2.14 Development of Fire Emissions Inventory Using Satellite Data

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Abstract There are multiple satellites observing and reporting fire imagery at various spatial and temporal resolutions and each system has inherent strengths and limitations. In this study, data are acquired from the Moderate Resolution Imaging Spectro-radiometer (MODIS) aboard the National Aeronautics & Space Administration's (NASA's) Earth Observing System satellites. The MODIS-equipped satellite is polar orbiting with one daytime equatorial crossing and a 1-km^2 resolution product. Fire-counts are obtained from two MODIS instruments aboard two different satellites having 10:30 AM and 1:30 PM equatorial crossing time, respectively. Here, a general methodology of processing the MODIS data is provided. An effective area burned estimate, obtained using the MODIS fire count product, is compared with fire occurrence and area burned estimates obtained independently from a 2002 ground-based fire database. Successful development and application of this technique for characterizing fire emissions in the United States (U.S.) could enhance the development of techniques for characterization of fire emissions for air quality modeling and its applications.

Keywords Air quality, fire emissions, satellite observations of fires

1. Introduction

Quantitative information about the spatio-temporal distribution of wildfires is indispensable to fire-ecology, wildlife and forestry management, as well as air quality management. Vegetation fires emit substantial amounts of carbon dioxide (CO_2), carbon-monoxide (CO), methane (CH_4), and nitrogen oxides (NOx). Emissions from biomass burning affect ambient concentrations of $PM_{2.5}$, ozone (O_3), air toxics, and regional haze. Fires contributed about 30% of the $PM_{2.5}$ primary emissions (Pace and Pouliot, 2007) in the U.S. Environmental Protection Agency's (EPA's) 2002 National Emissions Inventory (NEI). Prior to 2002, characterization of fires in emissions inventory developmental activities was not time- and location-specific. Annual emissions at the State level were apportioned to county-level (Pace, 2007). Inadequate spatial and temporal characterization of fires in the emissions inventory could lead to potentially ineffective plans for improving air quality.

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Hence, we strive in this project to improve the emission estimation methods for fires in the emission inventory to ensure that most appropriate air quality management decisions are made and are supported effectively by air quality modeling activities.

Wildfire detection from space has been discussed by Cahoon et al. (2000) and Kaufman et al. (1990a, b). This project evolved from an initial study on wildfire emissions modeling that was initiated using the Blue-sky modeling framework (Pouliot et al., 2005). We enhanced the initial study by making use of the two sets of MODIS fire observations from sensors aboard the Terra satellite at 10:30 AM equatorial crossing time and Aqua satellite with 1:30 PM equatorial crossing time over the continental United States (CONUS). The combined map is produced on a daily basis for emissions inventory purposes. In this project, the fire count data product was obtained from the MODIS sensors using the rapid response contextual algorithm (Giglio et al., 2003), the mid-infra red, and the thermal infra-red bands (Justice et al., 2002). An attempt was made previously to incorporate MODIS fire counts using a technique (Justice et al., 2002) to reallocate the year 2001 NEI emissions estimates and to check the model performance in terms of its prediction of total carbon and particulate fine-mass in the surface layer. We have already seen an improvement in chemical transport model's performance with MODIS-enhanced temporal and spatial resolution of the emissions from wildfires (Roy et al., 2007).

In the present study, we have advanced these techniques by generating biomass-burning emissions directly using the MODIS fire counts after establishing a reliable relationship between the MODIS pixel counts and the ground observed area burned estimates from the 2002 emission inventory (U.S. EPA, 2007). In 1990, the United States Congress amended the Clean Air Act (CAA) to require the EPA to address the regional haze problem, which is caused by emission of air pollutants from numerous sources located over a wide geographic region. As result of the Regional Haze Rule, five Regional Planning Organizations were formed across the United States to coordinate the affected states and tribes. The Regional Planning Organizations conducted an extensive effort to locate the size and timing of fires across the United States (U.S.). The results of this effort were incorporated into the 2002 National Emission Inventory (US EPA, 2007). The 2002 NEI provided ground-truth for the assessment and application of the MODIS data. Since the MODIS data from both Aqua and Terra instruments were only available for the August–December 2002 period, we concentrated our efforts on data for this period.

A suitable clustering technique is applied to produce daily maps of clustered fire counts over the CONUS before establishing the relationship between fire count and area burned. In order to develop a fire inventory, we consider the rapid response fire count product from the two MODIS instruments. The MODIS is a cross-track sensor and, because of the bow-tie effect, the dimensions of the remotely sensed pixel increases with swath angle; hence, the modified scan and track dimensions exceed the 1 km^2 regular pixel size which occurs only at the nadir. We have noticed that the pixel area sensed by MODIS increases monotonically with the total number of pixels clustered for each fire location.

The minimum detectable fire size with 100% probability of detection is 100 m^2 when the satellite is directly over the fire (nadir view); whereas for the non-nadir view, the probability of detection is 50% and the minimum detectable size is 50 m^2. Section 2 of the paper describes how MODIS fire counts are related to the ground-observed, and area burned estimates. The area burned per pixel count for various fire categories is described as well as the methodology of using the area burned per pixel information to obtain the emission rates in the inventory. In Section 2, we also provide a case study using the large Biscuit fire that occurred during the summer period of year 2002 in the state of Oregon. Section 3 provides a summary of this newly developed method and also provides some suggestions about potential improvement using multiple satellite products.

2. Relationship Between Fire Count and Area Burned

2.1. Creation of clustered fire count map for estimation of burned area per MODIS pixel

Our interest is the whole domain of the CONUS; hence, we need to allocate both the MODIS and NEI data at the 12 × 12 km horizontal grids. For the purpose of clustering, we have developed a scheme that first accumulates the pixel counts over all the grid cells that contain at least one candidate fire event based on the 2002 NEI, and then we integrate the daily MODIS pixel counts over all the days of the fire. This is represented by the following formula where Np is the accumulated pixel count, L is the life-time of the fire, and n is the total number of pixels registered over a period of one day at the fire location.

$$N_p = \sum_{fireday=1}^{L} \sum_{1}^{n} N \quad (1)$$

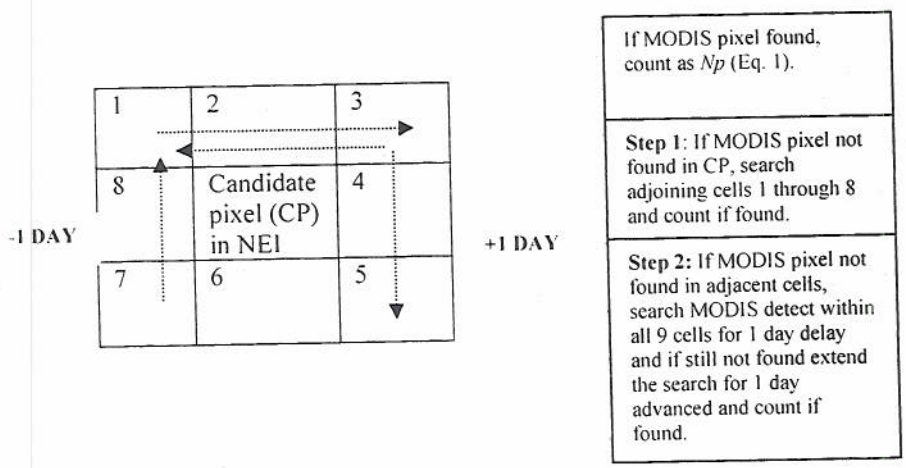

Fig. 1 The scheme for MODIS clustering using Eq. (1) and match-up with ground reports using the 12 km grid

There is an adjacency test done for each observed fire pixel (candidate fire in the 2002 NEI). MODIS data are searched first within the target area; if not found, then a search is done for detects in all the adjoining eight pixels as Step 1; then, if not found, Step 2 is exercised by repeating Step 1 but using a map for the previous and/or the next day. This is done to assure all appropriate fire counts are considered. The counting method is summarized in the schematic as shown below:

For processing purposes, we define three types of fires – "large" fires for size >10,000 acres per month; "medium" fires for sizes between 1,000 to 10,000 acres per month; and "small" fires for sizes <1,000 acres per month. In order to combine the ground based data with the MODIS data, we check the NEI to locate "large," "medium," and "small" fires and remove the duplicate detects occurring on the same day and over same location from the MODIS data set. For large fires, we match MODIS pixels with an NEI fire using the Federal Information Processing Standards (FIPS) code and the date. For small and medium fires, we match MODIS pixels with the NEI fire based on a 12 km gridded domain and then follow the test for obtaining a "match" of the fire following the method described in Figure 1. Then, we examine the land-use data in the area of the unmatched MODIS pixels. If the land-use is greater than 25% agriculture, then we assign the fire as an agricultural fire. This process results in the fire inventory being divided into five groups: (a) "large" fires with matching MODIS pixels and NEI acreage, (b) "small" and "medium" fires with matching MODIS pixels and NEI acreage, (c) "unmatched" NEI fires, (d) "unmatched" MODIS pixels that are assigned as agricultural fires, and (e) "unmatched" MODIS pixels that are not agricultural burning. The $PM_{2.5}$ emissions and acres burned for each category of fire are shown for all months of year 2002 in Figure 2 below. There are many unmatched cases in the MODIS-NEI data set. Soja et al. (2007) found 50% coincidence in MODIS and NEI data in Oregon and 20% coincidence in Arizona (coincidence criteria: 3 km distance between areas, time expanded four days on the beginning and end of NEI data range). However, because larger fires are detected, the area burned within the 50 and 20% of the number of fires is 97 and 69% of the wildland fires in Oregon and Arizona, respectively. There are several reasons for these discrepancies. First, MODIS instruments are overhead only 1 per day (2 instruments + 1 nighttime overpass = 4 total overpasses per day), although there is some overlap, particularly at higher latitudes. The instruments can not capture fires that burn when they are not overhead, particularly short-lived and/or agricultural fires. Additionally, cloud cover, high background temperatures, solar reflectance and thick canopy cover can obscure the instruments ability to detect fire (Flannigan et al., 1986; Robinson, 1991; Soja et al., 2004). Secondly, there are imperfections in the NEI ground-based data, which include errors in the dates and locations of recorded fire wildfires that vary by state. Some states have excellent records, others did not require precise record keeping, and others recorded many fires at the county centroid.

Additionally, the location for non-federal rangeland burning is not correct, although the area burned estimates are correct (NEI reference). Nonetheless, we believe the NEI data is the best area burned data available in the US, which when paired with satellite data can help improve emission estimates.

There are particular discrepancies in prescribed and managed fires in the outheastern (SE) states that require additional detailed analysis. Hence, for the SE ʼgion, we classify the unmatched area burned to prescribed and managed burns. 'or the 'unmatched' cases for other regions, we consider them as 'wildfires' For he agricultural burns, we use the fire related NEI emissions reallocation using the MODIS pixel counts as described in Roy et al. (2007).

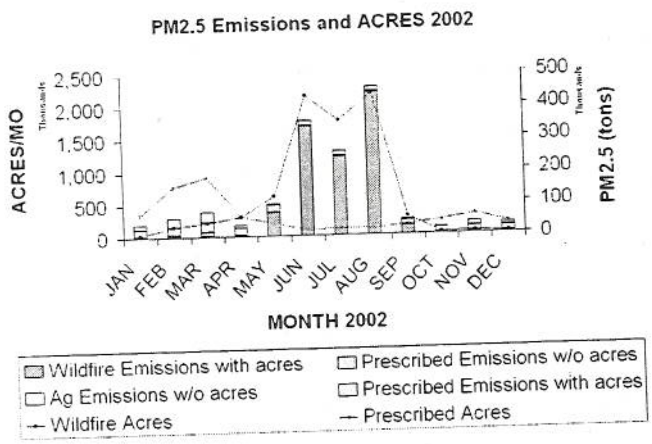

Fig. 2 The burned area in acres per month and corresponding $PM_{2.5}$ emissions (tons) for the different groups of the NEI fire inventory

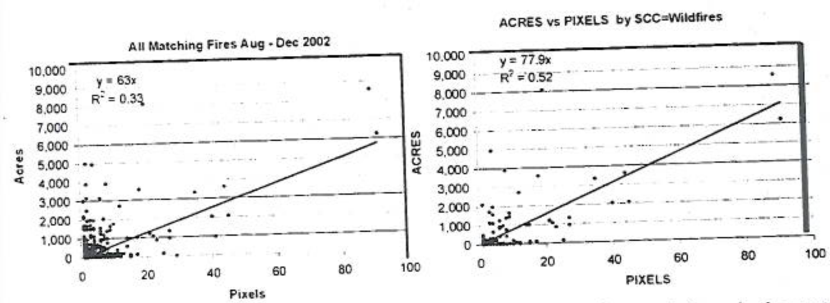

Fig. 3 (a) Scatter plot for NEI burned area (in acres) versus MODIS cumulative pixel count (N_p) by considering all fires in August–December 2002. (b) same as 4(a) but, scatter plot for the fires having Source Classification Codes (SCC) as 'wildfire' in the inventory

Using the matching methodology described above, the acres burned per pixel by region and month are estimated for the large, medium, and small fires, respectively. For the year 2002, we have analyzed the August–December 2002 NEI and obtained the burned area in acres per pixel on a per fire basis during the whole period. Figure 3 displays the relationship between the area burned from NEI data and MODIS pixel counts for all fires for the five month period.

Figure 3a shows the linear-fit between the NEI burned area versus MODIS pixel count and Figure 3b shows a similar relationship for the select fires that have the source classification codes as "wildfire" in the NEI. The correlation improves for the wildfire case alone, and the acres per pixel changes from 63 for all fires to 77 for wildfires. We could improve the correlation further by doing the computation on a per fire basis and by excluding the fires that are "partially" detected by MODIS. i.e., the fires whose lifetime as detected by MODIS do not match up with the NEI data even if the locations match up well. For small fires (<200 acres), it is difficult to establish the relationship (as shown in Figure 3a) since the MODIS frequently loses its detection capability due to its restricted field of view (Giglio et al., 2003). Hence, we will rely mostly on the ground reports for these small size fires. For the entire CONUS there were 65% of MODIS pixels that matched up with the ground reports, and in terms of area wild fire related area burned, MODIS matched up with approximately 91% of the total burned area acreage reported in the NEI.

2.2. Using burned area per MODIS pixel for emissions estimate

Once *Np* is ascertained for each ground reported fire, then the daily area burned, *A(i,t)*, in a spatial region (labeled by index '*i*') and during a fixed time period (labeled by index '*t*') could be calculated using the following equation where α is the constant of proportionality (acres burned per MODIS pixel count):

$$A(i,t) = \alpha N_p(i,t) \tag{2}$$

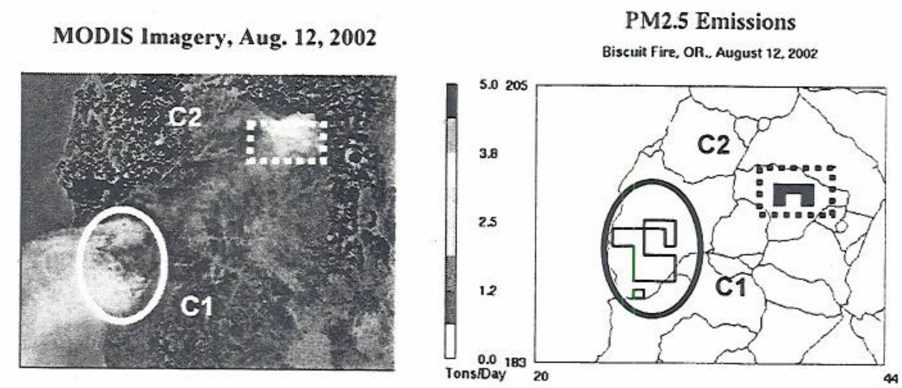

Fig. 4 Left panel shows the MODIS imagery captured on August 12 (Image courtesy: NASA http://veimages.gsfc.nasa.gov/3448/California.A2002224.jpg), 2002, and the right panel shows the fine mass ($PM_{2.5}$) emissions obtained from the Biscuit fire in Oregon. The circles and the squares represent respective fire clusters that match with the imagery

Comparing Figure 3a with b showing the linear fit between the NEI derived area burned and MODIS pixel counts, we can see that the correlation between area burned and MODIS fire count has improved when handling only wildfires. All fire ases include the prescribed (managed) and agricultural burns for which MODIS oes not detect as well. The emission rate (in grams per second) can then be stimated using the following equation:

$$Emission = Emission\,factor \times Fire\,Area \times Fuel\,loading \quad (3)$$

missions are calculated in grams per day while using emission factor is grams ollutant emitted per kilogram (kg) of material burned, fire size burned expressed s km^2 per day, and fuel-loading expressed in the units of kilograms per square kilometers. By applying these techniques, an emission inventory of fire emissions can be developed with better spatial and temporal resolution and with better estimates of emissions than has ever been compiled before. Using $A(i,t)$ as calculated based on Eq. (2) for a large fire case (Biscuit fire, July 14–31, 2002), we are able to compute the fine mass ($PM_{2.5}$) emission rates using Eq. (3). $PM_{2.5}$ emissions from the Biscuit fire in tons per day (the right panel in Figure 4) is shown along with the MODIS image acquired on the same day. Cumulative area for each cluster (C1 and C2 respectively) are used for $PM_{2.5}$ emission rates. Note that the $PM_{2.5}$ emissions from cluster C2 is higher than cluster C1. This is because the integrated area burned per day for the cluster C2 is higher than the cluster C1.

3. Summary

We have attempted to explore the relationship between the fire areas burned (including wild fires, prescribed fires, managed fires, and agricultural burns) with the MODIS fire count product and the 2002 NEI. From this relationship, we can use the MODIS fire count product to improve the NEI reporting for other years. We initially processed the MODIS data so that the data are clustered on a per fire basis. For this procedure, we identified a reasonably robust technique after determining that we have high confidence in the MODIS rapid response product. We illustrated that MODIS fire detect information can improve spatial and temporal allocation of emissions from large fires with a high degree of confidence. The NEI is suspected to have some inconsistencies especially for small fires. Nevertheless, the relationship can be applied to provide a temporal and spatial estimate of emissions from all fires, including small fires. Thus, we have developed a technique to improve the characterization of fires in the emission inventory which will enable improvements in air quality modeling for fine particles, regional haze, ozone, air toxics, and other applications.

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Discussion

... Venkatram: Could you comment on the uncertainty in the emission factor for $PM_{2.5}$ from fires?

... Mobley: Additional work on emission factors for $PM_{2.5}$ and other species is needed. Specifically, the $PM_{2.5}$ emission factors for most source categories, including fires, need improvement. Thus, I would classify the uncertainty as relatively high. Nevertheless, I am gratified that we now have the capability to estimate emissions from fires on a near real time basis and can utilize this information in emissions as well as air quality modeling activities. With application of this data, we can determine the importance and priority for better emission estimates which can help justify the resources for improving emission factors for fires.