,544	41.8%
		B	21,618	55,733	27.9%	30,072	48,683	38.2%	43,056	38,191	53.0%
		C	23,664	61,007	27.9%	33,103	53,070	38.4%	49,054	40,124	55.0%
		D	17,625	32,702	35.0%	24,277	27,168	47.2%	33,592	19,672	63.1%
	+/- 12 hours	A	31,635	151,790	17.2%	45,198	138,266	24.6%	71,014	112,541	38.7%
		B	23,187	70,120	24.9%	32,395	60,941	34.7%	46,579	46,816	49.9%
		C	25,145	77,300	24.5%	35,403	67,069	34.5%	52,861	49,675	51.6%
		D	18,899	41,005	31.5%	26,173	33,753	43.7%	36,425	23,543	60.7%
2005	+/- 0.25 hours	A	9,559	16,505	36.7%	11,820	15,011	44.1%	15,612	12,548	55.4%
		B	6,286	7,780	44.7%	7,669	6,903	52.6%	9,744	5,594	63.5%
		C	7,298	8,515	46.2%	8,915	7,459	54.4%	11,363	5,962	65.6%
		D	4,972	4,509	52.4%	5,991	3,867	60.8%	7,433	2,994	71.3%
	+/- 1 hour	A	28,847	52,628	35.4%	36,905	45,888	44.6%	50,857	36,277	58.4%
		B	20,309	24,134	45.7%	25,733	20,418	55.8%	33,126	15,511	68.1%
		C	22,310	27,220	45.0%	28,202	22,373	55.8%	37,309	16,269	69.6%
		D	16,167	13,788	54.0%	20,282	10,970	64.9%	25,344	7,677	76.8%
	+/- 3 hours	A	55,522	113,707	32.8%	75,007	98,701	43.2%	106,456	75,978	58.4%
		B	43,152	54,702	44.1%	56,566	44,673	55.9%	74,632	32,247	69.8%
		C	43,295	56,886	43.2%	57,966	45,708	55.9%	79,446	30,576	72.2%
		D	34,551	31,675	52.2%	45,018	23,896	65.3%	58,074	15,117	79.3%
	+/- 6 hours	A	73,581	156,235	32.0%	99,769	134,180	42.6%	142,417	100,155	58.7%
		B	59,246	81,324	42.1%	78,431	65,286	54.6%	104,395	44,892	69.9%
		C	57,712	81,975	41.3%	77,583	65,319	54.3%	107,431	41,823	72.0%
		D	47,550	49,418	49.0%	62,612	36,852	62.9%	81,913	21,854	78.9%
	+/- 12 hours	A	77,743	194,190	28.6%	105,153	166,897	38.7%	149,788	122,506	55.0%
		B	62,942	100,632	38.5%	82,946	80,735	50.7%	109,633	54,213	66.9%
		C	60,904	104,091	36.9%	81,618	83,462	49.4%	112,631	52,610	68.2%
		D	50,456	61,813	44.9%	66,128	46,220	58.9%	85,919	26,551	76.4%

Table I.v

Central America MODIS fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	a	10,003	53,238	15.8%	14,690	48,536	23.2%	23,046	40,195	36.4%
		b	6,154	57,087	9.7%	9,116	54,110	14.4%	14,892	48,349	23.5%
		c	9,812	49,301	16.6%	14,399	44,701	24.4%	22,523	36,590	38.1%
		d	6,052	53,061	10.2%	8,971	50,129	15.2%	14,620	44,493	24.7%
	+/- 1 hour	a	16,766	46,475	26.5%	23,613	39,613	37.3%	34,590	28,651	54.7%
		b	11,103	52,138	17.6%	15,685	47,541	24.8%	23,810	39,431	37.6%
		c	16,383	42,730	27.7%	22,990	36,110	38.9%	33,479	25,634	56.6%
		d	10,888	48,225	18.4%	15,349	43,751	26.0%	23,198	35,915	39.2%
	+/- 3 hours	a	21,652	41,589	34.2%	30,401	32,825	48.1%	43,194	20,047	68.3%
		b	15,199	48,042	24.0%	21,324	41,902	33.7%	31,745	31,496	50.2%
		c	21,059	38,054	35.6%	29,467	29,633	49.9%	41,586	17,527	70.4%
		d	14,851	44,262	25.1%	20,785	38,315	35.2%	30,840	28,273	52.2%
	+/- 6 hours	a	23,635	39,606	37.4%	33,110	30,116	52.4%	46,350	16,891	73.3%
		b	17,030	46,211	26.9%	23,969	39,260	37.9%	35,442	27,799	56.0%
		c	22,948	36,165	38.8%	32,038	27,062	54.2%	44,580	14,533	75.4%
		d	16,619	42,494	28.1%	23,326	35,774	39.5%	34,370	24,743	58.1%
	+/- 12 hours	a	24,211	39,030	38.3%	33,885	29,341	53.6%	47,409	15,832	75.0%
		b	17,478	45,763	27.6%	24,562	38,664	38.8%	36,242	26,999	57.3%
		c	23,503	35,610	39.8%	32,780	26,320	55.5%	45,581	13,532	77.1%
		d	17,054	42,059	28.8%	23,903	35,197	40.4%	35,150	23,963	59.5%
2005	+/- 0.25 hours	a	23,695	100,307	19.1%	36,463	87,535	29.4%	57,847	66,155	46.7%
		b	16,992	107,010	13.7%	26,521	96,818	21.5%	43,039	80,963	34.7%
		c	21,296	78,448	21.4%	32,373	67,371	32.5%	49,628	50,116	49.8%
		d	15,550	84,194	15.6%	24,004	75,889	24.0%	37,669	62,075	37.8%
	+/- 1 hour	a	39,267	84,735	31.7%	55,702	68,296	44.9%	80,073	43,929	64.6%
		b	29,331	94,671	23.7%	42,036	81,962	33.9%	62,062	61,940	50.0%
		c	34,852	64,892	34.9%	48,714	51,030	48.8%	67,687	32,057	67.9%
		d	26,470	73,274	26.5%	37,394	62,350	37.5%	53,424	46,320	53.6%
	+/- 3 hours	a	51,208	72,134	41.5%	70,263	53,735	56.7%	95,641	28,361	77.1%
		b	40,586	83,416	32.7%	55,392	68,606	44.7%	78,047	45,955	62.9%
		c	44,875	55,018	44.9%	60,329	39,415	60.5%	79,702	20,042	79.9%
		d	36,086	63,658	36.2%	48,373	51,371	48.5%	66,232	33,512	66.4%
	+/- 6 hours	a	56,837	67,165	45.8%	76,580	47,418	61.8%	101,441	22,561	81.8%
		b	45,704	78,298	36.9%	61,607	62,391	49.7%	85,287	38,715	68.8%
		c	49,514	50,230	49.6%	65,399	34,345	65.6%	84,239	15,505	84.5%
		d	40,343	59,401	40.4%	53,354	46,390	53.5%	71,912	27,832	72.1%
	+/- 12 hours	a	58,341	65,661	47.0%	78,360	45,638	63.2%	103,572	20,430	83.5%
		b	46,936	77,066	37.9%	63,037	60,961	50.8%	86,936	37,066	70.1%
		c	50,831	48,913	51.0%	66,916	32,828	67.1%	86,100	13,644	86.3%
		d	41,416	58,328	41.5%	54,569	45,175	54.7%	73,314	26,430	73.5%

Table I.vi

South America GOES fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	A	61,836	118,880	34.2%	80,379	106,177	43.1%	114,870	84,437	57.6%
		B	45,787	66,576	40.7%	58,575	58,096	50.2%	80,715	44,320	64.6%
		C	53,409	65,982	44.7%	67,888	56,191	54.7%	90,654	42,167	68.3%
		D	40,444	39,473	50.6%	50,617	32,846	60.6%	65,574	23,807	73.4%
	+/- 1 hour	A	203,765	394,555	34.1%	271,647	346,578	43.9%	400,701	260,555	60.6%
		B	157,845	216,310	42.2%	206,257	183,268	53.0%	288,269	130,556	68.8%
		C	176,576	218,509	44.7%	229,739	181,547	55.9%	316,422	125,407	71.6%
		D	139,678	127,760	52.2%	178,454	101,714	63.7%	235,238	66,316	78.0%
	+/- 3 hours	A	379,005	756,116	33.4%	510,918	653,456	43.9%	621,530	579,224	51.8%
		B	309,103	433,626	41.6%	408,803	358,019	53.3%	572,222	241,005	70.4%
		C	327,647	434,855	43.0%	430,828	355,865	54.8%	499,871	312,432	61.5%
		D	272,365	271,297	50.1%	352,432	211,515	62.5%	468,769	130,269	78.3%
	+/- 6 hours	A	472,816	1,062,909	30.8%	641,413	918,542	41.1%	946,293	667,773	58.6%
		B	394,815	629,189	38.6%	525,495	519,096	50.3%	731,126	353,680	67.4%
		C	409,487	630,203	39.4%	542,357	517,177	51.2%	754,714	344,198	68.7%
		D	348,113	413,780	45.7%	453,945	325,162	58.3%	603,362	205,994	74.5%
	+/- 12 hours	A	508,012	1,315,105	27.9%	686,720	1,145,875	37.5%	1,009,291	845,531	54.4%
		B	428,244	772,627	35.7%	567,373	641,932	46.9%	784,764	442,233	64.0%
		C	440,521	767,766	36.5%	580,988	635,042	47.8%	804,844	427,608	65.3%
		D	377,866	497,425	43.2%	490,192	392,104	55.6%	647,492	248,182	72.3%
2005	+/- 0.25 hours	A	54,243	118,205	31.5%	71,449	106,720	40.1%	104,538	85,454	55.0%
		B	38,727	62,277	38.3%	50,339	55,118	47.7%	70,204	41,987	62.6%
		C	46,899	67,317	41.1%	60,339	58,567	50.7%	82,752	44,583	65.0%
		D	34,344	38,546	47.1%	43,623	32,910	57.0%	57,441	24,065	70.5%
	+/- 1 hour	A	179,316	389,703	31.5%	240,840	345,729	41.1%	362,603	262,637	58.0%
		B	133,884	200,511	40.0%	175,380	171,853	50.5%	248,850	123,436	66.8%
		C	155,694	224,412	41.0%	203,919	190,674	51.7%	287,337	135,130	68.0%
		D	119,060	125,356	48.7%	152,439	102,823	59.7%	204,448	69,472	74.6%
	+/- 3 hours	A	330,353	741,917	30.8%	445,535	652,186	40.6%	670,664	482,253	58.2%
		B	261,450	395,428	39.8%	344,276	332,806	50.8%	485,629	229,866	67.9%
		C	286,341	435,774	39.7%	376,315	366,909	50.6%	532,557	251,400	67.9%
		D	231,548	256,084	47.5%	298,168	206,572	59.1%	400,289	133,847	74.9%
	+/- 6 hours	A	416,961	1,026,835	28.9%	564,641	900,295	38.5%	847,087	665,916	56.0%
		B	339,236	567,150	37.4%	448,610	475,068	48.6%	629,943	327,738	65.8%
		C	362,105	616,358	37.0%	478,221	517,666	48.0%	677,734	353,979	65.7%
		D	300,559	381,802	44.0%	389,212	307,695	55.8%	523,095	200,142	72.3%
	+/- 12 hours	A	450,400	1,261,580	26.3%	607,057	1,113,058	35.3%	904,048	834,897	52.0%
		B	370,181	691,735	34.9%	486,578	582,290	45.5%	676,408	406,759	62.4%
		C	391,904	742,098	34.6%	514,993	625,724	45.1%	724,130	431,025	62.7%
		D	328,374	452,199	42.1%	422,662	363,723	53.7%	562,579	235,098	70.5%

Table I.vii

South America MODIS fire pixels		5 km			10 km			25 km			
		Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	Matched fire pixels	Unmatched fire pixels	% with match	
2004	+/- 0.25 hours	a	157,733	650,592	19.5%	243,144	565,181	30.1%	336,286	472,039	41.6%
		b	123,957	684,368	15.3%	189,963	618,362	23.5%	270,363	537,962	33.4%
		c	148,503	555,785	21.1%	225,844	478,444	32.1%	304,378	399,910	43.2%
		d	118,358	585,930	16.8%	179,154	525,134	25.4%	248,837	455,451	35.3%
	+/- 1 hour	a	283,373	524,952	35.1%	403,358	404,967	49.9%	520,140	288,185	64.3%
		b	215,412	592,913	26.6%	301,246	507,079	37.3%	400,072	408,253	49.5%
		c	263,831	440,457	37.5%	369,002	335,286	52.4%	463,957	240,331	65.9%
		d	203,658	500,630	28.9%	280,549	423,739	39.8%	364,384	339,904	51.7%
	+/- 3 hours	a	359,155	449,170	44.4%	484,605	323,720	60.0%	524,522	283,803	64.9%
		b	282,565	525,760	35.0%	376,443	431,882	46.6%	480,030	328,295	59.4%
		c	332,452	371,836	47.2%	440,546	263,742	62.6%	477,699	226,589	67.8%
		d	264,859	439,429	37.6%	347,431	356,857	49.3%	434,233	270,055	61.7%
	+/- 6 hours	a	390,171	418,154	48.3%	514,317	294,008	63.6%	631,686	176,639	78.1%
		b	318,166	490,159	39.4%	417,319	391,006	51.6%	527,030	281,295	65.2%
		c	359,287	345,001	51.0%	464,518	239,770	66.0%	559,059	145,229	79.4%
		d	296,319	407,969	42.1%	382,208	322,080	54.3%	473,261	231,027	67.2%
	+/- 12 hours	a	407,446	400,878	50.4%	532,391	275,934	65.9%	652,683	155,642	80.7%
		b	333,774	474,551	41.3%	433,569	374,756	53.6%	546,210	262,115	67.6%
		c	374,967	329,320	53.2%	480,980	223,308	68.3%	578,415	125,873	82.1%
		d	310,298	393,990	44.1%	396,485	307,803	56.3%	490,066	214,222	69.6%
2005	+/- 0.25 hours	a	135,528	654,682	17.2%	207,823	582,386	26.3%	289,045	501,165	36.6%
		b	103,146	687,064	13.1%	157,510	632,956	19.9%	224,676	565,534	28.4%
		c	116,650	475,879	19.7%	175,350	417,178	29.6%	230,817	361,712	39.0%
		d	91,102	501,427	15.4%	136,514	456,186	23.0%	185,016	407,513	31.2%
	+/- 1 hour	a	255,053	535,157	32.3%	373,013	417,196	47.2%	488,704	301,506	61.8%
		b	187,876	602,334	23.8%	269,174	521,035	34.1%	365,978	424,232	46.3%
		c	216,417	376,112	36.5%	309,589	282,939	52.2%	385,443	207,086	65.1%
		d	164,204	428,325	27.7%	230,994	361,534	39.0%	300,694	291,835	50.7%
	+/- 3 hours	a	331,244	458,966	41.9%	456,244	333,965	57.7%	575,629	214,581	72.8%
		b	251,916	538,294	31.9%	341,370	448,839	43.2%	444,995	345,215	56.3%
		c	278,741	313,788	47.0%	374,649	217,879	63.2%	452,859	139,670	76.4%
		d	217,265	375,264	36.7%	288,465	304,063	48.7%	362,194	230,335	61.1%
	+/- 6 hours	a	364,617	425,593	46.1%	488,382	301,827	61.8%	606,082	184,128	76.7%
		b	290,732	499,478	36.8%	387,856	402,353	49.1%	498,537	291,673	63.1%
		c	304,454	288,075	51.4%	396,677	195,851	66.9%	472,987	119,542	79.8%
		d	248,454	344,075	41.9%	323,941	268,587	54.7%	400,967	191,562	67.7%
	+/- 12 hours	a	385,065	405,145	48.7%	509,326	280,883	64.5%	631,182	159,028	79.9%
		b	308,893	481,317	39.1%	405,143	385,066	51.3%	517,636	272,574	65.5%
		c	322,125	270,404	54.4%	414,708	177,820	70.0%	494,941	97,588	83.5%
		d	263,583	328,946	44.5%	337,632	254,896	57.0%	415,985	176,544	70.2%

Table I.viii

Table I key

- A: GOES fire pixels with or without a MODIS fire pixel match
- B: GOES filtered fire pixels with or without a MODIS fire pixel match
- C: GOES fire pixels with low confidence fire pixels excluded with or without a
MODIS fire pixel match
- D: GOES filtered fire pixels with low confidence fire pixels excluded with or without
MODIS fire pixel match

- a: MODIS fire pixels with or without a GOES fire pixel match
- b: MODIS fire pixels with or without a GOES filtered fire pixel match
- c: MODIS fire pixels with low confidence fire pixels excluded with or without a
GOES fire pixel match
- d: MODIS fire pixels with low confidence fire pixels excluded with or without a
GOES fire pixel match

Appendix II Fire pixel match characteristic statistics

			day	hour	latitude	T ₄	zenith angle	confidence	4 μm emissivity	11 μm emissivity		
2004	+/- 0.25 hours	μ	matched fires	216.5	15.2	-5.33	319.2	27.3	80.5	0.912	0.929	
			unmatched fires	194.0	15.3	0.14	314.5	28.8	67.9	0.882	0.900	
		σ	matched fires	86.51	3.82	14.48	9.45	10.24	15.80	0.180	0.181	
			unmatched fires	100.36	3.76	18.57	8.81	13.48	18.97	0.396	0.398	
	+/- 1 hour	μ	matched fires	217.1	15.1	-5.50	319.2	27.2	80.6	0.911	0.928	
			unmatched fires	195.4	15.1	0.98	313.8	29.4	67.4	0.880	0.898	
		σ	matched fires	85.54	3.96	13.96	9.58	10.07	15.78	0.179	0.180	
			unmatched fires	100.33	4.01	18.99	9.03	13.84	18.90	0.410	0.411	
	+/- 3 hours	μ	matched fires	216.1	15.4	-5.37	318.2	27.0	80.3	0.911	0.928	
			unmatched fires	196.8	14.9	2.60	312.4	31.3	67.3	0.883	0.901	
		σ	matched fires	85.47	4.20	13.66	9.60	9.96	15.80	0.180	0.181	
			unmatched fires	98.34	4.91	20.63	9.80	15.30	18.78	0.398	0.399	
	+/- 6 hours	μ	matched fires	216.6	15.8	-5.53	317.1	26.9	80.1	0.910	0.927	
			unmatched fires	199.7	14.9	3.11	310.9	32.0	67.4	0.886	0.903	
		σ	matched fires	84.94	4.44	13.60	9.86	9.85	15.72	0.181	0.182	
			unmatched fires	97.64	5.84	21.37	10.38	16.11	18.61	0.407	0.408	
	+/- 12 hours	μ	matched fires	217.0	15.8	-5.63	316.6	26.9	80.1	0.910	0.927	
			unmatched fires	196.1	14.9	2.75	311.5	30.4	67.6	0.887	0.904	
		σ	matched fires	84.83	4.73	13.46	10.06	9.76	15.70	0.182	0.183	
			unmatched fires	100.50	5.60	20.02	10.33	15.91	18.64	0.388	0.389	
	2005	+/- 0.25 hours	μ	matched fires	206.6	15.3	-2.15	319.2	27.5	80.1	0.914	0.931
				unmatched fires	191.3	15.3	1.64	314.0	30.1	68.7	0.880	0.897
			σ	matched fires	84.97	4.0	16.43	9.42	10.8	16.00	0.174	0.174
				unmatched fires	95.09	3.7	19.70	8.49	13.6	19.07	0.374	0.376
+/- 1 hour		μ	matched fires	208.2	15.2	-2.39	319.1	27.4	80.2	0.914	0.931	
			unmatched fires	192.2	15.3	2.27	313.7	30.5	68.6	0.878	0.896	
		σ	matched fires	83.44	4.1	16.04	9.53	10.7	15.92	0.174	0.175	
			unmatched fires	93.83	3.7	19.97	8.43	14.1	19.06	0.376	0.378	
+/- 3 hours		μ	matched fires	206.2	15.5	-1.98	318.0	27.3	79.9	0.914	0.930	
			unmatched fires	191.1	15.0	4.53	312.2	32.6	67.8	0.881	0.899	
		σ	matched fires	83.11	4.5	15.86	9.60	10.7	15.91	0.175	0.175	
			unmatched fires	92.07	4.9	21.75	9.34	15.8	18.91	0.377	0.379	
+/- 6 hours		μ	matched fires	206.1	15.8	-1.99	316.9	27.3	79.7	0.913	0.930	
			unmatched fires	192.7	14.8	5.54	310.8	33.6	67.5	0.885	0.902	
		σ	matched fires	82.36	4.9	15.87	9.89	10.6	15.84	0.174	0.175	
			unmatched fires	91.57	5.9	22.67	9.88	16.9	18.68	0.397	0.398	
+/- 12 hours		μ	matched fires	206.8	15.8	-2.18	316.4	27.2	79.7	0.913	0.930	
			unmatched fires	189.7	14.9	4.89	311.3	31.9	67.6	0.885	0.903	
		σ	matched fires	82.00	5.1	15.73	10.06	10.5	15.81	0.175	0.176	
			unmatched fires	94.49	5.7	21.37	9.85	16.7	18.71	0.382	0.383	

Table II.i

Mean (μ) and standard deviation (σ) of GOES fire pixel with and without a MODIS match.

			day	hour	latitude	T ₄	scan angle	confidence	4 μm emissivity	11 μm emissivity	
2004	+/- 0.25 hours	μ	matched fires	220.7	14.9	-5.33	336.3	31.3	74.71	0.913	0.930
			unmatched fires	220.5	14.3	-5.45	325.5	27.8	61.75	0.912	0.927
		σ	matched fires	81.75	4.5	15.94	23.54	20.0	28.05	0.180	0.181
			unmatched fires	84.48	5.0	20.38	16.02	19.2	31.56	0.235	0.236
	+/- 1 hour	μ	matched fires	222.3	15.0	-6.28	334.7	31.4	72.46	0.914	0.930
			unmatched fires	218.9	14.0	-4.64	323.1	26.4	59.16	0.911	0.926
		σ	matched fires	80.53	4.4	16.07	22.44	20.0	29.07	0.183	0.183
			unmatched fires	86.45	5.2	21.63	13.38	18.8	31.62	0.250	0.251
	+/- 3 hours	μ	matched fires	222.3	14.8	-5.94	333.4	31.3	71.23	0.914	0.930
			unmatched fires	218.1	14.1	-4.71	322.1	25.4	57.69	0.910	0.925
		σ	matched fires	80.76	4.5	16.45	21.75	19.9	29.39	0.184	0.185
			unmatched fires	87.48	5.3	22.39	12.21	18.4	31.77	0.262	0.263
+/- 6 hours	μ	matched fires	222.2	14.7	-5.94	332.8	31.0	70.45	0.914	0.930	
		unmatched fires	217.8	14.1	-4.59	321.9	25.2	57.65	0.910	0.925	
	σ	matched fires	80.76	4.5	16.67	21.44	19.9	29.73	0.187	0.188	
		unmatched fires	88.10	5.4	22.61	12.09	18.4	31.72	0.264	0.265	
+/- 12 hours	μ	matched fires	222.6	14.5	-6.05	332.3	30.8	70.16	0.914	0.930	
		unmatched fires	217.0	14.5	-4.32	322.2	25.3	57.43	0.910	0.925	
	σ	matched fires	80.34	4.8	16.61	21.40	19.9	29.71	0.189	0.190	
		unmatched fires	89.10	5.1	22.95	12.05	18.4	31.92	0.266	0.267	
2005	+/- 0.25 hours	μ	matched fires	208.3	15.0	-1.48	335.7	32.0	66.6	0.915	0.932
			unmatched fires	212.7	14.1	-3.75	325.7	27.6	50.4	0.913	0.929
		σ	matched fires	80.81	4.7	18.08	22.29	20.0	33.83	0.184	0.185
			unmatched fires	84.62	5.3	19.21	16.44	19.2	36.76	0.241	0.242
	+/- 1 hour	μ	matched fires	212.3	15.0	-3.25	334.4	31.7	64.5	0.916	0.933
			unmatched fires	210.9	13.9	-3.05	323.2	26.3	46.4	0.911	0.927
		σ	matched fires	79.25	4.6	17.60	21.75	19.9	34.53	0.177	0.177
			unmatched fires	87.22	5.5	20.01	13.71	18.8	36.46	0.263	0.263
	+/- 3 hours	μ	matched fires	212.5	14.8	-3.07	333.1	31.4	62.9	0.916	0.932
			unmatched fires	210.3	13.9	-3.25	322.2	25.3	44.0	0.911	0.926
		σ	matched fires	79.60	4.8	17.58	21.12	19.9	34.87	0.192	0.193
			unmatched fires	88.64	5.5	20.58	12.54	18.4	36.28	0.266	0.267
	+/- 6 hours	μ	matched fires	212.4	14.7	-3.10	332.5	31.1	61.9	0.916	0.932
			unmatched fires	210.2	13.9	-3.21	321.9	25.1	43.6	0.911	0.926
		σ	matched fires	79.72	4.8	17.62	20.83	19.8	35.11	0.195	0.195
			unmatched fires	89.36	5.6	20.81	12.37	18.4	36.32	0.269	0.270
+/- 12 hours	μ	matched fires	213.0	14.4	-3.27	332.0	30.9	61.8	0.915	0.932	
		unmatched fires	209.1	14.3	-2.93	322.2	25.2	42.7	0.911	0.926	
	σ	matched fires	79.45	5.0	17.52	20.82	19.8	34.96	0.198	0.199	
		unmatched fires	90.31	5.4	21.14	12.16	18.4	36.47	0.269	0.270	

Table II.ii

Mean (μ) and standard deviation (σ) of MODIS fire pixel with and without a GOES match.

			day	hour	latitude	T ₄	zenith angle	confidence	4 μm emissivity	11 μm emissivity	
2004	+/- 0.25 hours	μ	matched fires	216.0	14.9	-5.57	319.8	26.8	81.5	0.911	0.928
			unmatched fires	193.6	15.5	-1.77	315.8	27.0	69.6	0.890	0.908
		σ	matched fires	83.98	4.3	13.39	9.95	9.8	15.31	0.175	0.176
			unmatched fires	98.23	3.8	15.24	8.62	12.1	19.08	0.272	0.274
	+/- 1 hour	μ	matched fires	216.2	14.9	-5.70	319.7	26.7	81.5	0.910	0.927
			unmatched fires	193.6	15.4	-1.61	315.0	27.4	69.1	0.886	0.904
		σ	matched fires	83.43	4.4	13.06	10.01	9.7	15.28	0.180	0.181
			unmatched fires	98.45	3.9	15.32	8.63	12.2	19.02	0.285	0.287
	+/- 3 hours	μ	matched fires	215.6	15.4	-5.66	318.5	26.6	81.1	0.910	0.927
			unmatched fires	197.6	15.6	-1.69	314.1	27.9	70.1	0.889	0.906
		σ	matched fires	83.45	4.6	12.95	9.97	9.7	15.32	0.179	0.180
			unmatched fires	96.94	4.6	15.55	9.03	12.3	18.88	0.280	0.281
+/- 6 hours	μ	matched fires	216.0	15.9	-5.76	317.3	26.6	80.9	0.909	0.927	
		unmatched fires	202.7	16.0	-1.87	312.8	28.1	70.9	0.893	0.911	
	σ	matched fires	83.20	4.8	12.95	10.23	9.6	15.25	0.181	0.182	
		unmatched fires	96.99	5.2	15.78	9.67	12.6	18.62	0.269	0.271	
+/- 12 hours	μ	matched fires	216.5	15.9	-5.88	316.8	26.5	80.8	0.909	0.926	
		unmatched fires	197.8	15.9	-1.48	313.4	26.9	70.6	0.893	0.911	
	σ	matched fires	83.18	5.1	12.79	10.43	9.5	15.25	0.181	0.182	
		unmatched fires	100.36	5.0	14.83	9.65	12.5	18.67	0.266	0.267	
2005	+/- 0.25 hours	μ	matched fires	209.0	15.0	-2.16	319.8	27.1	81.1	0.913	0.930
			unmatched fires	196.4	15.6	0.24	315.3	28.5	70.9	0.881	0.898
		σ	matched fires	82.04	4.5	15.82	9.96	10.7	15.47	0.167	0.168
			unmatched fires	92.53	3.6	17.21	8.12	12.4	19.05	0.312	0.314
	+/- 1 hour	μ	matched fires	208.6	15.0	-2.34	319.6	27.1	81.2	0.913	0.930
			unmatched fires	196.5	15.7	0.51	315.1	29.0	70.7	0.877	0.895
		σ	matched fires	80.74	4.6	15.61	10.04	10.6	15.39	0.172	0.173
			unmatched fires	90.41	3.5	17.46	7.79	12.6	19.05	0.322	0.324
	+/- 3 hours	μ	matched fires	206.5	15.4	-2.00	318.3	26.9	80.7	0.913	0.930
			unmatched fires	196.6	15.8	1.29	314.1	29.9	70.7	0.880	0.898
		σ	matched fires	80.75	4.9	15.57	10.04	10.5	15.42	0.172	0.173
			unmatched fires	89.30	4.4	18.25	8.44	13.3	18.94	0.312	0.314
+/- 6 hours	μ	matched fires	206.2	15.9	-1.96	317.0	26.9	80.5	0.913	0.930	
		unmatched fires	198.9	16.1	1.26	313.0	30.0	71.1	0.887	0.904	
	σ	matched fires	80.25	5.3	15.62	10.33	10.5	15.37	0.172	0.173	
		unmatched fires	89.85	5.2	18.43	9.05	13.8	18.69	0.300	0.302	
+/- 12 hours	μ	matched fires	207.1	15.9	-2.18	316.5	26.9	80.4	0.912	0.929	
		unmatched fires	194.3	16.0	1.21	313.5	28.7	70.8	0.887	0.905	
	σ	matched fires	79.85	5.5	15.46	10.48	10.4	15.34	0.173	0.174	
		unmatched fires	93.99	4.9	17.30	9.00	13.7	18.75	0.295	0.297	

Table II.iii

Mean (μ) and standard deviation (σ) of GOES filtered fire pixel with and without a MODIS match.

			day	hour	latitude	T ₄	scan angle	confidence	4 μm emissivity	11 μm emissivity	
2004	+/- 0.25 hours	μ	matched fires	220.7	14.5	-5.37	337.1	31.7	76.06	0.912	0.928
			unmatched fires	220.5	14.5	-5.43	326.2	27.9	62.47	0.913	0.928
		σ	matched fires	79.78	4.9	15.11	24.37	20.0	27.04	0.180	0.181
			unmatched fires	84.79	4.9	20.22	16.59	19.3	31.58	0.231	0.232
	+/- 1 hour	μ	matched fires	221.9	14.5	-5.67	335.5	31.7	74.13	0.912	0.928
			unmatched fires	219.8	14.4	-5.28	324.9	27.2	60.77	0.913	0.928
		σ	matched fires	79.96	4.9	15.34	23.18	20.0	27.99	0.183	0.184
			unmatched fires	85.67	4.9	21.01	15.30	19.1	31.77	0.238	0.239
	+/- 3 hours	μ	matched fires	222.0	14.4	-5.52	334.1	31.5	72.68	0.912	0.929
			unmatched fires	219.4	14.5	-5.34	324.2	26.6	59.74	0.913	0.928
		σ	matched fires	80.06	4.9	15.75	22.55	20.0	28.58	0.183	0.184
			unmatched fires	86.49	4.9	21.57	14.51	18.9	31.92	0.246	0.247
+/- 6 hours	μ	matched fires	222.2	14.4	-5.78	333.7	31.3	71.85	0.912	0.929	
		unmatched fires	219.0	14.6	-5.07	323.7	26.3	59.33	0.912	0.927	
	σ	matched fires	79.70	4.8	15.89	22.40	19.9	29.06	0.183	0.184	
		unmatched fires	87.38	5.0	21.94	13.66	18.8	31.86	0.251	0.252	
+/- 12 hours	μ	matched fires	222.5	14.2	-5.94	333.2	31.1	71.46	0.912	0.929	
		unmatched fires	218.5	14.8	-4.88	323.8	26.4	59.27	0.913	0.927	
	σ	matched fires	79.26	5.0	15.84	22.33	19.9	29.15	0.184	0.185	
		unmatched fires	88.05	4.8	22.16	13.58	18.8	31.94	0.253	0.254	
2005	+/- 0.25 hours	μ	matched fires	209.2	14.6	-1.11	336.5	32.2	68.8	0.914	0.931
			unmatched fires	212.3	14.3	-3.68	326.3	27.9	51.3	0.913	0.929
		σ	matched fires	78.02	5.1	17.87	23.06	20.0	32.68	0.181	0.182
			unmatched fires	84.85	5.1	19.16	16.85	19.3	36.79	0.237	0.238
	+/- 1 hour	μ	matched fires	211.6	14.5	-2.25	335.2	31.9	67.1	0.915	0.931
			unmatched fires	211.5	14.3	-3.60	324.9	27.2	48.4	0.913	0.929
		σ	matched fires	78.05	5.2	17.43	22.50	19.9	33.26	0.178	0.178
			unmatched fires	86.35	5.1	19.65	15.34	19.1	36.77	0.248	0.249
	+/- 3 hours	μ	matched fires	211.9	14.4	-2.22	333.8	31.7	65.3	0.915	0.931
			unmatched fires	211.3	14.4	-3.84	324.3	26.6	46.8	0.913	0.928
		σ	matched fires	78.61	5.2	17.45	21.92	19.9	33.92	0.185	0.185
			unmatched fires	87.23	5.1	19.95	14.63	18.9	36.73	0.254	0.255
+/- 6 hours	μ	matched fires	212.5	14.3	-2.63	333.4	31.5	64.2	0.915	0.931	
		unmatched fires	210.6	14.4	-3.62	323.7	26.2	45.8	0.913	0.928	
	σ	matched fires	78.22	5.1	17.41	21.78	19.9	34.30	0.191	0.191	
		unmatched fires	88.42	5.2	20.26	13.74	18.8	36.66	0.256	0.257	
+/- 12 hours	μ	matched fires	213.0	14.2	-2.83	332.9	31.3	63.8	0.915	0.931	
		unmatched fires	210.0	14.6	-3.46	323.8	26.2	45.5	0.913	0.928	
	σ	matched fires	77.94	5.2	17.33	21.70	19.9	34.31	0.192	0.192	
		unmatched fires	89.02	5.1	20.44	13.66	18.8	36.75	0.258	0.259	

Table II.iv

Mean (μ) and standard deviation (σ) of MODIS fire pixel with and without a GOES filtered match.

Appendix III Fire pixel statistical analysis

Discriminant Analysis for 2004 Western Hemisphere fire pixels

		PC	HSS	PSS	match proportion	random skill	PC - random
GOES	+/- 0.25 hour	0.672	0.730	0.357	0.399	0.520	0.151
	+/- 1 hour	0.679	0.744	0.374	0.401	0.520	0.160
	+/- 3 hour	0.674	0.766	0.376	0.390	0.524	0.149
	+/- 6 hour	0.659	0.799	0.365	0.361	0.539	0.120
	+/- 12 hour	0.652	0.827	0.356	0.334	0.555	0.096
GOES filtered	+/- 0.25 hour	0.677	0.622	0.355	0.483	0.501	0.176
	+/- 1 hour	0.691	0.610	0.381	0.508	0.500	0.191
	+/- 3 hour	0.671	0.570	0.339	0.511	0.500	0.171
	+/- 6 hour	0.645	0.569	0.297	0.482	0.501	0.145
	+/- 12 hour	0.628	0.590	0.286	0.452	0.505	0.123
MODIS	+/- 0.25 hour	0.718	0.536	0.226	0.289	0.589	0.129
	+/- 1 hour	0.675	0.625	0.350	0.476	0.501	0.174
	+/- 3 hour	0.693	0.512	0.370	0.576	0.511	0.182
	+/- 6 hour	0.698	0.466	0.372	0.613	0.525	0.173
	+/- 12 hour	0.699	0.424	0.355	0.633	0.535	0.163
MODIS filtered	+/- 0.25 hour	0.751	0.452	0.176	0.222	0.654	0.096
	+/- 1 hour	0.693	0.536	0.245	0.353	0.543	0.150
	+/- 3 hour	0.674	0.671	0.356	0.444	0.506	0.168
	+/- 6 hour	0.684	0.621	0.369	0.492	0.500	0.184
	+/- 12 hour	0.684	0.596	0.366	0.510	0.500	0.183

Table III.i

Discriminant analysis for fire pixels in the Western Hemisphere in 2004. PC indicates the proportion correctly forecast by discriminant analysis, HSS is the Hiedke Skill Score, and PSS is the Peirce Skill Score. Match proportion is the number of fire pixels with a match compared to the total number of fire pixels. Random skill indicates the proportion of fire pixels that would be correctly forecast from a forecast based only on the proportion of fire pixels with a match and proportion of fire pixels with no match.

**Discriminant Analysis for 2004 Western Hemisphere fire pixels
excluding low confidence fire pixels**

		PC	HSS	PSS	match proportion	random skill	PC - random
GOES	+/- 0.25 hour	0.627	0.459	0.241	0.531	0.502	0.125
	+/- 1 hour	0.639	0.480	0.267	0.540	0.503	0.135
	+/- 3 hour	0.625	0.483	0.247	0.524	0.501	0.124
	+/- 6 hour	0.614	0.501	0.236	0.486	0.500	0.114
	+/- 12 hour	0.610	0.544	0.236	0.456	0.504	0.106
GOES filtered	+/- 0.25 hour	0.647	0.425	0.278	0.599	0.520	0.127
	+/- 1 hour	0.663	0.294	0.210	0.628	0.533	0.130
	+/- 3 hour	0.650	0.349	0.232	0.615	0.527	0.123
	+/- 6 hour	0.631	0.404	0.231	0.573	0.511	0.121
	+/- 12 hour	0.630	0.449	0.244	0.547	0.504	0.125
MODIS	+/- 0.25 hour	0.703	0.533	0.223	0.307	0.574	0.128
	+/- 1 hour	0.676	0.600	0.353	0.499	0.500	0.176
	+/- 3 hour	0.699	0.476	0.369	0.600	0.520	0.179
	+/- 6 hour	0.704	0.436	0.374	0.635	0.536	0.168
	+/- 12 hour	0.707	0.396	0.359	0.656	0.549	0.158
MODIS filtered	+/- 0.25 hour	0.735	0.428	0.163	0.240	0.636	0.099
	+/- 1 hour	0.676	0.528	0.240	0.376	0.531	0.146
	+/- 3 hour	0.677	0.642	0.359	0.469	0.502	0.175
	+/- 6 hour	0.689	0.594	0.375	0.517	0.501	0.188
	+/- 12 hour	0.687	0.565	0.369	0.535	0.502	0.185

Table III.ii

Discriminant analysis for fire pixels, excluding low confidence fire pixels, in the Western Hemisphere in 2004. PC indicates the proportion correctly forecast by discriminant analysis, HSS is the Hiedke Skill Score, and PSS is the Peirce Skill Score. Match proportion is the number of fire pixels with a match compared to the total number of fire pixels. Random skill indicates the proportion of fire pixels that would be correctly forecast from a forecast based only on the proportion of fire pixels with a match and proportion of fire pixels with no match.

Discriminant Analysis for 2005 Western Hemisphere fire pixels

		PC	HSS	PSS	match proportion	random skill	PC - random
GOES	+/- 0.25 hour	0.675	0.741	0.353	0.384	0.527	0.147
	+/- 1 hour	0.681	0.752	0.368	0.388	0.525	0.156
	+/- 3 hour	0.667	0.774	0.360	0.370	0.534	0.133
	+/- 6 hour	0.662	0.810	0.361	0.347	0.547	0.114
	+/- 12 hour	0.655	0.832	0.352	0.323	0.562	0.093
GOES filtered	+/- 0.25 hour	0.688	0.642	0.368	0.470	0.502	0.186
	+/- 1 hour	0.688	0.618	0.374	0.494	0.500	0.188
	+/- 3 hour	0.668	0.596	0.338	0.492	0.500	0.168
	+/- 6 hour	0.645	0.585	0.298	0.472	0.502	0.144
	+/- 12 hour	0.648	0.628	0.310	0.446	0.506	0.142
MODIS	+/- 0.25 hour	0.719	0.457	0.179	0.267	0.608	0.111
	+/- 1 hour	0.671	0.614	0.330	0.462	0.503	0.169
	+/- 3 hour	0.676	0.520	0.354	0.567	0.509	0.167
	+/- 6 hour	0.679	0.396	0.292	0.608	0.523	0.156
	+/- 12 hour	0.683	0.349	0.273	0.631	0.534	0.148
MODIS filtered	+/- 0.25 hour	0.756	0.469	0.177	0.202	0.677	0.079
	+/- 1 hour	0.693	0.496	0.216	0.337	0.553	0.140
	+/- 3 hour	0.666	0.646	0.320	0.429	0.510	0.156
	+/- 6 hour	0.668	0.596	0.332	0.484	0.500	0.168
	+/- 12 hour	0.666	0.577	0.332	0.504	0.500	0.166

Table III.iii

Discriminant analysis for fire pixels in the Western Hemisphere in 2005. PC indicates the proportion correctly forecast by discriminant analysis, HSS is the Hiedke Skill Score, and PSS is the Peirce Skill Score. Match proportion is the number of fire pixels with a match compared to the total number of fire pixels. Random skill indicates the proportion of fire pixels that would be correctly forecast from a forecast based only on the proportion of fire pixels with a match and proportion of fire pixels with no match.

**Discriminant Analysis for 2005 Western Hemisphere fire pixels
excluding low confidence fire pixels**

		PC	HSS	PSS	match proportion	random skill	PC - random
GOES	+/- 0.25 hour	0.651	0.550	0.303	0.503	0.500	0.151
	+/- 1 hour	0.660	0.558	0.323	0.510	0.500	0.159
	+/- 3 hour	0.644	0.535	0.286	0.497	0.500	0.144
	+/- 6 hour	0.631	0.558	0.265	0.470	0.502	0.130
	+/- 12 hour	0.643	0.593	0.279	0.444	0.506	0.137
GOES filtered	+/- 0.25 hour	0.664	0.490	0.321	0.570	0.510	0.154
	+/- 1 hour	0.672	0.481	0.348	0.597	0.519	0.153
	+/- 3 hour	0.661	0.429	0.288	0.592	0.517	0.144
	+/- 6 hour	0.639	0.426	0.247	0.562	0.508	0.131
	+/- 12 hour	0.649	0.487	0.285	0.541	0.503	0.146

MODIS	+/- 0.25 hour	0.686	0.422	0.157	0.305	0.576	0.110
	+/- 1 hour	0.656	0.543	0.309	0.516	0.501	0.155
	+/- 3 hour	0.673	0.346	0.257	0.625	0.531	0.141
	+/- 6 hour	0.688	0.309	0.263	0.664	0.554	0.134
	+/- 12 hour	0.689	0.005	0.003	0.691	0.573	0.116
MODIS filtered	+/- 0.25 hour	0.723	0.416	0.146	0.236	0.639	0.084
	+/- 1 hour	0.656	0.654	0.289	0.389	0.525	0.131
	+/- 3 hour	0.651	0.566	0.299	0.487	0.500	0.151
	+/- 6 hour	0.660	0.519	0.317	0.544	0.504	0.156
	+/- 12 hour	0.659	0.490	0.312	0.564	0.508	0.151

Table III.iv

Discriminant analysis for fire pixels, excluding low confidence fire pixels, in the Western Hemisphere in 2005. PC indicates the proportion correctly forecast by discriminant analysis, HSS is the Hiedke Skill Score, and PSS is the Peirce Skill Score. Match proportion is the number of fire pixels with a match compared to the total number of fire pixels. Random skill indicates the proportion of fire pixels that would be correctly forecast from a forecast based only on the proportion of fire pixels with a match and proportion of fire pixels with no match.

Discriminant Analysis for 2004 Western Hemisphere fire pixels

		Predictors
GOES	+/- 0.25 hour	confidence, day, ecosystem, hour, latitude, T ₄
	+/- 1 hour	confidence, day, ecosystem, hour, latitude, T ₄
	+/- 3 hour	confidence, day, ecosystem, latitude, T ₄
	+/- 6 hour	confidence, day, ecosystem, latitude, T ₄
	+/- 12 hour	confidence, day, ecosystem, latitude, T ₄
GOES filtered	+/- 0.25 hour	confidence, continent, day, ecosystem, hour, latitude, T ₄ , zenith angle
	+/- 1 hour	confidence, continent, day, ecosystem, hour, latitude, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, T ₄ , zenith angle
	+/- 12 hour	confidence, continent, day, ecosystem, hour, latitude, T ₄ , zenith angle, 4 μm emissivity
MODIS	+/- 0.25 hour	T ₄ , zenith angle
	+/- 1 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 12 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
MODIS filtered	+/- 0.25 hour	T ₄
	+/- 1 hour	T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 12 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle

Table III.v

The predictors used for 2004 Western Hemisphere fire pixels that yield the highest proportion of fire pixels correctly identified using discriminant analysis.

Discriminant Analysis for 2004 Western Hemisphere fire pixels excluding low confidence fire pixels

		Predictors
GOES	+/- 0.25 hour	confidence, day, latitude, simple ecosystem, T ₄
	+/- 1 hour	confidence, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, T ₄ , zenith angle
	+/- 12 hour	confidence, day, ecosystem, hour, latitude, T ₄ , zenith angle
GOES filtered	+/- 0.25 hour	confidence, day, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
	+/- 1 hour	confidence, day, latitude, simple ecosystem, T ₄ , 11 μm emissivity, 4 μm emissivity
	+/- 3 hour	confidence, day, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
	+/- 6 hour	confidence, day, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 12 hour	confidence, day, hour, latitude, simple ecosystem, T ₄ , zenith angle, 4 μm emissivity
MODIS	+/- 0.25 hour	T ₄ , zenith angle
	+/- 1 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 12 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
MODIS filtered	+/- 0.25 hour	T ₄
	+/- 1 hour	T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 12 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle

Table III.vi

The predictors used for 2004 Western Hemisphere fire pixels, excluding low confidence fire pixels, that yield the highest proportion of fire pixels correctly identified using discriminant analysis.

Discriminant Analysis for 2005 Western Hemisphere fire pixels

		Predictors
GOES	+/- 0.25 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 1 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 3 hour	confidence, day, ecosystem, latitude, T ₄
	+/- 6 hour	confidence, day, ecosystem, latitude, T ₄
	+/- 12 hour	confidence, day, ecosystem, latitude, T ₄
GOES filtered	+/- 0.25 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 1 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 12 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
MODIS	+/- 0.25 hour	continent, T ₄
	+/- 1 hour	confidence, continent, day, ecosystem, hour, latitude, simplified ecosystem, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, zenith angle, 4 μm emissivity
	+/- 12 hour	confidence, continent, latitude, day, ecosystem, hour, simple ecosystem, zenith angle, 11 μm emissivity
MODIS filtered	+/- 0.25 hour	continent, T ₄
	+/- 1 hour	T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 12 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity

Table III.vii

The predictors used for 2005 Western Hemisphere fire pixels that yield the highest proportion of fire pixels correctly identified using discriminant analysis.

Discriminant Analysis for 2005 Western Hemisphere fire pixels excluding low confidence fire pixels

		Predictors
GOES	+/- 0.25 hour	confidence, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 1 hour	confidence, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, T ₄ , zenith angle
	+/- 12 hour	confidence, day, hour, T ₄ , zenith angle
GOES filtered	+/- 0.25 hour	confidence, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
	+/- 1 hour	confidence, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
	+/- 3 hour	confidence, day, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
	+/- 6 hour	confidence, day, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
	+/- 12 hour	confidence, day, hour, latitude, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
MODIS	+/- 0.25 hour	T ₄
	+/- 1 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity
	+/- 12 hour	4 μm emissivity
MODIS filtered	+/- 0.25 hour	T ₄
	+/- 1 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 3 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle
	+/- 6 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity
	+/- 12 hour	confidence, continent, day, ecosystem, hour, latitude, simple ecosystem, T ₄ , zenith angle, 11 μm emissivity, 4 μm emissivity

Table III.viii

The predictors used for 2005 Western Hemisphere fire pixels, excluding low confidence fire pixels, that yield the highest proportion of fire pixels correctly identified using discriminant analysis.

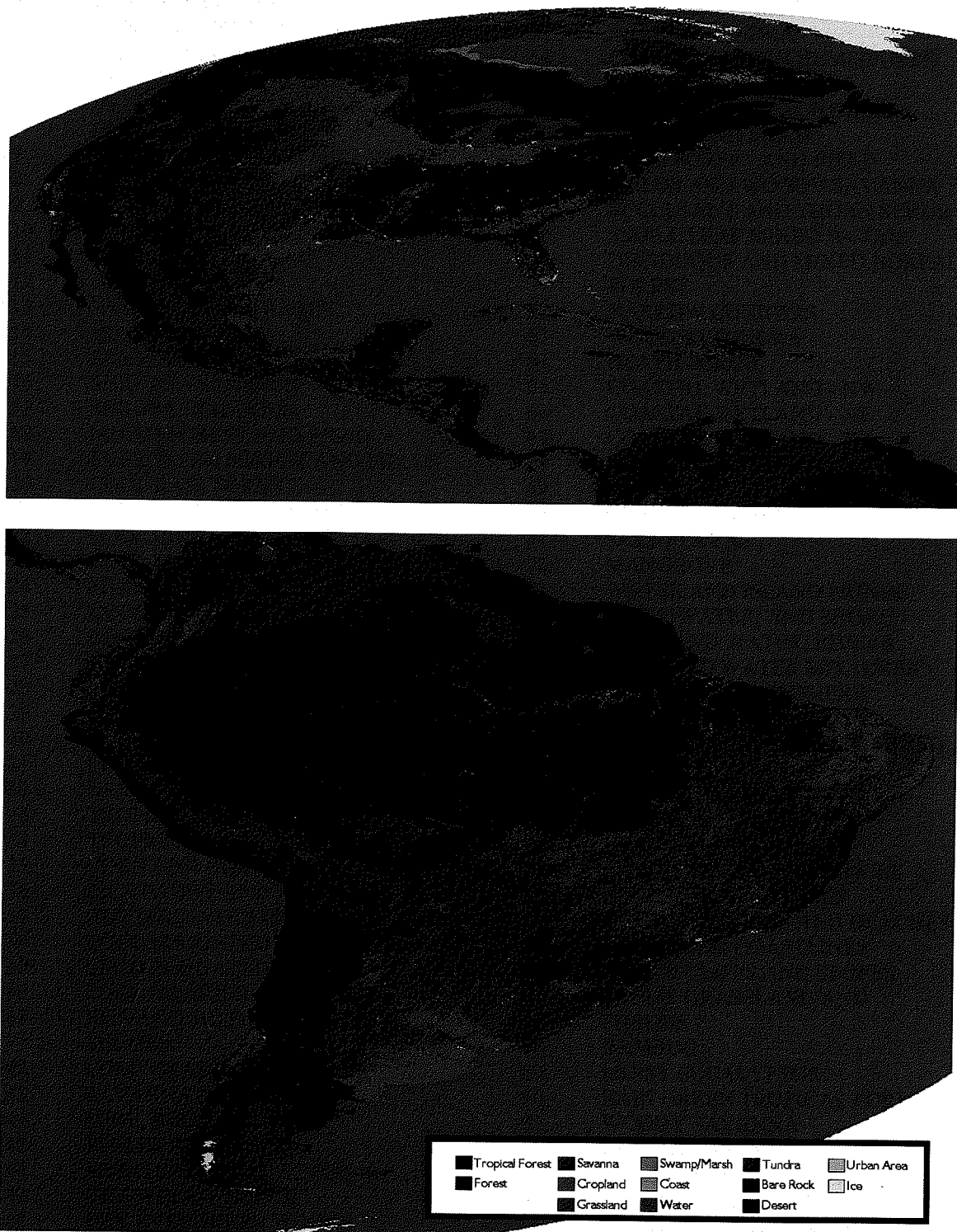
Appendix IV Ecosystem map and description

Figure IV.i
Landcover map of North America and South America

1	URBAN	51	SEMI DESERT SHRUBS
2	LOW SPARSE GRASSLAND	52	SEMI DESERT SAGE
3	CONIFEROUS FOREST	53	BARREN TUNDRA
4	DECIDUOUS CONIFER FOREST	54	COOL SOUTHERN HEMISPHERE MIXED FORESTS
5	DECIDUOUS BROADLEAF FOREST		
6	EVERGREEN BROADLEAF FORESTS	55	COOL FIELDS AND WOODS
7	TALL GRASSES AND SHRUBS	56	FOREST AND FIELD
8	BARE DESERT	57	COOL FOREST AND FIELD
9	UPLAND TUNDRA	58	FIELDS AND WOODY SAVANNA
10	IRRIGATED GRASSLAND	59	SUCCULENT AND THORN SCRUB
11	SEMI DESERT	60	SMALL LEAF MIXED WOODS
12	GLACIER ICE	61	DECIDUOUS AND MIXED BOREAL FOREST
13	WOODED WET SWAMP	62	NARROW CONIFERS
14	INLAND WATER	63	WOODED TUNDRA
15	SEA WATER	64	HEATH SCRUB
16	SHRUB EVERGREEN	65	COASTAL WETLAND - NW
17	SHRUB DECIDUOUS	66	COASTAL WETLAND - NE
18	MIXED FOREST AND FIELD	67	COASTAL WETLAND - SE
19	EVERGREEN FOREST AND FIELDS	68	COASTAL WETLAND - SW
20	COOL RAIN FOREST	69	POLAR AND ALPINE DESERT
21	CONIFER BOREAL FOREST	70	GLACIER ROCK
22	COOL CONIFER FOREST	71	SALT PLAYAS
23	COOL MIXED FOREST	72	MANGROVE
24	MIXED FOREST	73	WATER AND ISLAND FRINGE
25	COOL BROADLEAF FOREST	74	LAND, WATER, AND SHORE
26	DECIDUOUS BROADLEAF FOREST	75	LAND AND WATER, RIVERS
27	CONIFER FOREST	76	CROP AND WATER MIXTURES
28	MONTANE TROPICAL FORESTS	77	SOUTHERN HEMISPHERE CONIFERS
29	SEASONAL TROPICAL FOREST		
30	COOL CROPS AND TOWNS	78	SOUTHERN HEMISPHERE MIXED FOREST
31	CROPS AND TOWN		
32	DRY TROPICAL WOODS	79	WET SCLEROPHYLIC FOREST
33	TROPICAL RAINFOREST	80	COASTLINE FRINGE
34	TROPICAL DEGRADED FOREST	81	BEACHES AND DUNES
35	CORN AND BEANS CROPLAND	82	SPARSE DUNES AND RIDGES
36	RICE PADDY AND FIELD	83	BARE COASTAL DUNES
37	HOT IRRIGATED CROPLAND	84	RESIDUAL DUNES AND BEACHES
38	COOL IRRIGATED CROPLAND	85	COMPOUND COASTLINES
39	COLD IRRIGATED CROPLAND	86	ROCKY CLIFFS AND SLOPES
40	COOL GRASSES AND SHRUBS	87	SANDY GRASSLAND AND SHRUBS
41	HOT AND MILD GRASSES AND SHRUBS	88	BAMBOO
42	COLD GRASSLAND	89	MOIST EUCALYPTUS
43	SAVANNA (WOODS)	90	RAIN GREEN TROPICAL FOREST
44	MIRE, BOG, FEN	91	WOODY SAVANNA
45	MARSH WETLAND	92	BROADLEAF CROPS
46	MEDITERRANEAN SCRUB	93	GRASS CROPS
47	DRY WOODY SCRUB	94	CROPS, GRASS, SHRUBS
48	DRY EVERGREEN WOODS	95	EVERGREEN TREE CROP
49	VOLCANIC ROCK	96	DECIDUOUS TREE CROP
50	SAND DESERT	100	NO DATA

Table IV.i
Ecosystem category and description.

	Name	Ecosystem types
1	TROPICAL FOREST	28 29 32 33 34 90
2	FOREST	3 4 5 6 16 17 18 19 20 21 22 23 24 25 26 27 48 54 55 56 57 60 61 62 77 78 79 88 89 95 96
3	SAVANA	43 58 91
4	CROPLAND	30 31 35 36 37 38 39 76 92 93 94
5	GRASSLAND	2 7 10 40 41 42 46 47 20 59 64 87
6	SWAMP/MARSH	13 44 45 72
7	COAST	65 66 67 68 73 74 75 80 81 82 83 84 85
8	WATER (INLAND)	14
9	WATER (SEA)	15
10	TUNDRA	9 53 63 86
11	BARD ROCK	49 70
12	DESERT	8 11 50 51 52 69 71
13	URBAN	1
14	ICE	12

Table IV.ii
Simplified ecosystem category and description.

Approved: Prof. Steve Ackerman Date: 12/15/06