Estimating subpixel fire sizes and temperatures from ASTER using multiple endmember spectral mixture analysis

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Estimating subpixel fire sizes and temperatures from ASTER using multiple endmember spectral mixture analysis

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The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) shortwave infrared subsystem can acquire images of active fires during daytime and night-time from a polar orbit, providing useful data on fire properties at a nominal spatial resolution of 30 m. Binary fire/no-fire counts of ASTER pixels have also been useful in evaluating the performance of widely-used fire products from the Moderate-Resolution Imaging Spectroradiometer (MODIS), which have a nominal spatial resolution of 1 km. However, the ASTER fire pixels are actually mixed pixels that can contain flaming, smouldering and non-burning components, and ASTER fire pixel counts provide no information about the sizes or temperatures of these subpixel components. This paper uses multiple endmember spectral mixture analysis (MESMA) to estimate subpixel fire sizes and temperatures from a night-time ASTER image of a fire in California, USA, demonstrating new methods that can provide information on fires not available from other sources. As a fire’s size and its temperature exert strong influences on its gas and aerosol emissions, ecological impact and spreading rates, these MESMA estimates from ASTER imagery could contribute valuable new information towards monitoring, forecasting and understanding the behaviour and impacts of many fires worldwide.

1. Introduction

Fires play important roles in the Earth system at multiple scales, as fires are major sources of trace gases and aerosol emissions, as well as drivers of ecosystem disturbance and land-cover change. Some of the most useful datasets for monitoring fires and their effects come from the nearly identical Moderate-Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra and Aqua satellites, which can cover the entire planet multiple times each day. The ‘MODIS Thermal Anomalies/Fire (MOD14/MYD14)’ product provides fire detections from pixels with nominal spatial resolutions of 1 km, along with estimates of the total radiative power from the fires within each of these pixels (e.g. Kaufman et al. 1998, Giglio et al. 2003). However, measures of a fire’s radiative power (FRP) cannot separate a fire’s size and temperature: a small hot fire can have the same radiative power as a larger, cooler fire. Thus, FRP may not be ideal for some applications requiring precise measurements of fire sizes and temperatures, which have separate influences on a fire’s gas and aerosol emissions (Andreae and Merlet 2001), ecosystem impact (e.g. Hanley and

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Fenner 1998), and spreading rates (Pyne et al. 1996). FRP may nonetheless be suitable in many of these applications, such as for forecasting smoke emission rates, as presented in Ichoku and Kaufman (2005). However, other approaches exist that can separate a fire’s size from its temperature. For example, Dennison et al. (2006) described new methods for retrieving subpixel fire sizes and temperatures from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), a hyperspectral sensor with a high signal-to-noise ratio and ground spatial resolutions of ~4 to ~20 m, depending on aircraft altitude (Green et al. 1998). Even the ~5 m AVIRIS pixels containing fire in the image used by Dennison et al. (2006) were mixed pixels, in that they contained not only burning components but also non-burning components. This underscores the importance of attempting to analyse fire sizes and temperatures at the subpixel level, even for sensors with the spatial resolution of AVIRIS, but especially for sensors with coarser spatial resolutions. Despite the finer spatial resolution of AVIRIS, coarser-resolution sensors like MODIS are still vital to monitoring fires because AVIRIS is an airborne sensor, and thus collecting enough AVIRIS imagery for a representative sample of fires over a continental or global scale would be impractical.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) can image any point on the globe at least once every 16 days (Yamaguchi et al. 1998), and ASTER’s shortwave infrared (SWIR) subsystem can provide useful data on fires at nominal pixel sizes of 30 m, offering significantly more detail than the nominal 1 km resolution of MODIS fire products. Although ASTER typically acquires images for only a fraction of each orbit, and has suffered from recent problems with its SWIR system (Earth Remote Sensing Data Analysis Center 2008), hundreds of fires imaged by MODIS-Terra have also been imaged near-simultaneously by ASTER. Studies such as that of Morisette et al. (2005) have thus used binary fire/no-fire counts of ASTER pixels to validate MODIS fire products. However, ASTER itself is a relatively underutilized source of fire data that can provide more than just fire/no-fire detections. Prior to this paper, few studies, if any, had explored the potential for estimating subpixel fire sizes and temperatures from ASTER images. While a full understanding of fires and their regional and global impacts requires multiple sensors operating at a variety of spatial and temporal resolutions, estimates of subpixel fire properties from ASTER may represent a promising middle ground between the MODIS products, which are spatially and temporally comprehensive but at a coarse resolution, and AVIRIS, which can measure fire properties at greater precision but with a severely limited spatial coverage. The objective of this study was thus to develop and demonstrate methods for estimating subpixel fire sizes and temperatures from an ASTER image.

2. Background

Planck’s equation describes the spectral emitted radiance from a blackbody where \( T \) is the object’s kinetic temperature in Kelvin, \( h \) is Planck’s constant (6.63 \( \times \) \( 10^{-34} \) J s), \( c \) is the speed of light (3.00 \( \times \) \( 10^{8} \) m s\(^{-1} \)), \( \lambda \) is wavelength in metres, \( L_{\lambda} \) is emitted radiance at wavelength \( \lambda \), and \( k \) is Boltzmann’s constant (1.38 \( \times \) \( 10^{-23} \) J K\(^{-1} \)):

\[
L_{\lambda} = \frac{2hc^2}{\lambda^5(e^{hc/\lambda kT} - 1)}
\]  

(1)

Measured radiance \( L_{\lambda} \) for a pixel usually comprises the radiance emitted by several different objects (making it a mixed pixel) that may all have different temperatures.
Estimating subpixel fire sizes and temperatures

and spectral emissivities, instead of a single pure pixel containing only one object at a single temperature. Methods that can address this and other issues related to estimating subpixel fire properties include the analysis of FRP (Kaufman et al. 1998), the Dozier (1981) approach, and multiple endmember spectral mixture analysis (MESMA; Roberts et al. 1998).

2.1 The Dozier approach

Dozier (1981) developed a method for retrieving the sizes and temperatures of subpixel objects, which has been modified and applied widely to a variety of sensors. Dozier (1981) showed that as equation (2) exists for each band, and given at least two bands, the resulting system of equations can be solved to retrieve temperatures and subpixel areas of ‘hot’ and ‘background’ surfaces within a single pixel:

\[
L_\lambda = f_{hot}(\lambda, T_{hot}) + f_{background}(\lambda, T_{background}),
\]

where \(L_\lambda\) is measured radiance at wavelength \(\lambda\), \(f_{hot}\) is the fraction of the pixel covered by the hot surface of temperature \(T_{hot}\), \(f_{background}\) is the fraction of the pixel covered by the background surface of temperature \(T_{background}\), \(\beta(\lambda, T)\) is the Planck equation (see equation (1)), and \(f_{hot}\) and \(f_{background}\) sum to 1. Although others have modified this approach, the version presented in equation (2) assumes that the objects emit as blackbodies, and does not account for atmospheric influences on at-sensor radiance. This approach generally also requires assumptions that the pixel comprises only two objects with different temperatures, and that some of the unknowns can be constrained, such as estimating the background object’s temperature from adjacent pixels, or assuming that two adjacent pixels have the same temperatures for the hot and background objects.

2.2 The MESMA approach

Roberts et al. (1998) developed a technique called multiple endmember spectral mixture analysis (MESMA) to model a mixed pixel as a linear combination of subpixel features, called endmembers, allowing a different combination of endmembers for each pixel:

\[
L_{i\lambda} = \sum_{j=1}^{N} f_{ji} \times L_{j\lambda} + \varepsilon_{i\lambda} \quad \text{and} \quad \sum_{j=1}^{N} f_{ji} = 1,
\]

where the radiance at wavelength \(\lambda\) from a mixed pixel at location \(i\) is \(L_{i\lambda}\), which is modelled as the sum of \(N\) endmembers, \(L_{j\lambda}\), each covering a fraction \(f_{ji}\) of the pixel. The residual term \(\varepsilon_{i\lambda}\) describes the unmodelled portion of the radiance, and the chosen model for each pixel is the one that minimizes the root mean squared error (RMSE) over the included number of bands used in unmixing, \(B\):

\[
\text{RMSE} = \left[ \frac{1}{B} \sum_{k=1}^{B} (\varepsilon_{i\lambda})^2 \right]^{1/2}.
\]

While not specifically intended for application to active fires, MESMA has been used for this purpose before (Dennison et al. 2006, Eckmann et al. 2008). MESMA offers several advantages over the more commonly used Dozier (1981) and FRP approaches for measuring subpixel fire properties, as described in Dennison et al.
(2006). Perhaps the most important of these advantages is that MESMA is more flexible in the number and wavelengths of the bands it uses: ASTER does not have a band near 4 μm, which is typically required for FRP, and the Dozier approach typically uses only two bands, while MESMA can take advantage of the fact that ASTER has more than two bands that could be suitable for estimating subpixel fire properties.

3. Methods

The image selected for this study was acquired by ASTER on 15 September 2006 at 05:54:21 UTC (figure 1). This image is a night-time scene from California, USA, containing a human-caused fire burning in areas dominated by evergreen coniferous forest, with some shrubland and scattered patches of grassland and deciduous forest. Widely referred to as the ‘Sawmill’ fire, this fire started on 14 September 2006, and was declared 100% contained on 23 September 2006 after burning approximately 3008 ha (Incident Information System 2008). Both the MESMA and Dozier approaches were applied to this scene, to demonstrate the feasibility of using these approaches for estimating subpixel fire properties from ASTER, and to assess the extent to which outputs from these two approaches would be different.

A night-time fire image was selected primarily because all of the radiation measured by ASTER’s SWIR bands within the image is likely from fires, thus making the analysis more straightforward than would be the case for a daytime scene in which reflected solar radiation would also produce a considerable signal in the SWIR. Separating this reflected solar radiation from the radiation emitted by fires is difficult, and scattering of solar radiation by smoke may also be non-negligible. Fires typically burn more intensely during the day than they do at night, which, combined with the radiance from reflected solar radiation, also makes saturation of ASTER’s SWIR bands more likely in daytime images. Many significant challenges would thus make it more difficult to apply the methods from this paper to daytime scenes, which will be addressed in a future study. This is important because many fire managers and researchers may find fire

Figure 1. A band 9 (2.360–2.430 μm) image showing the portion of the ASTER scene used in this paper, which includes all of the areas visually identified as actively burning within the scene. The dashed white polygon outlines the nominal footprints of the MODIS pixels flagged as containing fire by the corresponding MOD14 product.
information from daytime scenes more useful than what is derived from night-time scenes.

ASTER’s visible/near-infrared (VNIR) bands were not used because at those wavelengths, smoke can strongly scatter emitted radiance from the surface and thus affect measurements of any burning areas obscured by smoke, whereas smoke is almost completely transparent to ASTER’s SWIR and thermal infrared (TIR) bands. ASTER’s TIR subsystem is thus also useful for measuring fire characteristics, but the emitted radiance from non-burning portions of the landscape also produces a considerable signal in ASTER’s TIR bands, so only ASTER’s SWIR bands were used for simplicity. Future research will assess the usefulness of ASTER’s TIR bands for estimating subpixel fire properties as well.

Following the methods of Dennison et al. (2006), fire endmembers for MESMA were generated from 500 to 1500 K at every 10 K step by assuming the fire to be emitting from the surface as a blackbody, and then simulating atmospheric effects on the corresponding radiance measured by ASTER using MODTRAN 4.3.1 (Berk et al. 1989). Giglio and Kendall (2001) discussed errors that may be introduced by assuming that fires emit as blackbodies, as this assumption may only be valid when the path length through the flames from the sensor’s view is approximately 6 m or longer, with shorter path lengths generally producing lower fire emissivities, and thus greater errors in retrieved fire sizes and temperatures. Although the effects may be different for MESMA, the sensitivity analysis of the Dozier approach in Giglio and Kendall (2001) found the blackbody assumption produced retrieved temperature errors of under ~20 K, but fire size errors of up to 60%, after testing a range of fire temperatures with a path length through the flames as low as ~1 m. Since Dennison et al. (2006) found this blackbody assumption to be valid for AVIRIS pixels with spatial resolutions of only ~5 m, it should also be valid for the ~30 m ASTER SWIR pixels used here, though this could be a source of error in MESMA retrievals.

Band-to-band misregistration may also cause errors in estimated fire sizes and temperatures. Shephard and Kennelly (2003) demonstrated this using a two-channel algorithm, based on the Dozier approach, to show that band-to-band co-registration errors of only 10% can produce substantial errors in estimates of subpixel fire sizes and temperatures. Iwasaki and Fujisada (2005) showed that ASTER band-to-band registration within the SWIR subsystem is often better than this, but it could still be an important source of error.

Although the present paper analyses individual pixels from ASTER, Zhukov et al. (2006) demonstrated how analysing clusters of fire pixels, instead of individual pixels, could eliminate the effects of band-to-band co-registration errors for the Bi-spectral InfraRed Detection (BIRD) satellite. The effects of co-registration errors vary with factors such as the fire’s size relative to the sensor’s resolution, and may be different for the MESMA approach because it uses more channels. Fortunately, uncertainties from band-to-band co-registration errors should produce random errors, not biases, in the fire sizes and temperatures retrieved by MESMA. Thus, these errors may be significant for a single pixel, but could essentially be cancelled out in calculating averages for samples of many pixels, such as would likely be used in studies of fire emissions over large areas or long periods.

Table 1 lists the MODTRAN settings used in generating the fire endmembers. All of these settings are based upon information that could be available in near real-time for virtually every ASTER scene, day and night, partially from the MODIS products listed in table 2, which are automatically generated for virtually every MODIS
granule. For example, metadata files for ASTER and MODIS supply pixel geolocation, sensor zenith angle, solar zenith angle, and ground altitude, and the MOD07 product supplies total-column precipitable water vapour, using the thermal-infrared method which works in daytime and night-time (King et al. 2003). The settings used in MODTRAN for these parameters were median values for the area of the ASTER scene in figure 1. These values are appropriate in generating fire endmembers for ASTER and MODIS because both ASTER and MODIS-Terra are on the same platform, and thus viewing angles and atmospheric properties are virtually identical for any ground area viewed near-simultaneously by the two sensors. These at-sensor fire endmembers were then resampled separately to the spectral responses of each ASTER band (figure 2).

Table 1. Settings used for generating fire endmembers with MODTRAN 4.3.1, taken primarily from the datasets listed in table 2.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date &amp; time</td>
<td>15 September 2006 at 05:54:21 UTC</td>
</tr>
<tr>
<td>Target latitude &amp; longitude</td>
<td>37.77° N, 118.39° W</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Mid-latitude summer</td>
</tr>
<tr>
<td>Extinction model</td>
<td>Rural extinction, 5 km visibility</td>
</tr>
<tr>
<td>Precipitable water vapour</td>
<td>0.503 cm (total-column)</td>
</tr>
<tr>
<td>Column carbon dioxide</td>
<td>385 ppm (from climatology)</td>
</tr>
<tr>
<td>Ground altitude</td>
<td>1.985 km</td>
</tr>
<tr>
<td>Sensor altitude</td>
<td>705 km</td>
</tr>
<tr>
<td>Sensor zenith angle</td>
<td>6.06° off nadir</td>
</tr>
<tr>
<td>Solar zenith angle</td>
<td>Sun below horizon (night-time)</td>
</tr>
</tbody>
</table>

Table 2. All the files and bands/data used from each file in this study, which were obtained from the Land Processes Distributed Active Archive Center (LP DAAC), located at the US Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS), and from NASA’s Level 1 and Atmosphere Archive and Distribution System (LAADS). All of these files were from the most recent collection versions available to the public at the time of this study. The * in each filename represents the processing date and time, which could vary because some of these products may be regenerated when ordered.

<table>
<thead>
<tr>
<th>Filename</th>
<th>Bands/data used</th>
</tr>
</thead>
<tbody>
<tr>
<td>AST_L1A_00309152006055421_*.hdf</td>
<td>ASTER geolocation data, sensor zenith angle, solar zenith angle, ground altitude, and swath-perspective at-sensor radiance, using the bands listed to the right</td>
</tr>
<tr>
<td>MOD03.A2006258.0550.005*.hdf</td>
<td>MODIS geolocation data, sensor zenith angle, solar zenith angle, ground altitude as ‘height above geoid’</td>
</tr>
<tr>
<td>MOD07_L2.A2006258.0550.005*.hdf</td>
<td>Total-column precipitable water vapour from the MODIS thermal-infrared method</td>
</tr>
<tr>
<td>MOD14.A2006258.0550.005*.hdf</td>
<td>Locations of MODIS pixels flagged as containing fire</td>
</tr>
</tbody>
</table>
To avoid confusion with sensor noise, only pixels with band 9 (2.360–2.430 μm) radiances of 0.5 W m\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\) and above were unmixed, as manual inspection revealed that pixels with radiances below this threshold appeared to contain only sensor noise and no burning areas (figure 1). Band 9 was chosen for this threshold to facilitate comparisons with Morisette et al. (2005), who used a band 9 radiance threshold for making fire detection masks from ASTER data. ASTER acquired the image in figure 1 with its SWIR subsystem in the ‘normal’ gain setting, which is described in Yamaguchi et al. (1998). Under this gain setting, many possible combinations of subpixel fire sizes and temperatures could saturate one or several of ASTER’s six SWIR bands (figure 3). Estimates of subpixel fire properties from the Dozier, FRP, and MESMA approaches would likely be inaccurate if saturated values were included in their calculations. Thus, only ASTER bands 4, 5, 6, and 7 were used

Figure 2. Examples of the fire endmembers generated using MODTRAN to simulate at-sensor radiance for the ASTER scene used in this paper (figure 1), for various surface temperatures (in K), before (a) and after (b) resampling to the spectral responses of each ASTER band. Endmembers were created using the settings in table 1, for every 10 K step from 500 to 1500 K, but only some of these are graphed here for clarity.
in the MESMA algorithm applied here, in order to minimize the number of pixels that were unavailable due to saturation while still providing enough bands to contain some information on spectral shape. Pixels that were saturated in any of those four included bands were not unmixed. This resulted in the exclusion of 426 pixels from unmixing, which is 4.0% of the total number of pixels at or above the band 9 radiance threshold of 0.5 W m$^{-2}$ µm$^{-1}$ sr$^{-1}$ used here.

MESMA thus unmixed the ASTER scene in figure 1, using one fire endmember for each ASTER SWIR pixel, and one background endmember containing zero radiance at all included wavelengths, which is appropriate because apart from slight sensor noise, non-burning areas in this night-time scene have essentially zero recorded radiance in the ASTER SWIR bands. The Dozier approach was also applied to this scene, assuming zero radiance from the non-burning (background) portion of each pixel, and using ASTER bands 4 and 7. These bands were chosen to maximize the spectral separation of the two bands used in the Dozier approach, and thus presumably the accuracy of the Dozier approach’s results, while remaining within the subset of bands employed for MESMA unmixing to facilitate comparisons between the two approaches. Atmospheric correction settings for the Dozier approach were also kept the same as those used for the MESMA approach (table 1).

4. Results and discussion

While the authors are not aware of any suitable data to assess the accuracy of the results presented here, as is common in studies involving remote sensing of active fire properties (e.g. Dennison et al. 2006), the temperatures modelled by MESMA are within the ranges expected for a fire of this type (figure 4; Pyne et al. 1996). The temperature maxima occur generally near the perimeters of the burning areas, suggesting the positions of the flaming fronts. Significant non-systematic spatial variation exists in the temperature distribution as well, with some of the hotter

Figure 3. Combinations of subpixel fire sizes and temperatures above which the ASTER SWIR bands would be at maximum input radiance in their normal gain setting, using values from Arai and Tonooka (2005) and the fire endmembers generated for this scene (figure 2). This assumes no radiance from the background portion of the pixel, which is a fairly realistic assumption for ASTER SWIR bands at night. This also assumes only a single fire temperature in each pixel.
temperatures occurring in the interior of some burning areas in addition to the perimeters, which is also present in the AVIRIS image of southern California’s Simi fire unmixed by Dennison et al. (2006). The Simi AVIRIS image contained generally larger subpixel fire sizes than are present in the Sawmill fire (figure 4), but after accounting for the difference in pixel sizes between that AVIRIS image (∼5 m) and

Figure 4. Fire temperature (a), fire size (b), and RMSE (c) from the MESMA unmixing of the ASTER scene described in this paper (also see figure 1). Pixels with saturated values in any of the four bands used for unmixing were excluded, as indicated.
the ASTER scene in figure 4 (~30 m), this discrepancy in subpixel fire sizes may be reasonable. For both sensors, and especially for the ASTER results presented here, the need for analysing fire properties at the subpixel level is apparent, as most pixels that contain fire include fire components covering only a very small fraction of the size of the pixel.

One potentially useful metric of relative uncertainty in the MESMA results presented in this paper is the RMSE value, described in equation (4) and displayed in figure 4. As was the case in the AVIRIS image from Dennison et al. (2006), RMSE values for this ASTER scene were generally higher where radiances were higher (compare figures 1 and 4). Figure 5 displays spectra measured by ASTER as compared with spectra modelled by MESMA for examples of different fire temperatures and sizes, along with the RMSE for these pixels. Some discrepancies exist between measured and modelled spectra, likely due to imperfections in the atmospheric correction and fire components of multiple temperatures within each pixel. However, the modelled spectra show generally good agreement with the measured spectra for these examples. This is particularly noteworthy as figure 5 shows a generally good match between measured and modelled spectra for all six of ASTER’s SWIR bands, whereas MESMA used only bands 4, 5, 6, and 7 for fitting the spectra. As modelled spectra from MESMA show generally good agreement with measured spectra for bands 8 and 9 as well, this indicates the results for these examples are physically reasonable, instead of merely good fits with the input data.

Figure 6 compares MESMA output to results from applying the Dozier approach to the same data. The two approaches agree closely for most of the pixels in the image, but also exhibit some substantial departures. For example, figure 6 shows areas where the estimated fire temperatures from MESMA were over 200 K hotter than the temperatures from the Dozier approach, and likewise some areas where MESMA estimates were over 200 K cooler. Discrepancies in fire sizes were over 1% of the size of a pixel in some areas. Although no suitable validation data exist for this scene to assess which approach is more accurate, the fact that MESMA takes advantage of a greater amount of available information suggests that it may be a superior approach in some respects. Since the two approaches produced such different results in some cases, it may be worthwhile for future studies to apply both approaches and compare their results, especially in cases where validation data are available.

Sources of uncertainty in applying MESMA or the Dozier approach to ASTER fire images could include reflected solar radiation for daytime scenes, multiple fire components of different temperatures within each ASTER pixel, ground cover such as trees obscuring ASTER’s view of surface burning, and clouds, which are mostly opaque in all of ASTER’s bands. Fortunately, clouds and sunlight did not interfere with the analyses presented here. Saturation can also be a source of uncertainty as it can reduce the number of ASTER bands available for analysis using MESMA, making MESMA ineffective for some of the brightest pixels because MESMA requires several unsaturated bands for accurate modelling. The MESMA approach could work with as few as two bands, though this would likely produce no significant advantages over the Dozier approach, which also uses two bands. ASTER’s lower gain modes, described in Arai and Tonooka (2005), could allow some fires in daytime and night-time conditions to be imaged without saturating ASTER’s SWIR bands, though some particularly hot and large fires may still produce saturated pixels even using ASTER’s lowest gain settings.
Figure 5. Comparisons of measured spectra versus spectra modelled by MESMA, for examples of pixels modelled as containing a relatively cool fire \((a)\), a warmer fire \((b)\), and a relatively hot fire \((c)\) from the scene in figure 1. MESMA fits and RMSE were computed using only bands 4, 5, 6, and 7, though bands 8 and 9 are also displayed here.
Full evaluation of the approaches presented in this paper will require many ASTER scenes from a variety of fire regimes and conditions, and on-the-ground validation data, but it appears that estimating subpixel fire sizes and temperatures from some ASTER scenes may be feasible. These subpixel estimates could potentially provide more information for assessing the performance of MODIS fire products than is available from the binary fire/no-fire counts used by Morisette et al. (2005) and similar studies. Data from ASTER and MODIS can support studies on the roles of fires in the carbon cycle at various scales, and possibly reduce some of the large uncertainties in studies that estimate gas or aerosol emissions from fires using remotely-sensed active fire data. For example, Wiedinmyer and Neff (2007) predicted their uncertainties in estimating CO$_2$ from fires in the United States to be larger than a factor of two. Estimates of subpixel fire sizes and temperatures from ASTER can also provide initialization and validation data for fire spread modelling, which could be especially useful for modelling complex fire behaviour (e.g. Colman and Linn 2007). Thus, the new methods presented in this paper could lead towards improved monitoring and understanding of fires and their effects, and possibly help to reduce the hazards that fires can pose to property and health.

Figure 6. Difference in fire temperature (a) and fire size (b), from estimates using the MESMA method minus estimates using the Dozier method, for the ASTER scene described in this paper (also see figure 4).
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