Table 2

Listing of ratios of toxic air pollutants to CO determined for a variety of fuel types. The bold type values in column 3 are the ratios recommended for use in making risk assessments and are calculated from the highest 1 to 3 values listed for each compound in column 2.

	Literature values	Values to be used for risk assessment
	mean molar ratio to CO ($x10^{-3}$)	mean molar ratio to CO ($x10^{-3}$)
	$1.50 \pm 0.93^{(12)}$	**$1.50 \pm 0.93^{(12)}$**
5-methylfuraldehyde	$0.30 \pm 0.19^{(12)}$	**$0.30 \pm 0.19^{(12)}$**
2acetylfuran	$0.33 \pm 0.16^{(12)}$	**$0.33 \pm 0.16^{(12)}$**
Phenol	$0.32 \pm 0.2^{(12)}$	**$0.32 \pm 0.2^{(12)}$**
o-cresol	$0.27 \pm 0.13^{(12)}$	**$0.27 \pm 0.13^{(12)}$**
m/p-cresol	$0.52 \pm 0.25^{(12)}$	**$0.52 \pm 0.25^{(12)}$**
Guaiacol	$0.17 \pm .081^{(12)}$	**$0.17 \pm .081^{(12)}$**
4-methylguaiacol	$1.00 \pm 0.83^{(12)}$	**$1.00 \pm 0.83^{(12)}$**
Vanillin	$0.50 \pm 0.57^{(12)}$	**$0.50 \pm 0.57^{(12)}$**
Acetol	$1.20 \pm 1.7^{(12)}$	**$1.20 \pm 1.7^{(12)}$**
Vinyl acetate	$1.70 \pm 2.1^{(12)}$	**$1.70 \pm 2.1^{(12)}$**
2-cyclopenten-1-one	$0.20 \pm 0.13^{(12)}$	**$0.20 \pm 0.13^{(12)}$**
Acetic acid	$7.40 \pm 6.2^{(12)}$; $22.6^{(11)}$; $8.70 \pm 6.1^{(15)}$; $1.60 \pm 2.4^{(16)}$; $8.00 \pm 4^{(17)}$; $3.20 \pm 0.4^{(15)}$; $2.60 \pm 6.8^{(17)}$	$7.40 \pm 6.2^{(11)}$ $22.6^{(11)}$; $8.70 \pm 6.1^{(15)}$ **12.1**
Formic acid	$1.50 \pm 1.5^{(12)}$; $1.6^{(14)}$; $9.1^{(11)}$; $2.60 \pm 2^{(15)}$; $0.17 \pm 0.27^{(16)}$; $20.0^{(17)}$; $35.00 \pm 22^{(17)}$	$9.1^{(11)}$; $35.00 \pm 22^{(17)}$; $1.6^{(14)}$; **15.2**
Propanoic acid	$0.39 \pm 0.19^{(12)}$; $0.66^{(14)}$	**$0.66^{(14)}$**
3-oxobutanoic acid	$0.41 \pm 0.44^{(12)}$	**$0.41 \pm 0.44^{(12)}$**
Methanol	$11.00 \pm 9^{(12)}$; $18.0^{(11)}$	$11.00 \pm 9^{(12)}$; $18.0^{(11)}$
Methane	$29.00 \pm 11^{(12)}$; $55.00^{(13)}$; $83.4^{(11)}$; $45.00 \pm 13^{(18)}$; $140.00 \pm 93^{(19)}$; $58.00 \pm 18^{(20)}$; $71.00^{(13)}$; $91.00 \pm 3.1^{(21)}$; $76.00 \pm 13^{(22)}$	$83.4^{(11)}$; $140.00 \pm 93^{(19)}$; $91.00 \pm 3.1^{(21)}$; **104.8**
Ethane	$2.50 \pm 1.2^{(12)}$; $9.4^{(11)}$; $4.00 \pm 1.4^{(18)}$; $6.80 \pm 5.2^{(21)}$	$9.4^{(11)}$; $4.00 \pm 1.4^{(18)}$ $6.80 \pm 5.2^{(21)}$ **6.7**
Ethene	$12.00 \pm 9^{(12)}$; $13.5^{(11)}$; $17.00 \pm 9.1^{(18)}$; $12.00 \pm 8.7^{(21)}$	$12.00 \pm 9^{(12)}$; $13.5^{(11)}$ $17.00 \pm 9.118^{(18)}$ **14.2**

Table 2(continued)

	Literature values	Values to be used for risk assessment
	mean molar ratio to CO ($x10^{-3}$)	mean molar ratio to CO ($x10^{-3}$)
Glycol	10.8[11]	**10.8**[11]
Formaldehyde	17.3[11]	**17.3**[11]
Ammonia	26.0[11]	**26.0**[11]
HCN	4.0[11]	**4.0**[11]
1,3-butadiene	1.10[1]	**1.10**[1]
Benzene	2.13[1]	**2.13**[1]
Toluene	1.79[1]	**1.79**[1]
o-xylene	0.24[1]	**0.24**[1]
m,p-xylene	0.43[1]	**0.43**[1]
n-hexane	0.06[1]	**0.06**[1]
Pyruvic aldehyde	6.2[14]	**6.2**[14]
Crotonic acid	0.21[14]	**0.21**[14]

Table 3

Example of application of data for prescribed fires in the Pacific Northwest used as an estimate of emissions exposure of 10 per cent flaming, 70 per cent primary smouldering, and 20 per cent secondary smouldering. The ratios can be multiplied by the concentration of CO to calculate either B[a]P or PM exposure. If only PM exposure is available, CO can be calculated and B[a]P estimated along with other air toxics found in Table 2.

Phase of combustion	CO (ppm)	PM ($\mu g/m^3$)	B[a]P ($\mu g/m^3$)	B[a]P/CO ($\mu g/m^3$/ppm)	B[a]P/PM ($\mu g/g$)	PM/CO ($\mu g/m^3$/ ppm)
F	140	15740	0.1284	0.0009	8.2	112.4
S1	113	8391	0.1608	0.0038	42.8	74.3
S2	26	1214	0.1024	0.0067	126.4	46.7
Weighted	98	7690		0.0040	56.1	78.2

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_2H_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_2H_6), ethyene (C_2H_4), and propene (C_3H_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.

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THE ROLE OF THE ATMOSPHERE IN FIRE OCCURRENCE AND THE DISPERSION OF FIRE PRODUCTS

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SUMMARY

The large-scale atmospheric controls on the spatial and temporal distribution of fires are discussed and related to a hierarchy of smaller scales. Interactions between scales and between the fire and the atmosphere are important in determining transport pathways and concentrations of fire- generated products. Climatic change on a range of time scales is considered in determining fire distributions. Sudden changes in climate are of particular concern.

Long-range, large-scale transports of fire-generated products can be calculated for prototypical conditions and used as guidelines for preparation and emergency planning. Methodology for the computation of trajectories and transports of particulates and trace gases are provided within a meteorological framework of synoptic states. Both direct and indirect recirculated products and concentrations are considered. A hierarchical classification of global fire regimes is proposed as a basis for developing an emergency response plan.

INTRODUCTION

An objective of this paper with respect to the WHO Health Guidelines on Episodic Vegetation Fire Events is to provide both

background as well as predictive information about the occurrence of large fires and the transport of their products.

Atmospheric processes which influence the temporal and spatial distribution of rainfall through the balance between precipitation and evaporation, directly influence the occurrence, distribution and nature of fires and their products. The occurrence of fire not only depends upon climatic and more immediate weather conditions, but is strongly influenced by the quantity and nature of the fuel available to the fire. This fuel is in turn, and in part, dependent upon climate. Feedback loops such as herbivory intensify the interaction between climate, fire, and vegetation (1).

Fire occurs within the atmospheric fluid system. An intense heat source, such as a fire, at the base of a fluid can create its own "storm". The resulting heat-driven turbulence and convective motions interact with the atmosphere's fields of motion prevailing over the fire. The result can be nonlinear and unexpected. Prediction of where and how fast the products of a fire will go requires as complete an understanding of these complex interactions as is possible.

Fire and the distribution of products from a fire, therefore, require an understanding of processes in the atmosphere which range in scale from motions occupying a significant fraction of the planet to motions on a scale smaller than that of the fire itself. The large scales of motion in the atmosphere such as the semipermanent subtropical anticyclones, occupying most of a given continent, such as northern or southern Africa for much of a season, represent potentially predictable, near steady state conditions. Similarly, the large seasonal oscillations of the Australian monsoon represent predictability in time and space of conditions both favourable and unfavourable to fire.

Fire at a given location, however, within these large-scale atmospheric circulations, is dependent both at inception and in its subsequent behaviour, on the interactions of a number of atmospheric scales of motion which range downwards from the large planetary scale, through storm, sub-storm (squall line), to convective (thunderstorm cloud), and turbulent scales. All of these scales interact with each other and with the fire itself. Predicting or even determining behaviour of a

fire and its products depends on our ability to understand these nonlinear processes. To do so precisely is not now possible, nor likely to be so at any point in the future. Part of the behaviour of the fire-atmosphere system will remain indeterminate, chaotic, and unpredictable. An attempt in this chapter will be to seek out the more deterministic and predictable aspects of this complex fire-atmosphere system.

CIRCUMSCRIPTION OF THE OCCURRENCE OF FIRE AND THE DISPERSION OF FIRE PRODUCTS

Spatial identification of fire-prone regions

Few fires produce the widespread and serious conditions to human and environmental health as did the fires over the Indonesian region in 1997. The need exists to detect the occurrence of fires which are likely to pose hazardous environmental health problems. The first step towards detecting serious fires is to identify globally vulnerable areas.

Fosberg and Levis (2) model fire upon climate in a framework shown in Figure 1. Climate, in turn, can be described in terms of the large-scale circulation fields of the globe. Figures 2 and 3 show the dominant large-scale meridional and zonal circulation patterns of the atmosphere. When these large-scale circulation fields are compared to global meridional pressure and rainfall fields (Figure 4 a & b) near coincidence is seen between

- upward motion, low surface pressure, and high annual rainfall; and
- downward motion, high surface pressure and low annual rainfall

(note that a paucity of measurements in high southern latitudes fails to show the high zonal pressure over Antarctica). The wet regimes of Figure 4b correspond to cyclone tracks along the corridors of the polar fronts in both hemispheres and to the equatorial trough about the meteorological equator. The dry regions correspond to the subtropical high pressure belts and the polar highs. Based on these simple meridional fields alone, we would not expect serious fires in either the wet or dry

zones of the globe. Serious fires are most likely in the margins of these zones where changes in precipitation can be the greatest.

An important departure to this simple meridional model is to be found in the zonal Walker circulations which are subject to reversal. The Low Phase of the Southern Oscillation, with an accompanying El Niño, results in either the diminution of upward motions over the Maritime Continent, and over the Amazon and Zaire Basins or actual reversal of the vertical velocity fields. A strong El Niño event such as that of 1996/1997 may reverse the upward motions of the La Nina creating sinking motions, persistent high pressures, inversions, and drought conditions.

All of these conditions point to serious fire hazards and pollution events, serving as a prototype example of fire-prone regions. Such fire-prone regions are typically regions where:

- the standard deviation from the mean of the rainfall is high;
- dry or extremely dry periods can occur and wet years are infrequent;
- biomass and fuel levels can be high;
- dry conditions are persistent in time, accompanied by large scale sinking in the atmosphere;
- large-scale sinking produces adiabatic warming and drying;
- cloud cover is reduced or absent, solar insulation is high, and with reduced water, conversion of solar radiation at the surface to sensible heat results in high surface temperatures;
- high daytime surface temperature produces enhanced buoyant mixing and deep mixed layers;
- large-scale sinking produces temporally persistent and spatially extensive capping inversions which trap and concentrate fire products;
- polluted layers under persistent inversions elevate temperatures in the layer, intensifying the inversion further; and
- stratification of the atmosphere may lead to strong low-level nocturnal winds which transport fire products over long distances.

Fire climatology documenting the distribution of large fires which pose health and environmental hazards should be compiled and compared with the above climatologically defined fire-prone regions. Satellite-based remote sensing of fires can be employed to provide a global view of fire occurrence and distribution. Figure 5 shows an example of the detail now available from satellite remote sensors. Methodology will have to be devised to identify the large fires which pose serious environmental threats, separating these from the many smaller and less serious fires.

Global rainfall distributions provide an initial indication of the transitional zones identified above as potential fire regions. Rainfall variability in terms of departures from the mean represents a guide to regions where serious fires are likely. Similarly, distribution of drought-prone regions provide additional guidance to fire-prone locations. In each case (rainfall, rainfall variability, and drought regions), consideration of fuel loads are crucial to the actual fire potential of the region.

Time-Dependent Fire Regimes

Climate change research has identified a range of periodicities in the system which have potential impact on the occurrence of fire (3, 4). The absence of adequate understanding of the cause or even clear existence of such periodicities should induce caution but not abstention from the use of these indicators.

Long-term (thousands to millions of years) temperature and rainfall records have been reconstructed for the earth (5). Inferences from such records can also be drawn regarding the strength and direction of surface winds and the associated transports. These records leave little doubt that the earth has undergone major changes in climate ranging through wet, dry, cold, and warm conditions. A model of an expanding and strengthened circumpolar vortex with a corresponding weakening of the tropical easterlies has been used to explain cool, dry conditions over the summer rainfall regions of southern Africa (6, 7). A weakening of the polar vortex would have the opposite effect. These changes in rainfall regimes occur on a global scale appearing in all of the continents and in the maritime regions.

Davis et al (8) have found a statistically significant oscillation in the strength of the Atlantic anticyclone over the past 100 years. Strengthening of the anticyclone corresponds to strong zonal (E-W, W-E) flow resulting in wet conditions in the tropics and subtropics and dry conditions in midlatitudes. A weakening of the anticyclone implies the opposite response in rainfall. These periodicities must be clearly reflected in the temporal changes of fire in temperate and tropical regions. Documentation of such temporal trends could provide useful guidance for planning any response to fires.

While much of the early climatological research suggested that climate changes occur gradually over long periods of time, recent research shows sudden discontinuous shifts from one level (of energy) to another (3, 4). Such sudden shifts in climate occurring in time intervals of less than a decade must be taken seriously in any plan to respond to serious fires.

Climate changes occurring on intermediate time scales ranging from annual to about 100 years are becoming increasingly well documented. Tyson (9) has documented a near 18-year periodicity in summertime rainfall which is seen to occur in the subtropics on a global scale. The approximately nine years of below and nine years of above average rainfall can depart from the mean by as much as $\pm$ 50 per cent. Such extended dry and wet periods provide a valuable guide to the probability and nature of fire in each period.

Similar periodicities have been suggested for the strong El Niño events (10, 11). While uncertainties exist on whether and what periodic functions may exist during the strong El Niño events, observational systems (particularly remotely sensed sea surface temperatures) provide excellent day-to-day documentation of the temperature fields and their temporal and spatial changes across the tropical Pacific Ocean. These data provide the basis for predicting potential fire conditions months in advance. Such guidance should clearly be incorporated as part of the overall response plan.

Droughts which last for periods of less than one season can have substantial influence on the occurrence of fire. Failure of the onset of rains in a region with strong seasonal cycles trigger outbreaks of fire.

Failure of the onset of the summer rains in monsoon regions brings the risk of fire and crop failures. Regions of the globe and times of the year of well-known increased fire risks can be systematically documented. In cases of lack of rain, conditions which amplify the risks of serious fire include:

- vegetation is already dry;
- precursor cloud convection is frequently accompanied by severe lightning;
- clear (cloudless) skies and low moisture content enhance nocturnal inversions and the occurrence of strong low level nocturnal winds; and
- inversions in the atmosphere are strong, widespread and persistent.

Particulate matter transport models

The transport of particulate matter as well as trace gases produced by a fire is a highly scale-dependent phenomenon. The antecedent conditions prior to the fire and potentially surrounding the fire after onset are governed by large and synoptic scale atmospheric conditions. These conditions not only influence rainfall, but control the three-dimensional velocity fields and the thermodynamic structure of the atmosphere. The existence or absence of vertical shear of the horizontal wind and the presence, intensity, height, and thickness of temperature inversions influence where and in what concentrations fire products will be transported.

Interactions of intense turbulent and convective circulations created by the fire with the surrounding atmospheric environment will ultimately dictate the transport patterns of a range of particle sizes. Large particles ($> 100\ \mu m$) will be elevated by the fire into the lower atmosphere. Transport away from the fire will depend not only on the velocity and thermodynamic fields of the atmosphere but also on the time of day or night. In the presence of nocturnal jets with speeds in excess of 20 m s^{-1} at altitudes of 500 m or less, particles of considerable size will be transported away from the fire. Similarly, plumes of smaller particles can be transported up to 1000 km during a 10-hour night in the presence of a nocturnal jet of 25 m s^{-1}.