

# **A pilot study of emission estimates of CO and Aerosols from wildland fires and their validation**

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## **Abstract:**

Forest fires are a major contributor of air pollutants like CO, Aerosols, and Ozone etc. Study of air pollutants due to forest fire becomes important when there's a significant amount of urbanization in the near vicinity of the forested land. Any increase in air pollutants above the EPA specified norms, as a result of forest fires will adversely affect the population near the source region. In the current study the Impassable fire which occurred in March of 2004 has been taken. This study focuses on the effect a forest fire of large magnitude fire had on the Carbon Monoxide concentration and PM<sub>2.5</sub> concentration and the plume dispersion pattern. A mesoscale model was used along with remote sensing data products to calculate the concentration and the plume behavior. Hourly ground station data measurements by Environmental Protection Agency (EPA) and satellite images were used to validate the model results.

## **Introduction:**

Forest fires release gaseous pollutants and considerable amount of particulate matter into the atmosphere which can alter the atmospheric radiation budget. The changes in the atmospheric radiation budget occur primarily due to multiple scattering due to the presence of aerosols and other gases. Carbon Monoxide and Carbon Dioxide are the major carbon containing compounds released by biomass combustion, it has been seen that more than 95% of carbon emitted by biomass burning is in the form either Carbon Monoxide or Carbon Dioxide (Radojevic, 2003).

Carbon monoxide is an important trace gas in the atmosphere and which plays a significant role in atmospheric chemistry. CO substantially affects the budgets of hydroxyl radicals and ozone, two of the most important constituent in the troposphere (Jane et al., 2005) It has been documented that biomass burning accounts for about one quarter of CO emission in the atmosphere with an average of around 600 Mt CO per year (Khalil et al., 1999).

Most emissions take place during the flaming and smoldering stages. These two processes are quite different in appearance, types of chemical reactions involved, and products emitted. The flaming stage is characterized by high temperatures and visible flames, while temperatures are much lower during smoldering and the fire burns without any visible flames. CO can form in fuel-rich parts of the flame and at temperatures too low for the formation of OH radicals. Flaming takes place under high oxygen concentrations (Radojevic, 2003). Compared to other areas in the world, like the Savannas, or the Tropics biomass burning in North America does not produces significant Carbon Monoxide emission from vegetation fires, but it does have sizeable impacts on the air quality in the continent. Along with the presence of suitable transport mechanism it can affect a larger area than the source region, as it has been seen that severe forest fires in Canada in 1995 led to increased CO levels in the United States (Wotawa & Trainer, 2000). Carbon Monoxide emission from forest fires in fires occurring at a heavily populated areas can be relatively less compared to the anthropogenic sources of Carbon Monoxide due to vehicular emissions, household heating and industrial sources, where as Carbon Monoxide emissions due to forest fire in some areas of Amazons or African regions can be least influenced by sources other than the fires. Aerosols are present in the atmosphere in different sizes and chemical composition; they play a major role in weather, climate, air quality and the transport of trace substances. It has been seen that aerosols and smoke due to forest fire can also results in delay in onset of precipitation (Andreae et al 2004). Aerosols and smoke together also can reduce the visibility in the affected areas. The main focus of the project will be to calculate the emission particularly carbon monoxide and PM<sub>2.5</sub> due to wild land fires and proscribed burning. A Mesoscale model, OMEGA (Operational Multiscale

Environment model with Grid Adaptivity) will be used to generate a carbon dioxide emission and dispersal maps based on the area burnt, type of fuel burning and the duration of the fire.

### **Study Area:**

The study area for this project is located near the border of Florida and Georgia where a massive fire occurred during the first week of March in 2004, named Impassable fire. Fig 1 shows the location of the fire as viewed by the Moderate Resolution Imaging Spectroradiometer (MODIS). The fire rough destroyed about 38,000 acres of forested and swamp land in the Osceola National Forest situated in Florida. The initially began fire due to a prescribed burning but it went out of control, growing under windy conditions on March 7. The MODIS image below was taken of March 9 2004.

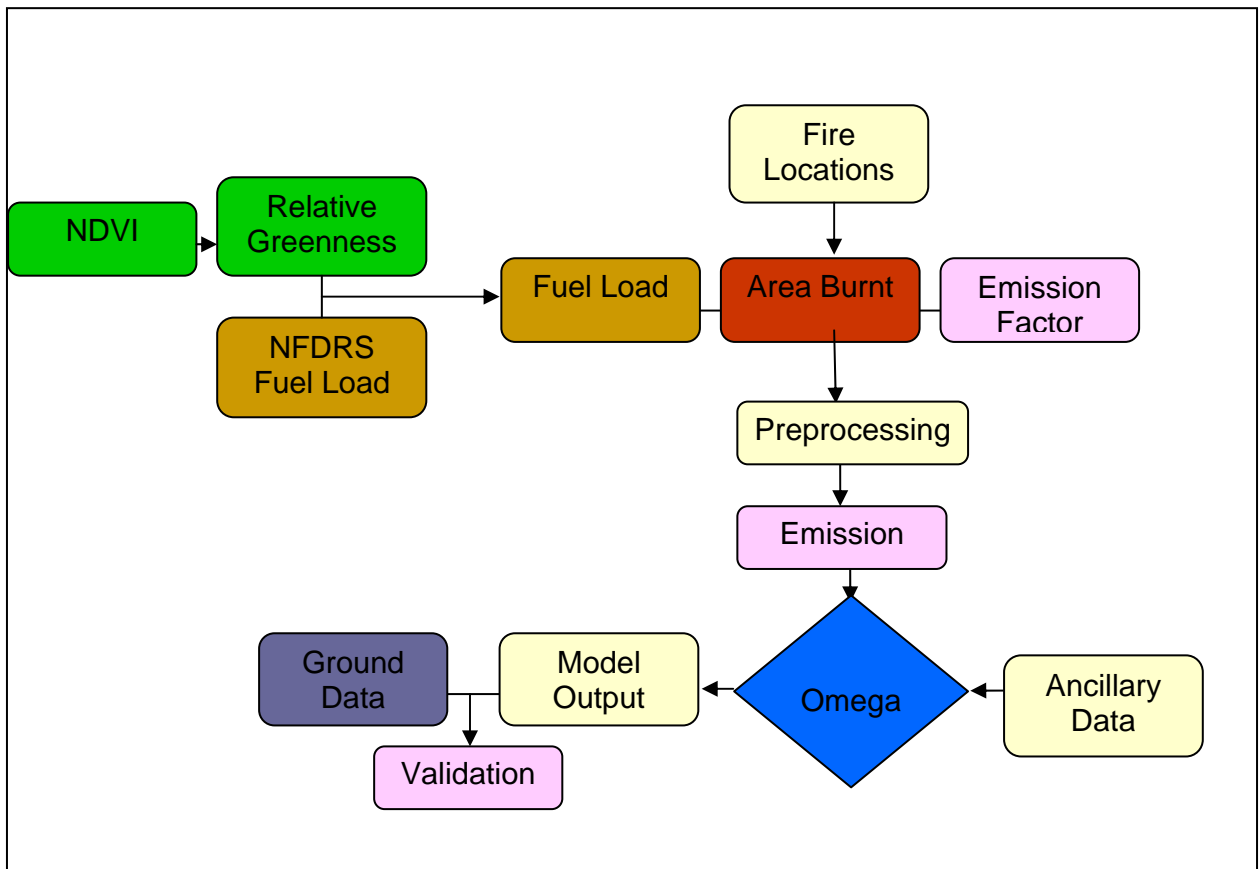


**Fig 1. True Color Image of the Impassable fire acquired by MODIS (March 9 2004)**

### **Methodology:**

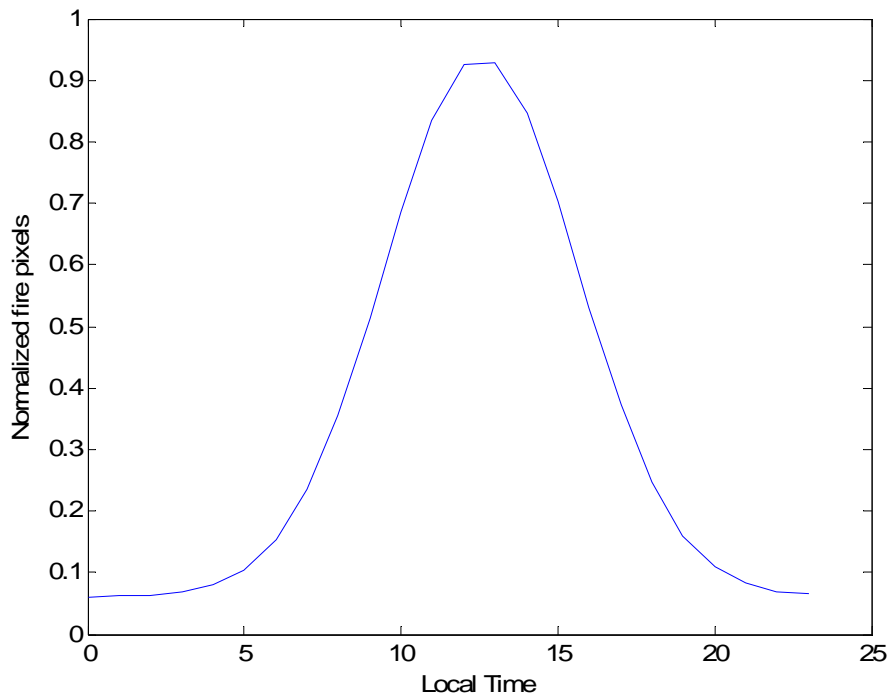
In this study we followed the process as depicted in the Fig 2. 16 day NDVI composite data of one kilometer resolution was collected for four years (2001-2004) for the entire United States from University of Maryland. Then the minimum and maximum NDVI was

calculated so as to get the relative greenness map. NFDRS fuel load in combination with the relative greenness data was used to calculate the fuel load for the study area.



**Fig 2. Flow chart of the methodology**

Burnt area maps was then computed using short wave and near infrared band of MODIS, as described in later section of the report. The fuel load is then calculated for the areas burnt using the relative greenness in combination with the NFDRS fuel model map. The fuel load was calculated for both prior to the fire event and after the event. The difference between the two fuel loads gave the net amount of fuel consumed due to the fire. Based on the fuel load burnt and EPA emission estimated for various fuel types the net emission was calculated. A diurnal curve as shown in fig 3 was then used to calculate the



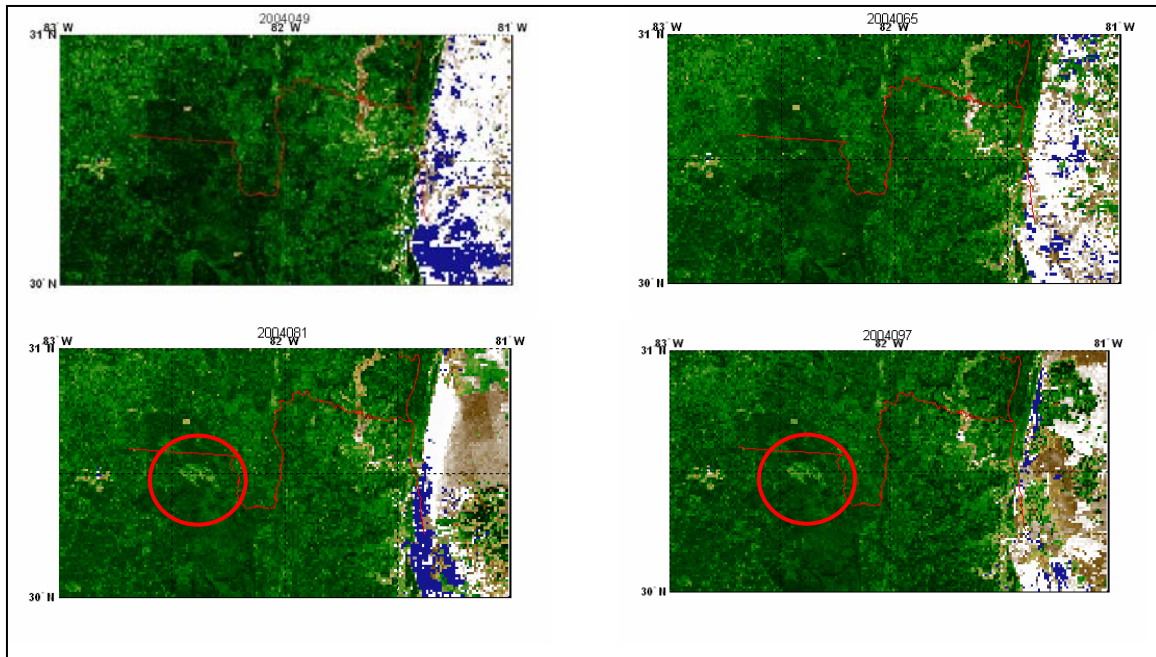
**Fig 3. Diurnal distribution of active fire pixels for the southern United States  
Southern USA (Justice et al)**

emission amount on an hourly basis, this was done by first dividing the net emission estimates by the number of days the fire burnt in order to calculate the emission per day, and then partitioning the emission per day according to the curve. Once this process was completed the emission data was fed into the OMEGA model to calculate the concentration and dispersion pattern for the next 3 days, starting from the day when the fire actually started spreading out i.e. on 7<sup>th</sup> of March 2004. The output is then compared with satellite images to validate the plume dispersion behavior, the EPA hourly station measurement for CO and PM<sub>2.5</sub> is used to validate the concentration measurements that we made using the model. The detail process to get the various parameters is described in the following section.

### Relative greenness

Relative greenness (RG) is calculated using the Normalized Difference Vegetation Index (NDVI) (Goward et al 1990). The NDVI data can be either derived from the Advanced Very High Resolution Radiometer (AVHRR) or Moderate Resolution Imaging Spectroradiometer (MODIS). In our case MODIS data has been used to calculate the relative greenness. The RG is calculated by the following formula

$$\text{Relative Greenness} = (NDVI - NDVI_{\min}) / (NDVI_{\max} - NDVI_{\min}) * 100$$



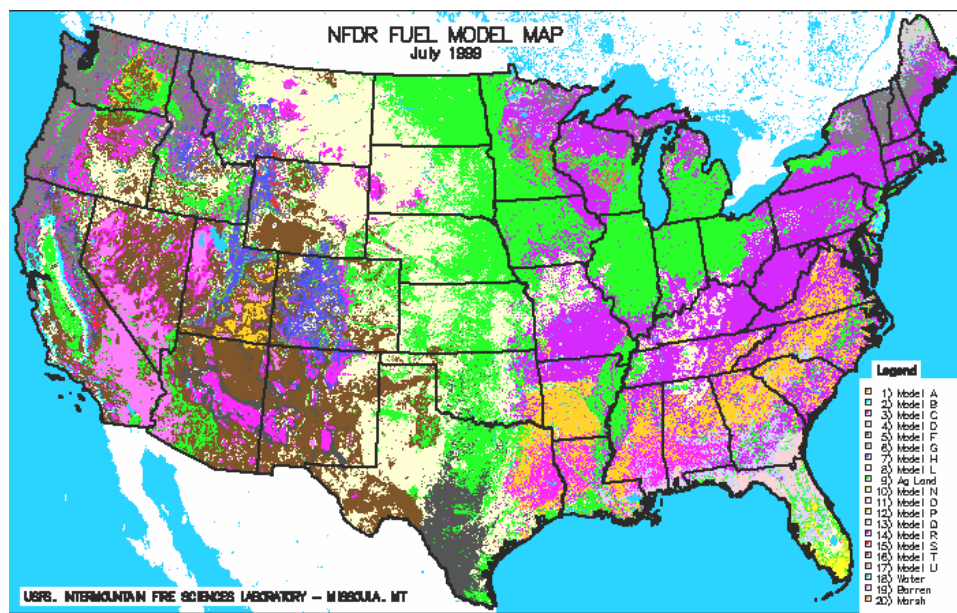
**Fig 4. Relative greenness images of the study area**

Where NDVI is the current vegetation index value,  $NDVI_{\min}$  is the historical minimum value of the NDVI data for that pixel and  $NDVI_{\max}$  is the historical maximum value of vegetation index for the pixel. The RG gives us an indication of how green a pixel is with respect to historical NDVI measurements. RG values is expressed in a scale from 1 -100, low values indicating that the greenness of that pixel is approaching the historical minimum greenness and vice versa. In our case we have taken a 16 days composite MODIS one kilometer resolution generated by university of Maryland. We took 4 years

of 16 days NDVI data starting from January 2001 to December 2004 to build up our statistics for the Relative greenness calculation.

### **NFDRS Fuel Model and Fuel Load calculation**

Fuel load available for any area is dependent on factors like with fuel type, type of vegetation, vegetation density, vegetation mix and the age of the vegetation. Due to a lack of reliable high resolution data on fuel loading, previous estimates of fire emissions (e.g., Cahoon et al., 1994) have assumed total fuel loading and consumption based on fire experimental data.



**Fig 5. NFDRS Fuel model map**

In our current study we have used the NFDRS (National Fire Danger Rating System) fuel model to calculate the fuel load. NFDRS fuel maps define live and dead fuel loads by size class, surface area to volume ratios of the various size classes, heat content, wind reduction factors etc. NFDRS fuel model map was calculated using ground sample data was obtained from 2560 1 km square plots scattered randomly across the U.S. This data, along with a landcover class data and an Omernick Ecoregion maps was used to prepare

NFDR Fuel Model	Fuel Load (T/Hectare)		Extinction Moisture (%)	Vegetation Represented
	Live	Dead		
A	0.67	0.45	15	Western annual grasses
B	25.78	17.93	15	California mixed chaparral
C	2.91	3.14	20	Pine grass savanna
D	8.41	6.73	30	Southern rough
E	—	—	—	Hardwoods (winter)
F	20.18	13.45	15	Intermediate brush
G	29.14	21.30	25	Short needle conifers with heavy dead load
H	6.73	10.09	20	Short needle conifers with normal dead load
I	—	—	—	Heavy logging slash1
J	—	—	—	Intermediate logging slash1
K	—	—	—	Light logging slash1
L	1.12	0.56	15	Western perennial grasses
M	—	—	—	Agricultural land
N	4.48	6.73	25	Sawgrass or other thick stemmed grasses
O	20.18	17.93	30	High pocosin
P	3.36	4.48	30	Southern pine plantation
Q	12.33	14.57	25	Alaskan black spruce
R	2.24	3.36	25	Hardwoods (summer)
S	3.36	3.36	25	Alpine tundra
T	6.73	3.36	15	Sagebrush-grass mixture
U	2.24	7.85	20	Western long-needle conifer
V	—	—	—	Water1
W	—	—	—	Barren1
X	—	—	—	Marsh1

**Fig 6. Live and Dead Fuel load for various NFDRS Fuel model Classes**

an initial NFDR fuel model map. This was then further refined by field personnel who were well versed in the location and extent of vegetation in the region.

To calculate the fuel load from the NFDRS fuel map, first the Relative Greenness is converted to a fractional value

$$RG_f = RG/100$$

Relative greenness factor ( $RG_f$ ) is then used to calculate the current live fuel load for the model assigned to the pixel.

$$LL_p = RG_f * LL_{fm}$$

Where

$LL_p$  = live fuel load for the pixel

$LL_{fm}$  = live load for the fuel model

The dead fuel load for the pixel ( $DL_D$ ) is calculated as follows. The dead fuel load is the one that we are interested in for our current study. This is the material that is supposed to be the major contributor for the fire burn

$$DL_D = (1 - RG_f) * LL_{fm} + DL_{fm}$$

$DL_p$  = dead fuel load for the pixel

$DL_{fm}$  = dead fuel load for the fuel model

It should be emphasized that fuels characterization and their spatial distribution are important factors to simulate fire behavior and to make any kind of emission estimates.

### **Burnt Area Mapping**

Burnt area maps for our current study were done using MODIS data. Prior to MODIS people were using AVHRR data for burnt area calculation. The benefits of using MODIS over AVHRR for fire monitoring (Kaufman et al., 1998a; Justice et al., 2002; Roy et al., 2002; Ichoku et al., 2003; Kaufman et al., 2003; Li et al., 2004) is that we have a higher saturation limit for the MODIS 3.7  $\mu\text{m}$  channel. MODIS also has a longer mid-IR channel near 4 $\mu\text{m}$  where incoming solar radiation quite less. MODIS has a shortwave (SW) IR channel around 1.6  $\mu\text{m}$ . which can be used for burned area detection. A study of using vegetation index derived from a combination of SWIR channel around 1.6  $\mu\text{m}$  and NIR was seen to have a better detection capability of burning even for older fires (Kaufman and Remer, 1994). We have used the following method to calculate the burnt scar map as initially proposed by Kaufman et al.

$$SWVI = \frac{(SWIR - NIR)}{(SWIR + NIR)}$$

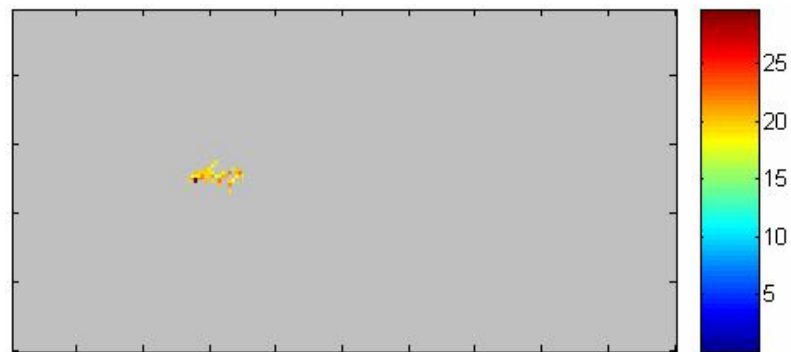
### **Emission Estimates**

Emission factors are an important parameter for emission estimates due to fires. It tells us the gas and particulate emission yields due to fuel consumption. For large-scale fire emissions modeling, the EFs is calculated using biomass burning experiments in the

same vegetation type (Cofer et al., 1988; Goode et al., 2000). In our case we have taken the standard emission factors as given by EPA. The following method is used to calculate the net emission in the current study.

$$\text{Available Fuel Consumption} = \text{Areas burned} \times \text{Fuel per unit area}$$

$$\text{Emission} = \text{Net Fuel Consumption} \times \text{Emission Factors}$$

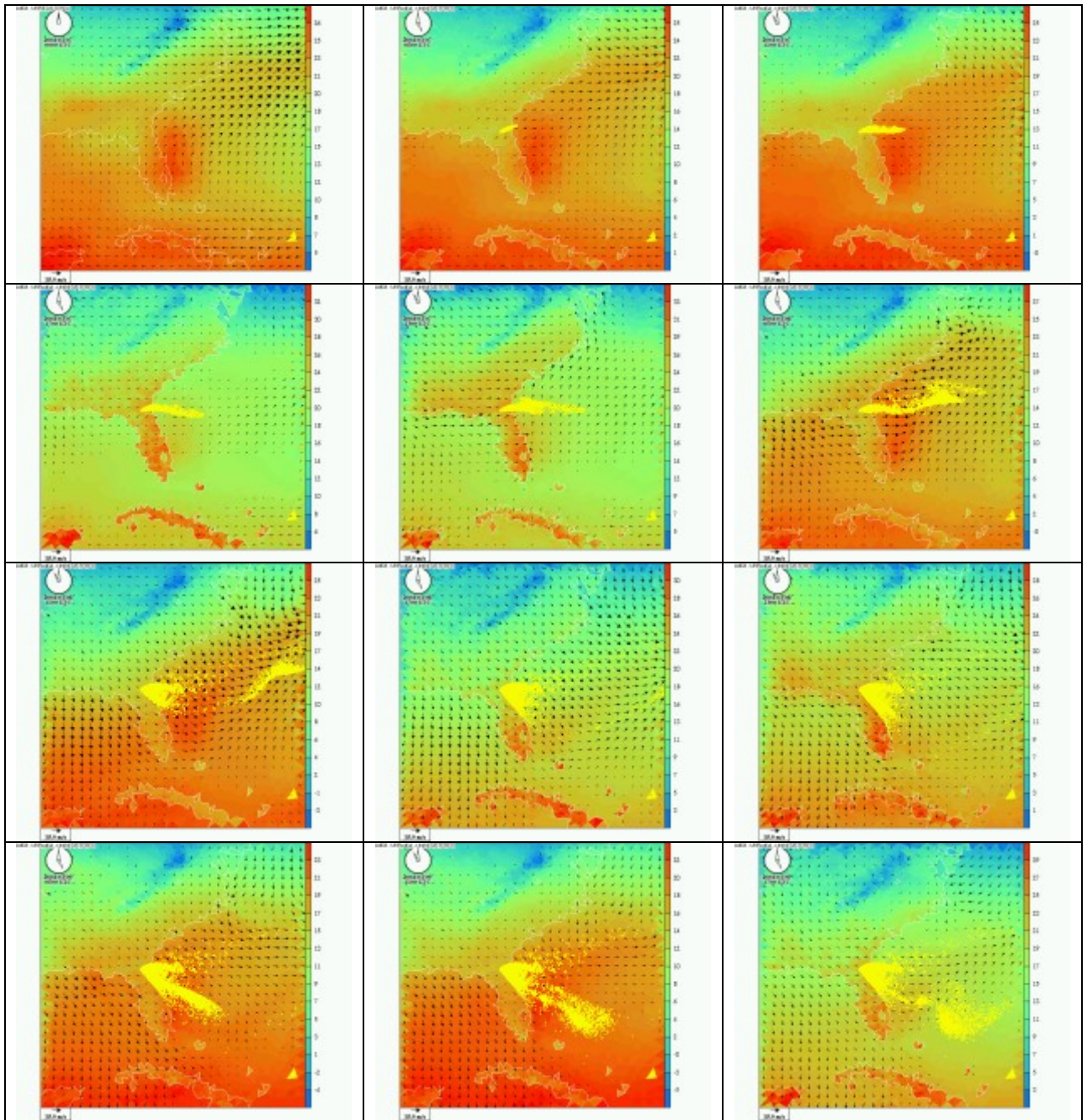


**Fig 7. Net amount of fuel consumed due to the fire**

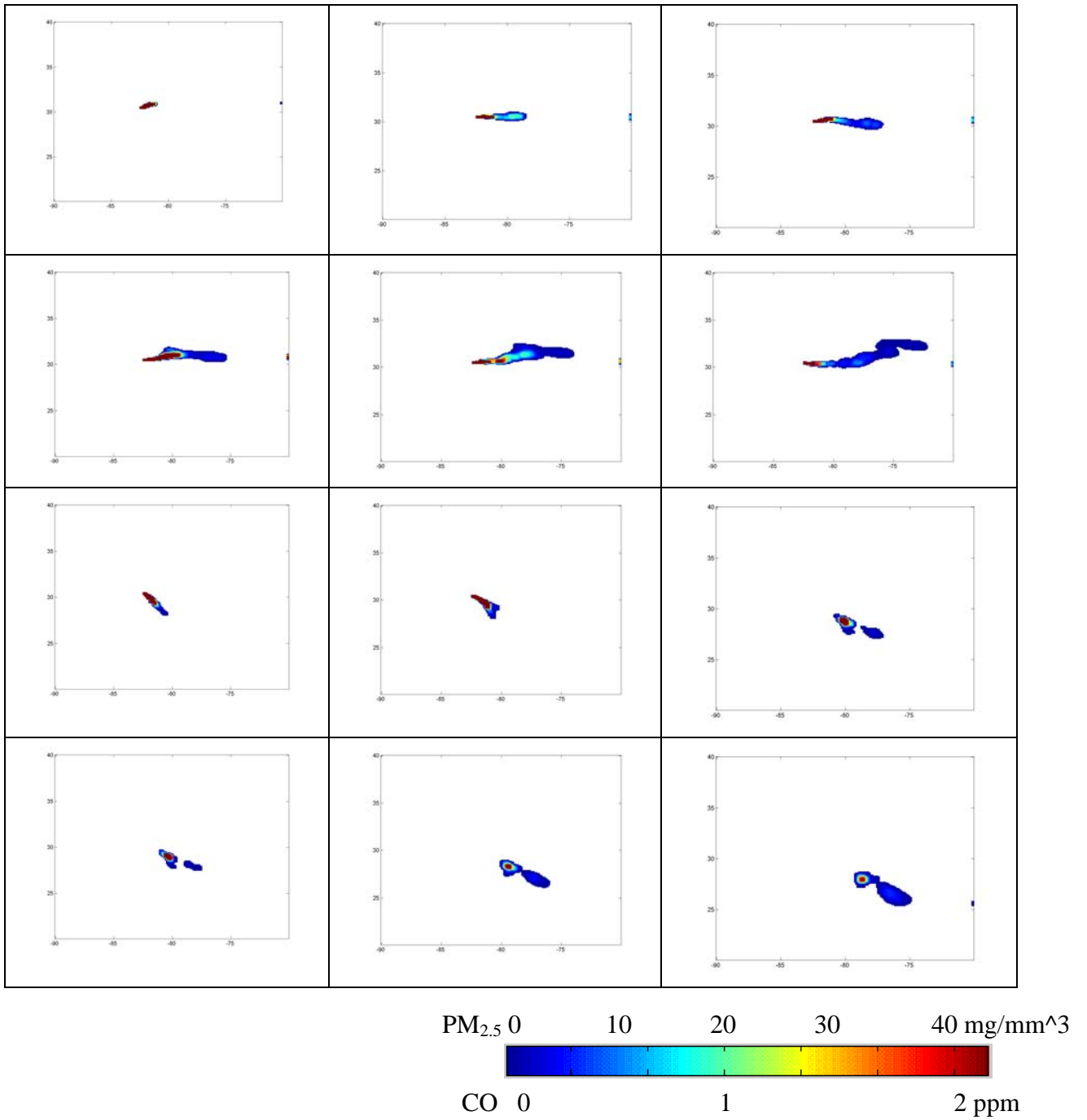
The net fuel consumption is calculated by using the pixels that are burnt and then calculating the fuel load for each of those pixels. Emission factors are then used to calculate the net emissions for CO and PM<sub>2.5</sub>. These emission factors are also dependent on fire conditions and the conditions can vary for each of the pixels depending if it is a smoldering or flaming pixel. Emissions of pollutants like CO are much higher under smoldering conditions than under flaming conditions. In our case since it was difficult to find the ratio we have taken both of them to be equally dominant in the pixel.

**Omega Model:**

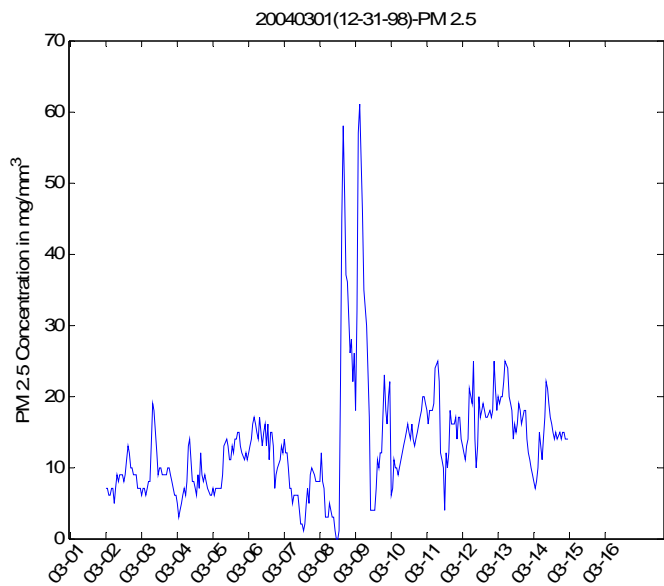
OMEGA is an atmospheric simulation system and is used for advanced, high-resolution weather forecasting and atmospheric release of aerosols and gases from various sources. OMEGA was developed by Science Applications International Corporation (SAIC). The grid resolution ranges from 100 km to 1 km in horizontal direction and ranges from few meters to 1 km in the vertical direction. Unlike other operational forecast models in which are scale-specific, OMEGA uses a unstructured in the horizontal direction, and very well adapts to the underlying surface features and can dynamically adapt to atmospheric phenomena as they evolve. OMEGA has the ability to resolve the surface terrain down to scales of 1 km and along with that the local perturbations on the larger scale wind field. This local wind field perturbation is of extreme importance in determining the trajectory of an aerosol or gas release or plume. To calculate this local perturbation physical parameters and processes, which affect the local flow are taken into account i.e. features like topography, land use, the land/water composition, the vegetation, the soil moisture, the snow cover and the surface moisture and energy budgets. The inclusion of this additional physics, some of which is only appropriate because of the increased spatial resolution makes OMEGA a robust model.



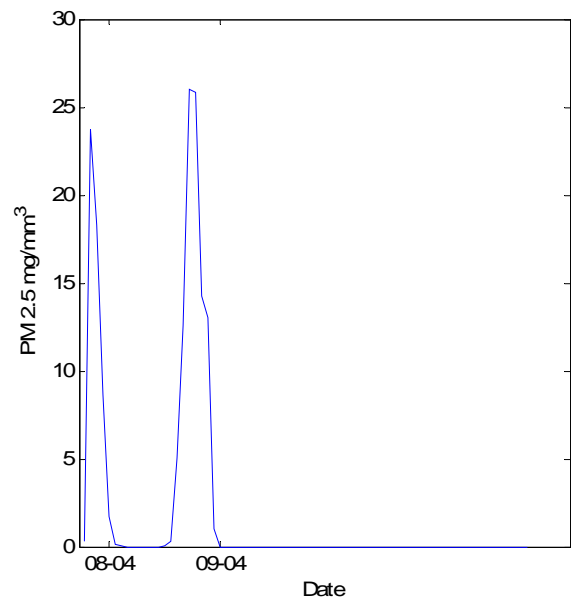
**Fig 8. Particles dispersion due to the forest fire (March 7<sup>th</sup> – March 9<sup>th</sup>) in a 6 hour time step**



**Fig 9. Concentration of CO and PM<sub>2.5</sub> (March 7<sup>th</sup> – March 9<sup>th</sup>) in a 6 hour time step**

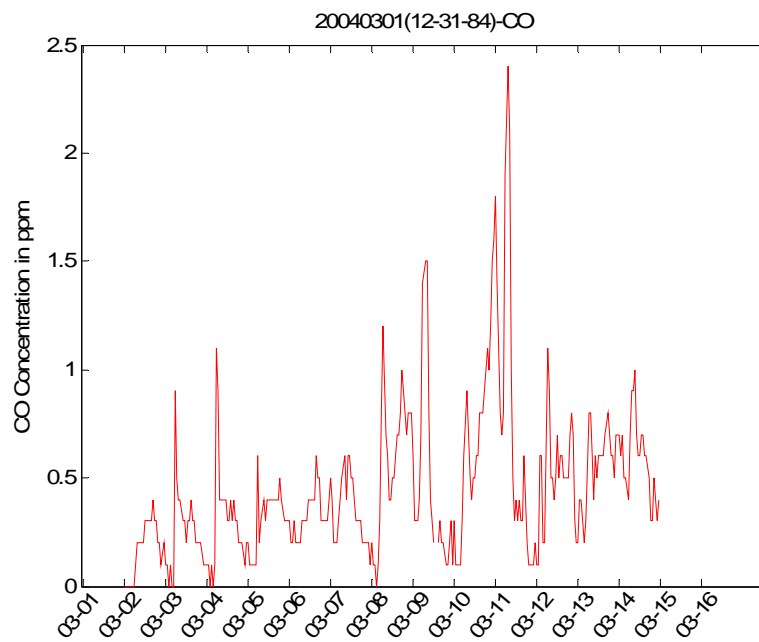


**Ground station data**



**Model Data**

**Fig 10 Comparison of model PM<sub>2.5</sub> and Ground station data**



**Fig 11. CO data measured from by EPA ground station**

## **Results and Discussion:**

From the current study we found that there is a general agreement as far as the plume dispersion pattern is concerned. Out of the various ground sampling sites, (EPA site 12-13-98) showed a high degree of match with the model calculation. However the absolute value was found to be quite less than what was to be expected. There were one good CO (EPA site 12-31-84) measurement site which had an anomalous increase in the CO concentration but we did not find any data from the model output at that location. This might be because the condition we have assumed did not reflect accurately the actual fire release pattern. In our work one of the major constraints was lack of release height for individual pixels. Out of various scenarios release at 100 meters gave us the current result but it is highly improbable that there was a uniform release height throughout the burnt area. This is one of the factors that need to be investigated further. One more restraining factor in our current study was lack of accurate data of percentage of burning in individual pixels. For the current study we have assumed that there was an uniform burning. Nevertheless we have tried to integrate of real time remote sensing data products with a faster model. This can help in emergency response, and resources can be focused to areas which are expected to be most affected. It should also be noted that lot of information that we might need may not be readily available for all fire events, like detail puff temperature, combustion rates, fire progress. It will be a challenging job to design a reliable system that can work well within these limitations.

## **Acknowledgements**

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