ANALYTICAL METHODS FOR MONITORING SMOKES AND AEROSOLS FROM FOREST FIRES: REVIEW, SUMMARY AND INTERPRETATION OF USE OF DATA BY HEALTH AGENCIES IN EMERGENCY RESPONSE PLANNING

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EMISSION AND TRANSPORT

Forest fires result in emission of range of gases and aerosols which can travel thousands of kilometers from the fire. A pair of field experiments conducted in 1992 serve to illustrate both the emissions and the species received downwind of the fire: the South Tropical Atlantic Regional Experiment (SAFARI) was conducted in Africa from mid-August to mid-October; the Transport and Atmospheric Chemistry Near the Equator--Atlantic (TRACE-A) mission was conducted from mid-September to late October over Brazil, Africa, and the South Atlantic (1).

Anderson et al (2) discuss aerosols emitted from biomass burning in Brazil and Africa. Measurements were made using a passive cavity aerosol scattering probe in the range from 0.1 to 3 microns, which is the range of most interest in terms of human health effects. Near Ascension Island in the South Pacific, fine aerosol number concentrations were found to be 200-300 per cm$^3$ in the lower 2 km. Nearer the source regions, fine aerosol number concentrations greater than 1000/cm$^3$ were recorded. Aerosols may be the greatest health risk from biomass burning at downwind locations.
Blake et al (3) give concentrations for a number of hydrocarbons near biomass burning sites in both Brazil and Africa. While the concentrations for each hydrocarbon are relatively low in the boundary layer, the aggregate for hydrocarbons is relatively high.

Cheng et al (4) measured CO, NO, NO$_2$ and O$_3$ in Edmonton, Alberta in early June 1995 from a fire 300 km north of Edmonton. They found significant enhancements of all species above their seasonal climatological means, with O$_3$, for example, reaching 92 ppb compared with a climatological mean of 24 ppb. These readings are especially significant given the fact that the back trajectory calculations indicate that the smoke travelled about 1000 km to reach Edmonton. Among the hydrocarbons, alkanes had the highest concentration.

Browell et al (5) used an airborne UV differential absorption lidar (DIAL) system to measure ozone and aerosol profiles above and below the NASA DC-8 used in TRACE-A. The African plumes had both aerosols and ozone, while the long-distance Brazilian plumes had only ozone, since the process of convective lofting of the plumes stripped the aerosols out.

Gregory et al (6) discuss the chemical characteristics of tropical South Atlantic air masses arising from biomass burning. They point out that ratios of short- to long-lived species can be used to determine the approximate age of the air mass. For example, the ratio of acetylene (C$_2$H$_2$) to CO is >3 for air less than 1 day from the source, approximately 1.5 for 3-5 days, and <1 for >5 days. Such information might be of use in determining the source region for forest fire plumes.

Hao et al (7) measured the emissions of CO and various hydrocarbons from fires in savannas in Zambia and South Africa. They found CO to have 19 times the emission rate of methane, and ethene to have 23 per cent of the emission rate of methane. Other hydrocarbons were emitted at less than 10 per cent of the methane rate, with ethane (C$_2$H$_6$), ethyne (C$_2$H$_2$), and propene (C$_3$H$_6$) each being emitted about 7 per cent of the methane rate. This information is useful in determining which hydrocarbons to measure, should hydrocarbons be of interest.

Singh et al (8) discussed the impact of biomass burning emissions on the reactive nitrogen and ozone in the South Atlantic troposphere. They found ozone mixing ratios enhanced by about 20 ppb above the marine boundary layer (MBL). The South Atlantic is different from land masses in that the
MBL is relatively stable while the BL over land masses is turbulent and more rapidly mixes with air aloft. Thus, enhancement of ozone should be considered an important consequence of biomass burning.

**INSTRUMENTS**

The measurements of interest are the following:

1 - meteorological parameters;

2 - aerosols:
   a - aerosol loading at the surface
   b - visibility
   c - aerosol loading above the surface

3 - molecular species
   a - CO
   b - ozone
   c - hydrocarbons

**Meteorological parameters**

It is important to include meteorological information in any analysis regarding the transport of smoke from forest fires and other biomass burning. Such factors as wind speed and direction at a number of altitudes, the existence of low- and high-pressure regions, cloud cover, precipitation, temperature (surface and profile), etc., all play important roles in the transport and transformation of aerosols and gases from burning regions. Most likely, meteorological stations already exist throughout much of the regions that are of interest. The existing stations should be identified and compared with the network required that would best provide the information useful in studying transport, and any gaps identified.

Campbell Scientific, Inc. manufactures weather stations. Didcot Instrument Company Ltd. also manufactures a small automatic meteorological station. It measures wind, solar radiation, air temperature and humidity, net radiation, and rainfall.

Handar manufactures weather stations with a number of sensors. Met One Instruments manufactures weather stations with a number of sensors.
Their system is called MicroMet Data System, and includes MicroMet Plus software; and sensors are available that measure wind velocity, solar radiation, temperature, relative humidity, dew point, precipitation, evaporation, barometric pressure, soil water potential, and leaf wetness.

Vaisala manufactures an automatic weather station (MAWS). It can measure wind, relative humidity, temperature and pressure; and sensors are also available for measuring global solar radiation. It has a mass of 15 kg, can be set up on a tripod, and has a RS-232 output port for transmitting data to a remote location.

Visibility

One additional factor of particular interest is visibility. Most likely, it is determined by manual observations. However, such measurements are not possible at night. There are electro-optic techniques for measuring visibility, generally involving lasers, which could be installed at a few sites if deemed important enough.

Belfort Instruments manufactures a visibility sensor, Model 6210. It is a point monitor that uses a xenon flashlamp and measures forward scatter from aerosols to determine visibility. It can measure visibility over a range of 5 m to 50 km.

Handar manufactures a visibility sensor with a visibility range from 0.25 to 30 km.
Vaisala manufactures the PWD11 which emits laser radiation and senses forward scattering a few cm from the laser. It can measure visibility in the range from 10 m to 2000 m, as well as amount and type of precipitation with a sensitivity of 0.1 mm/hr. They also manufacture the FD12P Weather Sensor which is a larger version of the PWD11, and can measure visibility up to 50 km and detect precipitation down to 0.05 mm/hr.

**Aerosols - in situ**

AIRmetrics manufactures a MiniVol Portable Air Sampler. It is lightweight and compact and can run off a battery or AC power. It can sample ambient air for particulate matter [total suspended particulates (TSP), particle mass concentrations for particles less than 10 microns (PM$_{10}$) or 2.5 microns (PM$_{2.5}$) in diameter] and non-reactive gases such as CO and NO$_x$. The system makes up to six "runs" at a time over a period of up to 24 hours or a week. Ambient air is pumped through the unit at a rate of 5 liters/minute. For TSP, filters are used. For PM$_{10}$ and PM$_{2.5}$, impactors are used. For gases, 6-liter Tedlar bags are used. The advantages of this instrument include that it is lightweight and portable, can operate using a battery, and is relatively inexpensive. The disadvantage is that the material obtained by the unit must be collected and analyzed in a laboratory with the proper analytical equipment, such as highly accurate balances. This instrument may be more suited to industrial site evaluations than to monitoring of forest fire emissions.

Met One Instruments, Inc. manufactures aerosol mass monitors. The Beta-Attenuation Mass Monitor, BAM 1020, uses beta rays from $^{14}$C (60 $\mu$g/m$^3$) to measure the amount of aerosol collected on a filter tape in the instrument. This model was shipped to Malaysia for installation at various sites. Another particulate monitor, Model GT-640, is a portable monitor that can be used to measure TSP, PM$_{10}$, PM$_{2.5}$, or PM$_{1.0}$. A laser optical sensor is used to detect and measure particulate concentrations up to 1 mg/m$^3$ on a continuous flow basis. It is more commonly used than the BAM 1020.

Rupprecht and Patashcnick manufacture a line of aerosol samplers in their Partisol line. The Model 2000 is manual, and can measure PM-10, -2.5, -1 and total suspended particulates (TSP). The Model 2025 automatically changes the filter.

**Aerosols - remote**
Handar manufactures a ceilometer that measures cloud heights to 8
km, and can, most likely, be used for aerosol plume measurements as well.

Vaisala manufactures a laser ceilometer, Model CT25K. It transmits a
laser beam and detects backscatter up to 7.5 km above the surface. The
wavelength employed is 905 nm, and it is an eye-safe system. While it is
generally used at airports to detect cloud bottom heights, it can also be used
to measure aerosol profiles such as those associated with forest fire plumes,
and to monitor the transport of smoke plumes.

There are also lidar systems operating in such countries as Indonesia.
A lidar system is installed in Jakarta, where it has been used to monitor the
atmospheric boundary layer (9). Another advantage of lidar systems is that
they can give the top of the boundary layer as one of the measurement
parameters. This permits a determination of the total depth of the boundary
layer, which can be used to estimate the concentrations of pollutants trapped
in the layer: the thinner the layer, the higher the concentrations, other things
being the same. Of course, during the day, the top of the boundary layer
increases during daylight hours and decreases during non-daylight hours due
to solar heating.

Solar radiation

As mentioned above, a number of companies manufacture solar
radiation sensors, including Didcot, Met One Instruments and Vaisala.

Yankee Environmental Systems manufactures several instruments
which may be of interest in monitoring emissions from forest fires. Their
best known product is probably their ultraviolet pyranometer, used for
monitoring solar UV-B radiation reaching the surface (10). There are two
reasons why this instrument might be of interest here. First, smoke plumes
from biomass burning reduce UV-B radiation reaching the surface, so
monitoring UV-B is one way to determine whether smoke plumes are passing
overhead. Of course, such measurements would have to be augmented with
other factors such as time of day and cloud cover. Second, UV-B radiation
kills microorganisms, and there is reason to believe that reduced UV-B
radiation leads to increased disease incidence in the tropics (11).

A second Yankee instrument of interest is the multi-filter rotating
shadow-band radiometer (12). This instrument is useful for monitoring
global, diffuse, and direct solar irradiance. It includes a rotating sun blocker
which, when between the sun and the detector, blocks direct solar irradiance, leading to a measurement of diffuse solar irradiance. The presence of an aerosol plume would reduce the direct solar irradiance while increasing the diffuse solar irradiance. Such a device might be quite useful in determining the amount of aerosols overhead as well as determining the presence of clouds. Broken or scattered clouds show up in the increased variability of irradiance (13). The signals at the various wavelengths from 415 to 940 nm can be used to determine the coarse aerosol size distribution. This would be useful, for example, in separating out crustal material aerosols, which tend to be large, from biomass burn aerosols, which tend to be small, especially near the source region. This radiometer is fully automated and the data obtained using it can be transmitted to a central location over a phone line.

Solar Light Co. also makes a sun photometer, which is a five-band instrument, and does not include the rotating shadow band. Thus, it is less expensive. The instrument is similar to that used by Forrest Mims III, since he developed the prototype. In his report on using a 4-band sun photometer (14), he describes a transect through a diffuse smoke plume obtained by driving along a mountain road in Wyoming. The shortest wavelength (376 nm) measured over 4 times the optical depth (0.22) as did the longest wavelength (1020 nm). Since the ratio of wavelengths was only 2.7, this indicates the presence of fairly small particles, as expected from fresh biomass burning aerosols. Had the optical depth scaled inversely with wavelength, it would have indicated the presence of large aerosols.

Cimel Electonique manufactures the Cimel CD 318-2 Sun Photometer. It is a direct solar-viewing photometer with filters at 440, 670, 870, and 1020 nm for measuring atmospheric aerosol optical thickness. It has a filter at 936 nm for measuring atmospheric water vapour. It also has 3 polarized filters at 870 nm. It does not separate direct from diffuse radiation, but is thought to be quite accurate for aerosol measurements. It has been used quite successfully to invert data to obtain aerosol volume size distributions from 0.1 to 8 µm with good accuracy (15). It has been adopted in the AERONET programme (15), and is used in 167 locations worldwide as of 1997. All sites are listed at the AERONET web site (http://spamer.gsfc.nasa.gov). An advantage of adopting Cimel CD 318-2 Sun Photometers is the ability to participate in the AERONET network and take advantage of algorithm developments, etc., from others participating in the network.
Point monitors

Dasibi Environmental Corp. manufactures UV photometric ozone analyzers. They use the 254-nm mercury line to monitor absorption through a cell with ambient air, then compare these measurements to those with ozone removed from the ambient air stream. They make two models, the Series 1003, which is the basic instrument, and the Series 1008, which is a microprocessor-based instrument.

Thermo Environmental Instruments makes a number of analytical instruments that are useful for monitoring smoke emissions from forest fires. One is a methane, non-methane analyzer. It uses the principle of gas chromatography to separate the hydrocarbons, then a flame ionization detector (FID) to measure the amount of hydrocarbons present. Methane, being the lightest hydrocarbon, is the first one to emerge from the column. After methane is measured, a valve is closed to reverse direction of flow in the column, back-flushing the other hydrocarbons to the FID. This instrument is useful in regions closer to anticipated forest fire regions, since many of the hydrocarbons are removed during transport. Hydrocarbons are of interest for several reasons: they are indicators of forest fires, they have minor health impacts, and they are precursors of ozone. However, in the tropics with so many trees, photochemical production of ozone is probably limited by NO\(_x\) rather than hydrocarbons (16).

Another instrument manufactured by Thermo Environmental is a chemiluminescence NO-NO\(_2\)-NO\(_x\) analyzer. It can measure over the range from sub parts per billion (ppb) to 100 parts per million (ppm). Ozone is generated to react with NO and produce a characteristic chemiluminescence. NO\(_2\) is converted to NO in order to enable its measurement. It monitors continuously with 10- to 300-sec averaging times, and can be accessed remotely over telephone lines.

Thermo Environmental Instruments also manufactures a UV photometric ozone analyzer. It monitors continuously with a 20-sec response time, and has a precision of 1 ppb. Use of the mercury line at 254 nm has become the standard way of monitoring ozone.

Finally, Thermo Environmental Instruments manufactures a gas filter correlation CO analyzer. The gas filter has two components, one containing CO, the other, N\(_2\). When the CO cell is between the infrared source and detector, a background signal is obtained, independent of CO. When the N\(_2\)
cell is inserted, the signal increases, with greater increases corresponding to lower CO concentrations. CO has a comb-like absorption band in the 4.6-micron region which enables this approach to work well. The precision is one per cent of the reading or 0.05 ppm, and the response time is 60 sec. It monitors continuously and can be accessed over a phone line.

Vistanomics, Inc. manufactures ozone badges that can be used to measure personal exposure to ozone. The badge has a paper coated with an iodine compound that changes colour upon exposure to ozone, similar to the old potassium iodide wet chemistry approach for measuring ozone. After a 1- or 8-hour exposure, the colour of the paper can be compared with the colour set provided with the badge to determine the average ozone concentration during that period. The badge measures in 40-ppb steps, so is a bit coarse. However, since human health effects begin at levels above about 80 ppb, the badge would be useful in determining whether levels adverse to health had been reached. Geyh et al (17) describe a similar instrument that used nitrite which reacts with ozone to form nitrate.

**Network**

Thus, there are a number of instruments which can measure pollutants and meteorological parameters both in situ and remotely. There is probably some redundancy, possible in the use of various instruments. Forest fires generally have emission factors for various pollutants that are closely linked to each other; i.e., if one pollutant emission rate is known, a number of others can be estimated fairly closely. As a result, not all of the instruments would be required, and certainly not at each monitoring station. However, having several, including redundant ones, would enable continuous monitoring even when one or more instruments failed.

The value of monitoring increases considerably when the instruments are integrated into a network of stations located between the likely fire regions and population centres. This way, both the transport of the pollutants and the concentrations or column loading of the pollutants can be determined. In addition, by operating the stations prior to the burning season, background levels can be determined, and the instruments can be brought back into working order.

Networks of stations with meteorological instruments and some pollution monitoring instruments are already set up in some southeast Asian countries. Each country could be contacted to learn what is already in place.
INTERPRETATION AND USE OF MONITORING DATA BY HEALTH AGENCIES

As discussed above, there are a number of analytical instruments that can be used to obtain both in situ and remotely-sensed data on molecular species and particulates associated with forest fires that pose various degrees of health risks, as well as meteorological parameters. By having a network of instruments, the emissions can be followed as they are transported towards highly populated regions. By using a combination of sightings of fire and plume locations and meteorological information that can be used for forecasting future air mass motion as a function of altitude, the time of arrival at the population centres can be estimated. Also, the loading can be estimated so that more serious health risks can be assessed. By continuing to monitor the molecular species and particles between the fire locations and the population centres, information leading to estimates of the anticipated changes in pollution loading in the population centres can be obtained.
Once the health agencies have the information, what can they do with it? First, they will have both real-time and advance information on the concentrations of pollutants in the populated regions. They may also have information regarding the expected duration and magnitude of the source fires. They can assess which pollutants pose the most serious threat to health and safety based on concentrations, expected doses, and health effects vs. concentration and dosage. Since different pollutants have different impacts on people; some acting through the lungs, with various short- and long-term effects, and some affecting the eyes, the health agencies could determine which impacts are most likely. Armed with information about the health impacts of various pollutants as a function of concentration and duration, they will be able to make estimates of how much pollution the people should experience before, say, long-term adverse consequences ensue.

Second, they could make decisions to reduce the impacts of the pollution. Perhaps, simple particle masks could be distributed. Perhaps people should stay indoors if possible. Perhaps, they should not do strenuous physical activity. Perhaps, as a long-term measure, buildings should be equipped with air purifiers. Perhaps, airports should be closed if visibility goes below safe levels. Perhaps, fossil fuel combustion in vehicles and for power generation should be reduced in order to reduce total pollution levels. All of these decisions would be made in an economic framework; i.e., if serious adverse impacts were to ensue by shutting down production for two weeks, the policy makers would probably elect not to shut down.
REFERENCES


Company contact information

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