MODELING AIR POLLUTION DUE TO FOREST FIRE

Gooi Bee Sung, Koh Hock Lye* and Ahmad Izani Md. Ismail

School of Mathematical Sciences, Universiti Sains Malaysia,
11800 USM Pulau Pinang, Malaysia

*Corresponding author: hlkoh@cs.usm.my

Abstract: *Air pollution has long been a major environmental concern in many countries. The major sources of air pollution are vehicles exhausts, open burning and emission from industrial stacks and power generation stations as well as forest fires. Air pollution poses hazards to human health, poisons rivers and lakes, damages trees and kills wildlife. Major pollutants are carbon monoxide, sulphur dioxide, nitrogen oxides and particulate matters. Forest fire is a large scale, unenclosed and freely spreading natural combustion process that consumes various ages, sizes and types of vegetative matter of the forest. When it rages out of control, it produces tons of pollutants which then trapped in our atmosphere and the forming of smog to lower the visibility over the cities such as the case of the Indonesian forest fire effects on our country. Hence, the ability to simulate air pollution scenarios that may arise from various sources is urgently needed in order to provide a means for mitigation and protection. This paper will present the application of a suite of air pollution models known as ISC-AERMOD View, which is developed by Lakes Environmental Software in collaboration with the United States Environmental Protection Agency (USEPA). This package combines three of the most versatile air dispersion models available, namely The Industrial Source Complex – Short Term regulatory air dispersion model (ISCST3), "AERMOD" and The Industrial Source Complex – Plume Rise Model Enhancements (ISC-PRIME). Some preliminary results will be discussed.*

Keywords: air dispersion modeling, forest fire mapping

1. INTRODUCTION

Forest fire is a part of the earth's natural process of renewal. However, in the process of such renewal, it also become one of the sources for the production of various gaseous and particulates into the atmosphere. It is a type of biomass burning which includes the combustion of living and dead materials in the forest. It is a large-scale, unenclosed and freely spreading natural combustion process which consumes various ages, sizes and types of vegetative matter of the forest.

The cause of a forest fire can be natural (e.g. lightening strike, volcanic eruption), accidental (e.g. cigarette stubs, campfire left unattended) or intentional (e.g. prescribed burning, deforestation for agricultural or industrial purposes).

Unfortunately, recent estimates indicate that most of this fire is human-initiated (Levine, 1994).

The size and intensity of forest fires depend directly to variables such as meteorological conditions (season, wind conditions), fuel (the species of vegetation involved and their moisture content) and the topography of the area. The complete combustion of a wildfire requires a heat flux (temperature gradient), adequate oxygen supply and sufficient burning time. When an ideal burning condition is not achieved (especially during the smoldering phase of the burning stage), chemicals such as carbon monoxide (CO), methane (CH_4), nonmethane hydrocarbons (NMHCs), nitrogen oxides (NO_x) and others will be produced and therefore cause an impact on the atmospheric condition.

The purpose of this paper is to predict and analyze the changes in ambient air quality arising from forest fire by using air dispersion modeling. The estimation of some of the input parameters such as the emission rate will also be discussed. Although many air quality models are available, ISC-AERMOD View will be used in this paper.

2. METHODOLOGY

ISC-AERMOD View was developed by the Lakes Environmental Software and since then its superiority recognized by consultants and academics. It has been selected as the tool of choice for use of air dispersion modeling across all of 39 regions in China. It was also announced that the UK Meteorological Office would be teaming up with Lakes to provide software, services, meteorological data, and training using ISC-AERMOD View.

ISC-AERMOD View is a complete and powerful Windows air dispersion modeling system which seamlessly incorporates three popular USEPA models into one interface: ISCST3, AERMOD and ISC PRIME.

(i) The Industrial Source Complex – Short-term regulatory air dispersion model (ISCST3) is a Gaussian plume model and is widely used to assess pollution concentration and/or deposition flux on receptors from a wide variety of sources.

(ii) AERMOD is the next generation air dispersion model which incorporates planetary boundary layer concepts.

(iii) The Industrial Source Complex – Plume Rise Model Enhancements (ISC-PRIME) dispersion model is similar to the ISCST3 model but contains enhanced building downwash analysis.

Since this paper won't involve any building downwash, ISC-PRIME won't be used in our simulation. Both ISCST3 and AERMOD models are based on the Gaussian Plume Model. For a steady-state Gaussian plume, the hourly concentration at downwind distance x (m) and crosswind distance y (m) is given by (USEPA, 1995b):

$$\chi = \frac{QKVD}{2\pi u_s \sigma_y \sigma_z} \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] \quad (1)$$

where:

Q = pollutant emission rate (mass per unit time)
K = a scaling coefficient to convert calculated concentrations to desired units (default value of 1×10^6 for Q in gs^{-1} and concentration in μgm^{-3})
V = vertical term
D = decay term
σ_y, σ_z = standard deviation of lateral and vertical concentration distribution (m)
u_s = mean wind speed (ms^{-1}) at release height

Eq. (1) is a basic formula of the model for point sources, examples of which are chimney and smokestacks in ISCST3 model. In the case of the AERMOD model, it contains new or improved algorithms for dispersion in both the convective and stable boundary layers; plume rise, buoyancy and penetration into elevated inversions; treatment of elevated, near-surface and surface level sources; computing vertical profiles of wind, turbulence and temperature and treatment of receptors on all terrain. However, its algorithms remain almost the same as Eq. (1).

The area source model is based on a numerical integration over the area in the downwind and crosswind directions of the Gaussian point source plume formula given in Eq. (1). Individual rectangle area sources may be represented as rectangles with aspect ratios (length/width) not exceeding 10. The rectangle may also be rotated relative to a north-south and east-west orientation. Using the polygon-area source or the circular area source can simulate irregularly shaped area.

The ground-level concentration at a receptor located downwind of the source area is given by a double integral in the downwind (x) and crosswind (y) directions as follows:

$$\chi = \frac{Q_A K}{2\pi u_s} \int_x \frac{VD}{\sigma_y \sigma_z} \left(\int_y \exp\left[-0.5 \left(\frac{y}{\sigma_y} \right)^2 \right] dy \right) dx \qquad (2)$$

where:

Q_A = area source emission rate (mass per unit area per unit time, $gs^{-1}m^{-2}$)
K = units scaling coefficient [Eq. (1)]
V = vertical term
D = decay term as a function of x

The ISC-AERMOD View model user's guide (Thé et al., 2002) may be consulted for additional information on how to use the model. Even though the ISC-AERMOD View is very flexible, there are limitations and uncertainties because of some assumptions and constraints in its calculations.

3. CONCEPTUAL CASE STUDY

This section will present some simple preliminary applications of ISC-AERMOD View by using the area source approach in a hypothetical forest fire. The estimation of source parameters will be discussed in this section. The concentrations of CO and NO_x will be estimated for averaging period of 1 hour.

3.1 Input Parameters

As mentioned in the introduction section, there are many factors that contribute to the amount of emissions of a forest fire. Therefore, researchers have developed a mathematical formula to estimate the emission of a forest fire. Eq. (3) shows the formula stated in USEPA guideline for air pollutant factors (USEPA, 1995).

$$E_i = P_i * L * A \qquad (3)$$

where:

P_i = yield for pollutant "i", aka emission ratio (mass of pollutant/unit mass of forest fuel consumed)
L = fuel loading consumed (mass of forest fuel/unit land area burned)
A = land area burned

E_i = total emissions of pollutant "i" (mass pollutant)

As seem in Eq. (3), the emission ratio, fuel loading and the size of a burned area must be known in order to estimate an emission. Table 1 shows the emission ratios for some of the major pollutants and Table 2 shows the biomass characteristics for forest fire emission to calculate the fuel loading.

Table 1: Emission ratio for some of the pollutants

Substances	Forest wildfires ($g\ kg^{-1}$)	Prescribed forest burning ($g\ kg^{-1}$)	Grassland ($g\ kg^{-1}$)
Carbon monoxide	70[c]	112[c]	83.6[d]
Lead and compounds[a]	4.34×10^{-4}	9.18×10^{-4}	5.10×10^{-4}
Mercury and compounds[a]	1.11×10^{-4}	2.34×10^{-4}	1.30×10^{-4}
Nickel and compounds[a]	1.53×10^{-4}	3.24×10^{-4}	1.80×10^{-4}
Oxides of nitrogen	2[c]	2[c]	6.36[d]
Particulate matter ≤ 10 μm[c]	7.48	12	10
Sulfur oxides	Negligible	-	-
Total hydrocarbon	12	-	-
Total particulate	8.5	-	-
Total volatile organic compounds	10.60[c, b]	6.40[c]	4.90[d]
Zinc and compounds[a]	7.14×10^{-4}	1.52×10^{-3}	8.40×10^{-4}

Source: [a] CARB (1991a), [b] CARB (1991b), [c] USEPA (1995a), [d] DEST (1996)

Table 2: Biome characteristics for forest fire emission estimates

Biome	Biomass ($kg\ m^{-2}$)	Above-ground biomass fraction	Burning efficiency
Boreal forest[a]	25	0.75	0.2
Temperate forest[a]	35	0.75	0.2
Mediterranean forest	15[b]	0.75[c]	0.25[c]
Scrubland[a]	7.5	0.64	0.5
Grassland (steppe)[a]	2	0.36	0.5[d]

Source: [a] Seiler & Crutzen (1980), [b] EEA (1999), [c] Rodriguez (1994), [d] which is a subjective estimate, assuming burning efficiency of European grass/shrub lands is less than the data on tropical biomes for which Seiler & Crutzen suggests 0.8

The forest fire was assumed to have occurred in a boreal forest and the size of the burned area is 700 m^2. The terrain is considered to be flat and simple. The dispersion and concentrations of CO will be simulated for 1-hour averaging

period. From Table 1, it is shown that the emission ratio for CO is 70 g kg^{-1}. Fuel loading (Levine, 1994; EEA, 1999) for boreal forest,

$$L = 25 \text{ kg m}^{-2} * 0.75 * 0.2$$

$$= 3.75 \text{ kg m}^{-2} = 3.75 * 10^4 \text{ kg ha}^{-1}$$

Some countries such as USA and Australia have a government department to calculate and estimate the fuel loadings of their particular forest. Unlike our equations and estimation shown earlier that only sought to find a general fuel loading value of certain type of forest (Table 2), their estimations involve a lot of field and laboratory studies. Therefore, these values tend to be more accurate and adequate than our estimation. However, logistical problems (such as size of the burning area) and difficulties in safety situating personnel and equipment close to the fire have prevented the collection of any reliable emissions data on actual wildfires. Therefore, until such measurements are made, the only available information is that obtained from burning experiments in the laboratory. It must be emphasized that the value presented here are adequate for laboratory-scale emissions estimates, but that substantial errors may still occurred if they are used to calculate wildfire emissions.

Eq. (3) was used in order to estimate the emission of CO in this conceptual case study. Emissions for CO per hour,

$$E_{CO} = P_i * L * A$$
$$= 70 \text{ g kg}^{-1} * 3.75 \text{ kg m}^{-2} * 700 \text{ m}^2$$
$$= 183{,}750 \text{ g} = 183.75 \text{ kg}$$

This value will then be converted into 0.0729 $gs^{-1}m^{-2}$ through some simple mathematic calculation to become the input for the simulation. It should be noted that this calculation does not consider the wind and slope factor thus the spread factor. The main concern in this estimation is to have an average and constant value such as the averaged area burned and the averaged emission, etc.

The released height of the plume of the pollutants is also crucial to our simulation. In this case, the height of the flame must be known. The height of the flames is the most obvious characteristic of a fire. It is the vertical distance that continuous flames extend above the fuel bed. While flame height is easy to observe and is often reported or recorded by visual observation, it is quite difficult to obtain a consistent measure. It is normally estimated by observing the average maximum height of continuous flames over a period of time and for some distance around the perimeter of the fire.

Flame height is strongly influenced by fuel type, and also air temperature and humidity. It can be measured and estimated by the aforementioned method but it can also be calculated by measuring the heat release rate of the fire according to the *SFPE Handbook of Fire Protection Engineering*. Figure 1, taken from McCaffrey (1995), shows normalized flame height, *L/D*, as a function of a Froude number, $\dot{Q}^*$ (represented as $\dot{Q}^{*2/5}$ to compress the horizontal scale), from data correlations available in the literature. This Froude number is defined in Eq. (4).

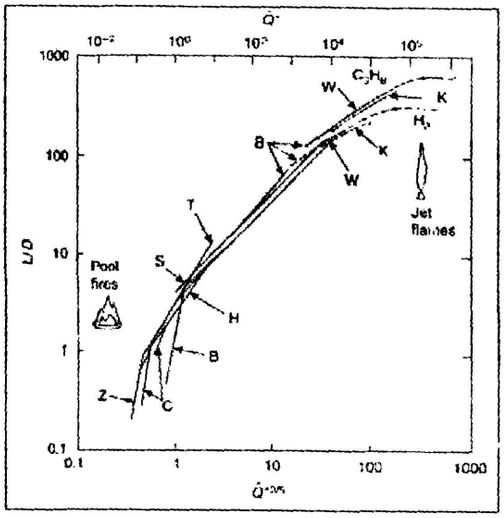


Figure 1. Flame height correlations compiled by McCaffrey (1995). Capital letters without subscripts correspond to various researchers as follow: B = Becker and Liang, C = Cox and Chitty, H = Heskestad, K = Kalghatgi, S = Steward, T = Thomas, W = Hawthorne et al. and Z = Zukoski. Capital letters with subscripts represent chemical formula.

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{gD}D^2} \tag{4}$$

where:

$\dot{Q}$ = total heat release rate (given in terms of the mass burning rate, $\dot{m}_f$, as $\dot{m}_f H_c$), kW

ρ_∞ = ambient density , kg m^{-3}

T_∞ = ambient temperature, K

c_p = specific heat of air at constant pressure $= \left(\frac{\partial q}{\partial T}\right)_p$, kJ kg^{-1} K^{-1}

g = acceleration of gravity, ms^{-2}

D = diameter of the fire source (or effective diameter for noncircular fire sources such that $\frac{\pi D^2}{4}$ = area of fire source), m

$\dot{m}_f$ = mass burning rate, kg s^{-1}

H_c = actual lower heat of combustion, kJ kg^{-1}

In this conceptual case, the heat release of the forest fire was assumed to be 500,000 kW and the ambient temperature was assumed to be 298 K. Through some calculation by using Eq. (4) and the correlation in Figure 1, the flame height was estimated at 10.2 m. The correlation used in this matter is by Zukoski since the $\dot{Q}^*$ obtained by the calculation was in the range of its correlation. Hence, this completed the requirement of the source parameters for ISC-AERMOD View Model. The wind direction in this case will be assumed at north-east.

3.2 Results and Discussions

Figure 2 depicts the dispersion for CO in 1 hour averaging time in ISCST3 model. The little red dotted rectangular in Figure 2 is the area sources (where the forest being burned). The maximum concentration in this case is estimated at 11.77 mgm^{-3} at (180,150). The WHO standard for CO for 1 averaging hour is 30 mgm^{-3}.

Do take notice that a forest fire near a nuclear and chemical waste site could potentially release contaminants that have accumulated over time within the forest biota, into the atmosphere in a very short period. The population living downwind such sites could be exposed to hazardous contaminants through inhalation, dermal contact, as well as by the contamination that enters the food chain.

The change of wind direction also clearly affects the transport of smoke plume. This can have direct implications for assessment of potential human exposures during a wind pattern modification which might caused by sea breeze.

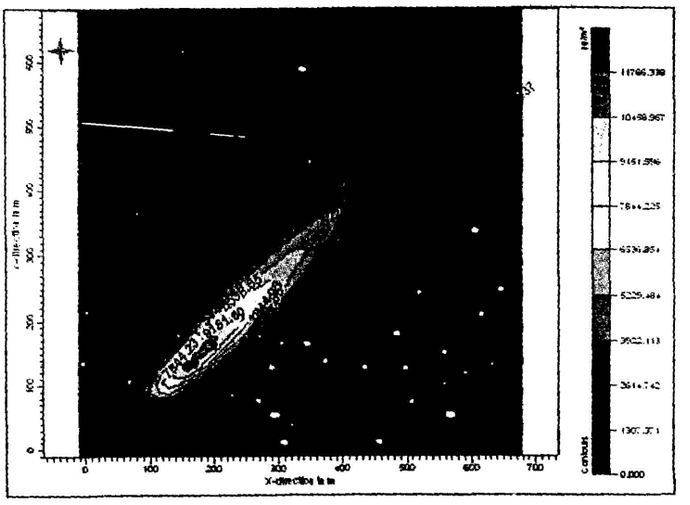


Figure 2. Concentrations of CO for 1 averaging hour with a single wind direction (to north-east)

4. ACTUAL CASE STUDY

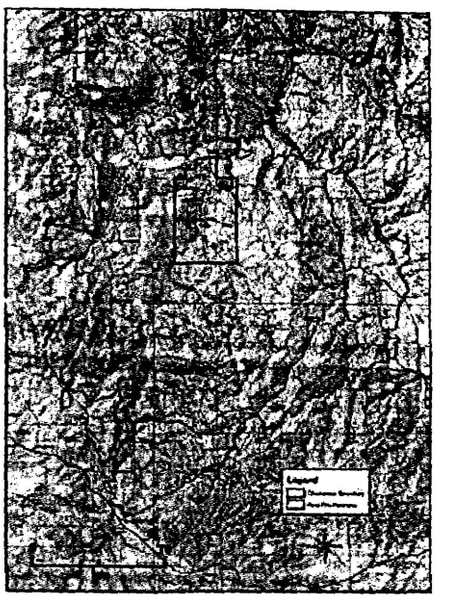
From the moment the Hayman fire started on June 8 in Colorado, USA, it burned actively due to the high winds, low humidity and low fuel moistures and continuous surface fuels which caused rapid spread rates, torching of trees and frequent spotting. The final perimeter of the Hayman fire contained approximately 558.9 km^2 and it spread over four counties of the state of Colorado – Park, Teller, Douglas, and Jefferson. It is the largest fire in the history of Colorado which impacts both locally and nationally (USDA Forest Service, 2003). The main focus in this study is to estimate the concentration and dispersion of CO for 1 hour averaging period.

4.1 Source Parameters

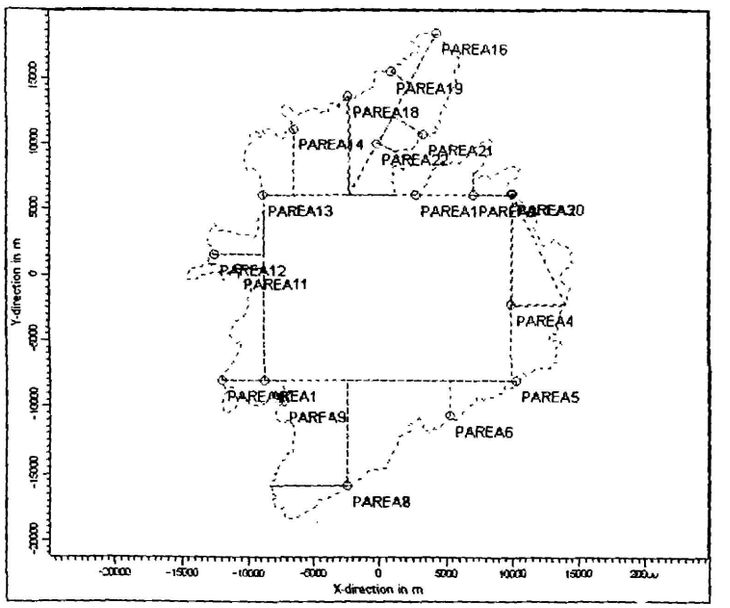
As mentioned in earlier sections, several parameters such as the size of the burned area, emission rate and flame height were needed in order to simulate the case study by using ISC-AERMOD View. In the case of the burned area, a scale map was obtained from the USDA Forest Service as shown in Figure 3(a). In the map, the shape and the boundary of the burned area can be clearly seen. It was then inserted into the ISC-AERMOD View to trace its outline.

A total of 21 area sources were used in this case study – 20 being poly-area sources while one being rectangle area source. The coordinates were followed as the same scale of the map, therefore the size of our total area source was equal to 558.9 km^2. Figure 3(b) shows the size and shape of our area sources.

As we can see, the shape and the boundary of the burned area are almost identical to those in Figure 3.



(a)



(b)

Figure 3. (a) Hayman fire area topography, and (b) the shape and boundary of the area sources for ISC-AERMOD View simulation

Source: USDA Forest Service (2003)

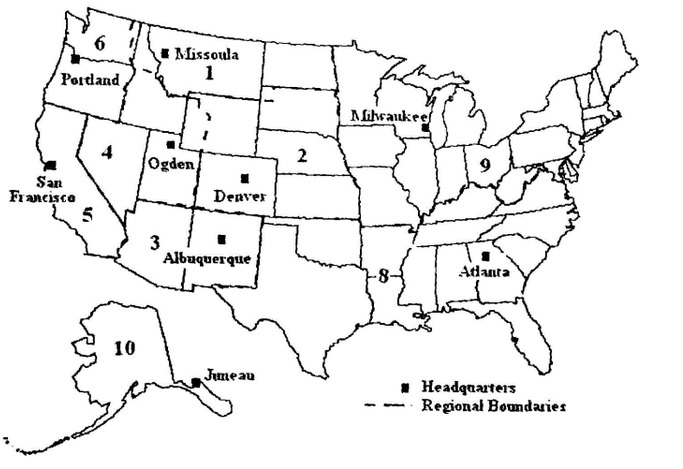
The reason we applied 21 area sources instead of one large area source is mainly because of the software limitation – a maximum of 20 nodes in each poly-area source. Since a major poly-area source of the said boundary would certainly required more than 20 nodes, we decided to "cut" the area into several "pieces" and therefore achieved the result we desired.

Another important input for source parameter is the emission rate of the pollutants. As discussed earlier in Section 3, the calculation of an emission for certain pollutant required three major parameters – size of the burned area, fuel loading of the biomass and the emission ratio of the pollutant. It was calculated in a similar manner as the emission rate in Section 3.

The fuel loading of this case study won't be estimated by using the value in Table 2 because the US Forest Service already had our study site – Colorado categorized as Region 2 (refer to the map in Table 3) and had a more comprehensive estimation of the said area. Therefore, the fuel loading of this case study would be considered as 67 Mg ha^{-1} (refer Table 3).

Table 3: Estimated average fuel loadings for forest wildfires in US and US region boundaries

National region	Estimated average fuel loading (Mg ha^{-1})
Rocky Mountain	83
Region 1: Northern	135
Region 2: Rocky	67
Mountain	22
Region 3:	17.8*
Southwestern	43
Region 4:	40
Intermountain	135
Pacific	36
Region 5: California	135
Region 6: Pacific	25
Northwest	20
Region 10: Alaska	20
Coastal	25
Interior	25
Southern	22
Region 8: Southern	27
Eastern	
North Central	
Region 9: Conifers	
Hardwoods	



Source: USEPA (1973)

* February 12, 2002 – Correction: This number was changed from 40 to 17.8

4.2 Meteorological Parameters

The meteorological data such as wind speed, wind direction and ambient temperature in this case were taken and modified (such as unit conversions) from the Manitou Experimental Forest Weather Station, which is located 28 miles (45 km) northwest of Colorado Springs, Colorado (Latitude: 39.127N, Longitude: 105.116W) and covers about 67.3 km^2 in the South Platte River drainage (one of the burned area of Hayman fire). It is actually one of the stations which located inside the perimeter of the Hayman fire. The data used in this analysis were hourly averaged. The elevation of the station is approximately 2,491 m. The anemometer height was assumed as 6 m in our simulation. The value of anemometer height is normally range from 6 to 9 m.

Figure 4 shows the wind rose from June 8 to June 22, 2002 (the duration of the Hayman fire) that was converted from the Manitou Experimental Forest RAWS annual meteorological data. The data was modified and then imported into WRPLOT View (a software among the package of ISC-AERMOD View), which then automatically produced a wind rose figure and other useful information.

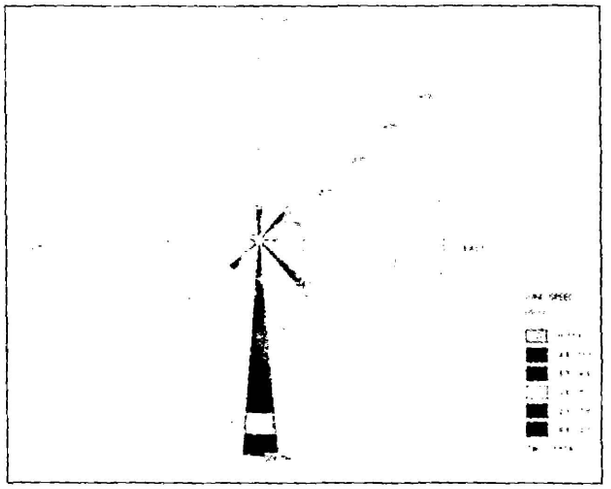


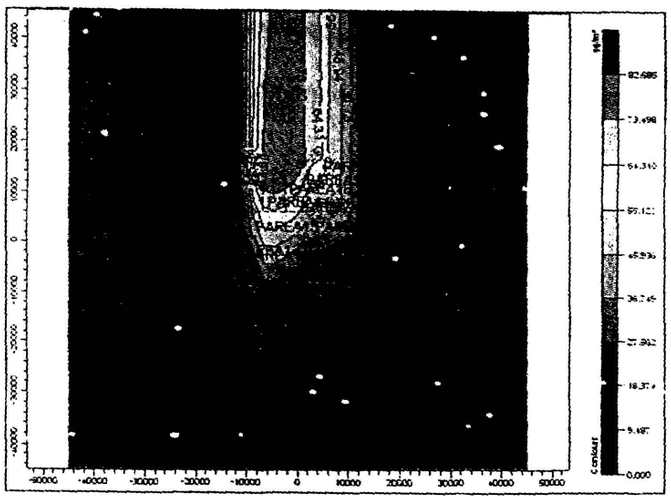
Figure 4. Wind rose from June 8 to June 22, 2002 from Manitou Experimental Forest RAWS

The stability classes for this case study were determined by categorizing the wind speed, solar radiation and opaque cloud cover of the said site. The Pasquill Stability Class concept was used in this case study. The opaque cloud cover data was taken from the Colorado Springs Municipal Airport which located near our RAWS Station since such data was not available from the Manitou Experimental Forest RAWS. Mixing heights for the study site in the year of 2002 was also unavailable, therefore they were taken from a past year meteorological

data in Colorado from www.webmet.com (WebMET, 2002) one of the largest online meteorological resource center.

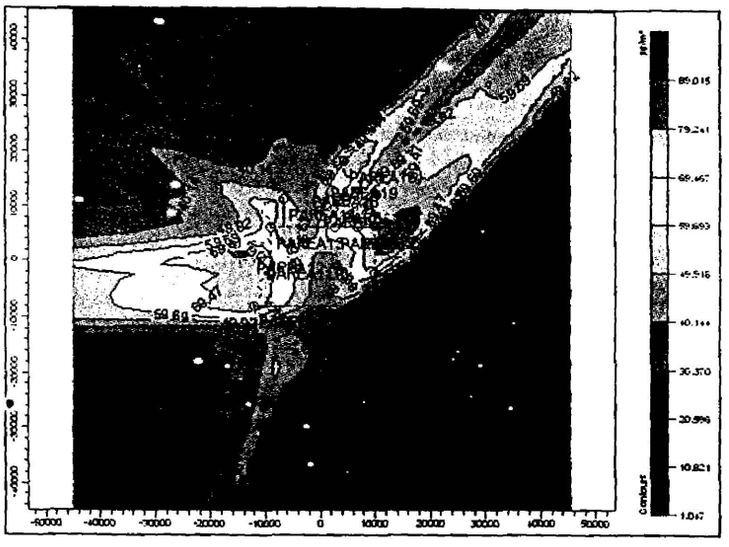
4.3 Results and Discussions

Figure 5(a) depicts the dispersion for CO in 1 hour averaging time in a neutral, almost calm condition. The little red dotted rectangular in Figure 5 is the area sources (where the forest being burned). The maximum concentration in this case is estimated at 82.7 at (–100, 15800). Figure 5(b) depicts the dispersion with the Manitou Wind Rose and the maximum concentration is estimated at 87.6 μgm^{-3} at (13000, 5000). The WHO standard for CO for 1 averaging hour is 30 mgm^{-3}. It was simulated by using the ISCST3 model in the ISC-AERMOD View package. This case was assumed in simple terrain, therefore, its results would be derivative from the actual scenario in Colorado. It is merely a humble attempt to estimate and simulate this case study.



(a)

Figure 5. (a) Concentrations of CO for 1 averaging hour with neutral and almost calm condition, and (b) concentrations of CO for 1 averaging hour with wind rose from June 8 to June 22, 2002 *(continued)*



(b)

Figure 5. *(continued)*

The receptor boundary simulated in this graph is actually the maximum limit since ISC-AERMOD recommends the receptor parameter to be in 50 km radius. However, we can still shift the receptor more to other directions to simulate more results for a longer distance. One of the bigger problems in this modeling was actually not running the software itself, finding the data was actually more difficult. Many of the data were unavailable and many that needed other concepts and calculations to convert them into our software requirement.

5. CONCLUSION

Forest fire is a very dangerous source for air pollution. It usually produces tons of smokes that get trapped in our atmosphere thus creating smog which not only can lower our city's visibility but spread out to other countries as well. Research in our country in this subject is still relatively new compared to others. However, M. Mahmud (1999) also make a similar approach in the study of forest fire about its emissions. It is hoped that more researches would be done in future in the field of forest fire in our country.

6. ACKNOWLEDGEMENT

We would like to acknowledge the research grant funded by IRPA Gran #203/PMATHS/670054.

7. REFERENCES

California Air Resources Board (1991a). *Identification of particulate matter species profiles*. ARB Speciation Manual. 2nd ed., vol. 2. California, USA: Author.

_____ (1991b). *Identification of volatile organic compound species profiles*. ARB Speciation Manual. 2nd ed., vol. 1. California, USA: Author.

Department of the Environment, Sport and Territories (1996). *Agriculture: Workbook for non-carbon dioxide gases from the biosphere*. Canberra: DEST, National Greenhouse Gas Inventory Committee.

EEA (1999). *Emission inventory guidebook*. Available at: reports.eea.eu.int/ EMEPCORINAIR3/en/B1103vs12.pdf

Levine, J.S. (1994). Biomass burning and the production of greenhouse gases. In: Righard G. Zepp (Ed.). *Climate biosphere interaction: Biogenic emissions and environmental effects of climate change*. New York: John Wiley and Sons, Inc.

Mahmud, M. (1999). *Forest fire monitoring and mapping in South East Asia*. National Seminar on LUCC and GOFC. Bangi, Malaysia: NASA/EOC.

McCaffrey, B. (1995). *The SFPE handbook of fire protection engineering*. 2nd ed. Quincy, MA, USA: Society of Fire Protection Engineers and National Fire Protection Association.

Rodriguez Murillo, J.C. (1994). The carbon budget of the Spanish forests. *Biogeochemistry* 25: 197–217.

Seiler, W. and P.J. Crutzen (1980). Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change* 2: 207–247.

Thé, J.L., C.L. Thé and M.A. Johnson (2002). *ISC-AERMOD View user's manual*. Lakes Environmental Software.

USDA Forest Service (2003). *RMRS – Hayman fire case study analysis*. Rocky Mountain Research Station, General Technical Report RMRS-GTR-114 (Revision). Available at: www.fs.fed.us/rm/hayman_fire/index.html.

United States Environment Protection Agency (1973). *Development of emission factors for estimating atmospheric emissions from forest fires*. North Carolina, USA: USEPA, Research Triangle Park.

_____ (1995a). *Compilation of air pollutant emission factors, stationary point and area sources*. AP-42, vol. I, 5th ed. North Carolina, USA: USEPA, Research Triangle Park. Available at: www.epa.gov/ttn/chief/ap42/ch13.

_____ (1995b). *User's guide for the industrial source complex (ISC3) dispersion models, Volume 2 – Description of model algorithms*. North Carolina 27711: USEPA Office of Air Quality Planning and Standards Emissions, Monitoring, and Analysis Division Research Triangle Park.

WebMET (2002). The Meteorological Resource Center. Available at: www.webmet.com.