Vertical velocities within the fire can range between 20 and 40 m s^{-1}. A 20 m s^{-1} upward velocity operating over 10 min will elevate material to 12 km. While a number of factors such as dilution by entertainment of air outside of the active fire plume into the plume will dilute and reduce such upward transports, considerable uncertainty exists as to the mean or modal height to which most of the fire products will be transported. Knowledge of what this height is, is critical to determining where the fire plume will go. The uncertainties are such that the best approach is to choose a range of heights above the fire and to calculate forward trajectories. Based upon those heights, a comparison between the trajectories and the observed (satellite) smoke plume will provide an indication of the height of the core transport.

Long-range, large-scale transports

Calculation of long-range, large-scale transports from a fire depend upon knowledge of the properties of the surrounding atmosphere. In many locations where serious fires occur, information on the structure of the atmosphere is likely to be lacking.

From the above discussion, it is recommended that the general structure (wind and thermodynamic fields) be characterized according to the dominant synoptic systems of the region [see Tyson et al (12); Garstang et al (13, 14) for the procedures]. Such models of the dominant synoptic systems will provide generalized information on the horizontal velocity fields as a function of height and the vertical thermodynamic structure (presence of inversions) of the atmosphere. Locations (heights) of the dominant inversions should be considered when choosing the heights at which the calculation of forward trajectories should be initiated.

Prototype trajectory calculations prior to and in the absence of fires could be run for fire-prone regions at the times of year when fire hazards are greatest. The "time of year" will dictate the most likely dominant synoptic situation. Choice of such synoptic conditions will provide the framework for trajectory calculations based upon actual meteorological conditions. These prototype trajectories will provide guidance on the most likely transport pathways, average transport velocities, plume heights and sizes, and potential concentration levels of particulate material along the transport pathway. The occurrence and character of inversions present under the archetypical synoptic conditions will be important in determining concentrations and plume heights. Circulation patterns associated with the archetypical synoptic system will govern the degree to which recirculation takes place. Recirculation will influence the concentration, particle size distribution, and elemental composition of the plume.

Kinematic trajectory calculations are recommended over other (isobaric, isotropic, constant absolute vorticity) methods of calculating trajectories (15). The kinematic technique (as do all other methods) depends upon knowledge of the existing meteorological fields. Provision would have to be made to acquire large-scale numerical model generated wind fields, such as those produced by the European Center for Medium Range Weather Forecasting (ECMWF). Such fields would be required for at least five levels in the atmosphere (875, 850, 700, 500 and 200 hPa) every six hours. A point of origin (geographic coordinates) would be chosen over the fire and forward trajectories at each chosen level would be calculated for as long as the fire presented a hazard. Initial conditions would be chosen some five days before the fire. Trajectories would then be calculated for those five days using the principle of Lagrangian advection. Horizontal (u,v) and vertical (w) wind components at the starting point are used to compute a new downstream location every 15 min. New trajectories would be started at least once per day for every day considered. As time progressed beyond the starting time of five days before the fire, trajectories would be accumulated. Vertical planes normal to the trajectory pathway such as illustrated in Figure 6, should be constructed. The construction of the core transport is based upon a contour enclosing 95 to 98 per cent of all of the trajectories striking a given plane as illustrated in Figure 7.

Once the 95 or 98 per cent transport area has been identified on the x,z planes normal to the trajectory pathway, a volume transport can be calculated by multiplying the area in the plane by the transport velocity. Volume fluxes may be converted to mass fluxes using information available on concentrations in the plume. If successive measurements of concentrations are available along the trajectory pathway then deposition rates can be estimated.

Vertical distribution of the temperature and velocity fields surrounding a fire will govern the degree to which recirculation of fire-generated products will occur. Fire-prone regions and times of occurrence of fires are likely to coincide, dominated by anticyclonic circulation fields in the atmosphere. Semipermanent anticyclones dominate fire-prone regions in the subtropics. Transient but often persistent high pressure systems are typical of dry or drought and fire-prone states in mid-latitude forests. As described above, sinking and warming air characteristic of high pressure systems produces strong, widespread and persistent inversions. Under such conditions, fire products are concentrated in stratified layers and trapped into recirculating gyres which frequently bring fire products back to the vicinity of their origin.

The trajectory methods described above and presented in greater detail in Garstang et al (16) and Tyson et al (17) are capable of keeping track of the recirculated material. The individual trajectories originating at the prescribed heights above the fire are tracked through each of the vertical planes erected normal to their transport. The spatial and temporal location on the plane (x,y,z,t) of each trajectory strike is noted. Forward trajectory strikes are distinguished from return trajectory strikes (see Figures 6 and 7). The fraction (per cent) of return trajectories is easily determined. An ensemble of trajectories calculated for a given fire over a period of time will allow the percent return flow to be calculated. Extreme pollution events are often characterized by such trapping and recirculation. It is thus, important to determine whether such processes are at work.

Long-range, large-scale trajectory calculations will provide general guidance to the transport of material from the fire providing information on the plume width, plume height, plume level, plume direction, and concentration along the plume. If sufficient observations of concentrations are available, the trajectory calculation will also provide an estimate of deposition. The trajectory calculation will work best under conditions in which atmospheric circulations are persistent or changing only slowly. Clearly, the trajectory calculation depends upon the existence of observations and a model-generated database. The large-scale trajectory calculation will not be reliable under conditions in which marked weather changes are occurring (thunderstorms, squall lines, cyclones, etc.). However, these weather conditions may not be likely in

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Figure 1

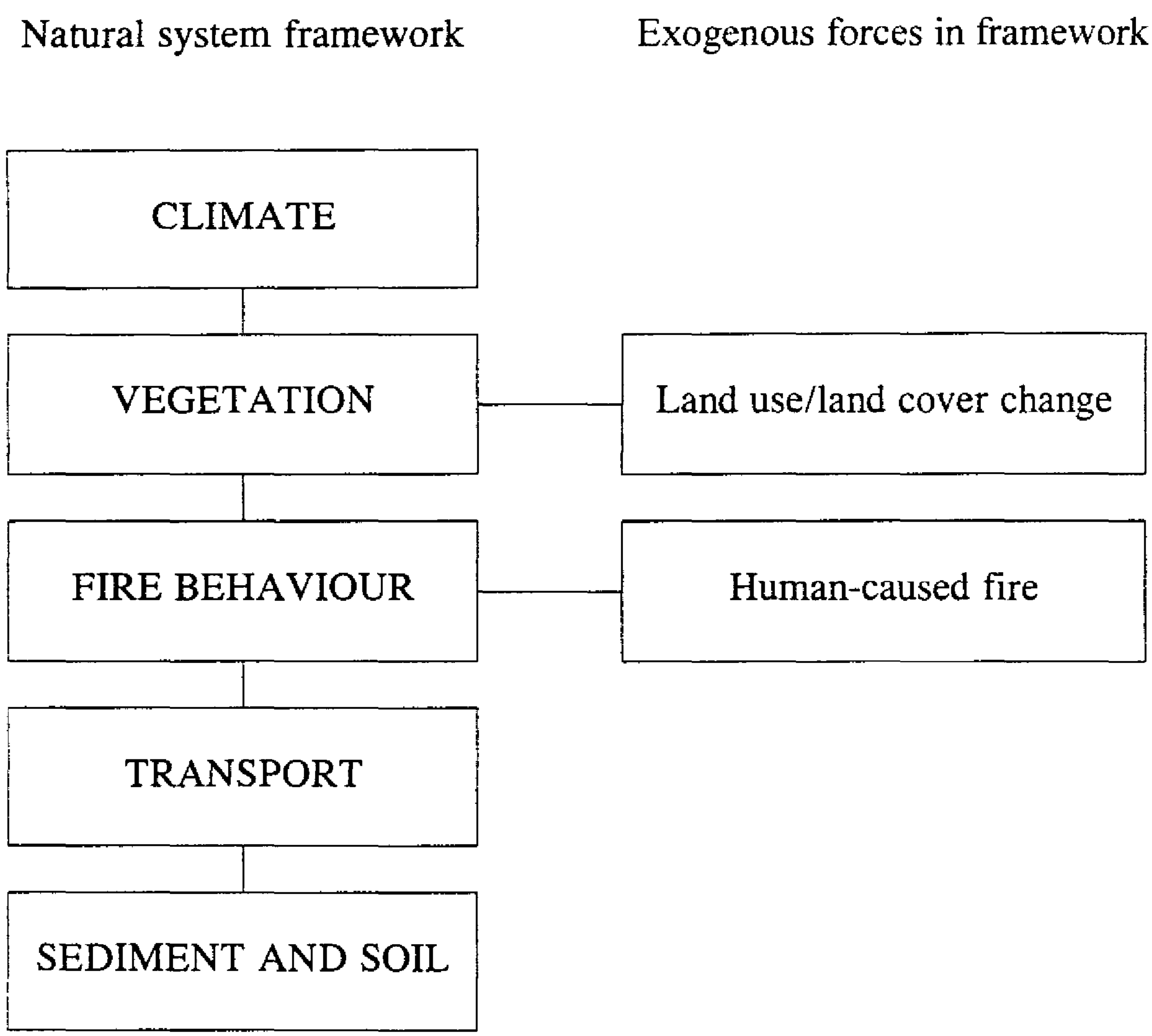

Natural system framework
Exogenous forces in framework
CLIMATE
VEGETATION
Land use/land cover change
FIRE BEHAVIOUR
Human-caused fire
TRANSPORT
SEDIMENT AND SOIL

Figure 2

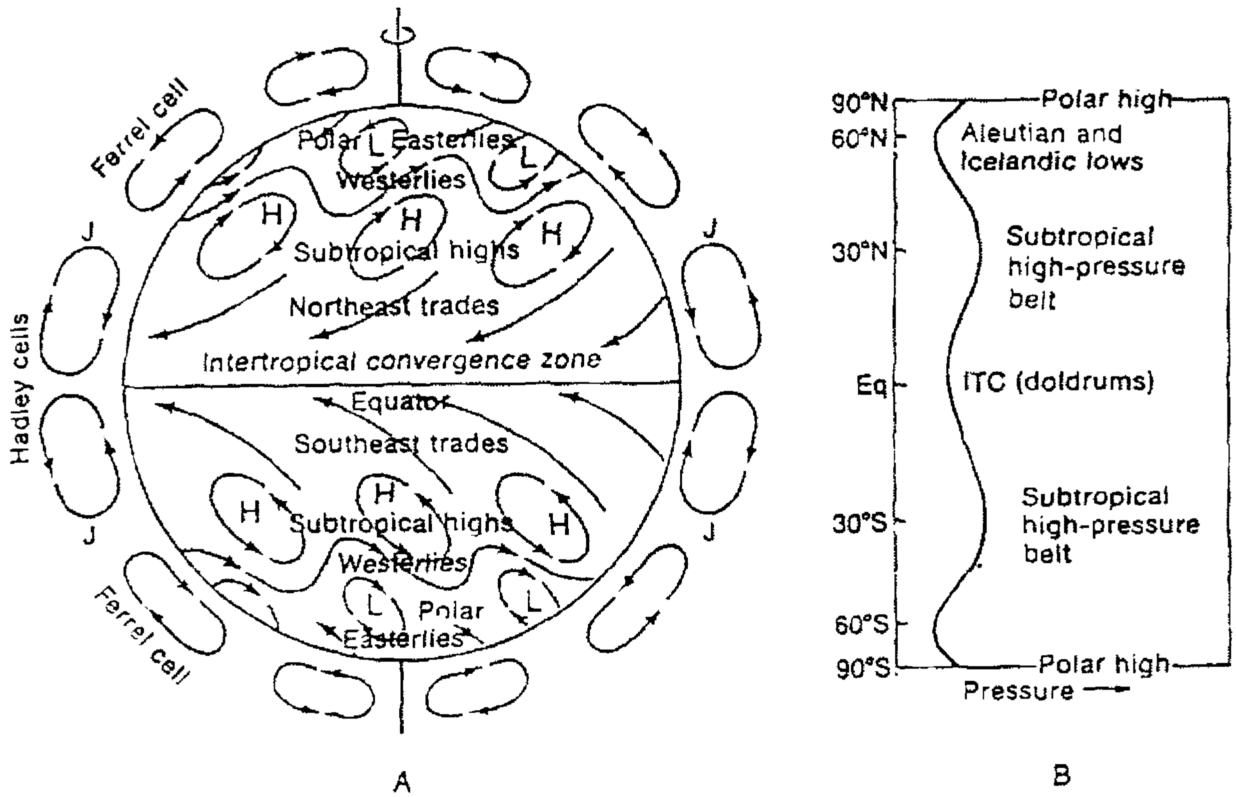
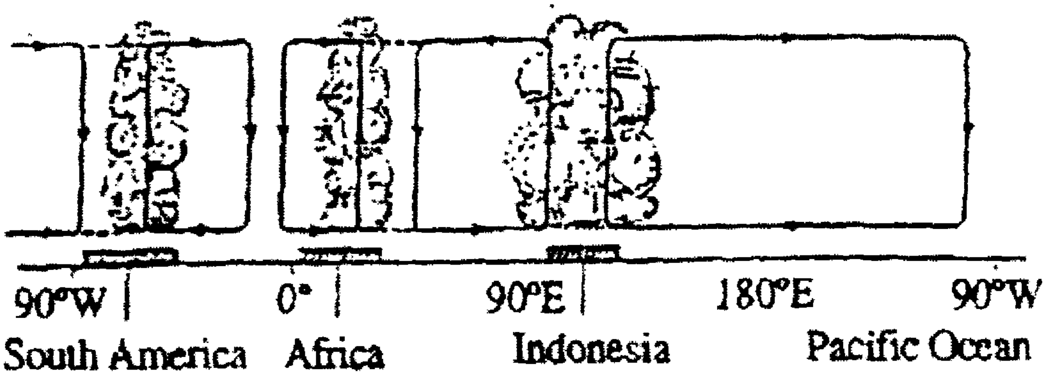

Ferrel cell
Polar Easterlies
Westerlies
Subtropical highs
Northeast trades
Intertropical convergence zone
Equator
Southeast trades
Subtropical highs
Westerlies
Polar
Easterlies
Hadley cells
Ferrel cell
J
H
L
A
90°N
60°N
30°N
Eq
30°S
60°S
90°S
Polar high
Aleutian and
Icelandic lows
Subtropical
high-pressure
belt
ITC (doldrums)
Subtropical
high-pressure
belt
Polar high
Pressure
B

Figure 3

(a)

High Phase



(b)

Low Phase

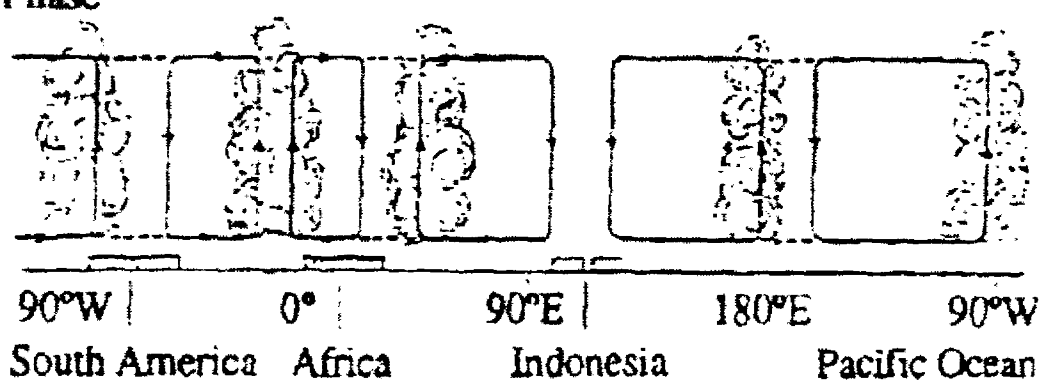


Figure 4(a)

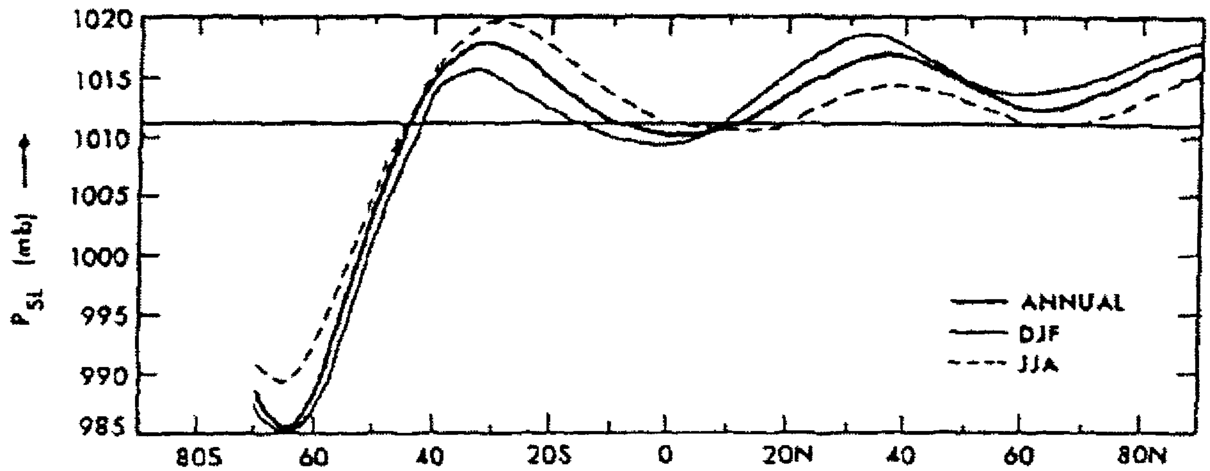


Figure 4(b)

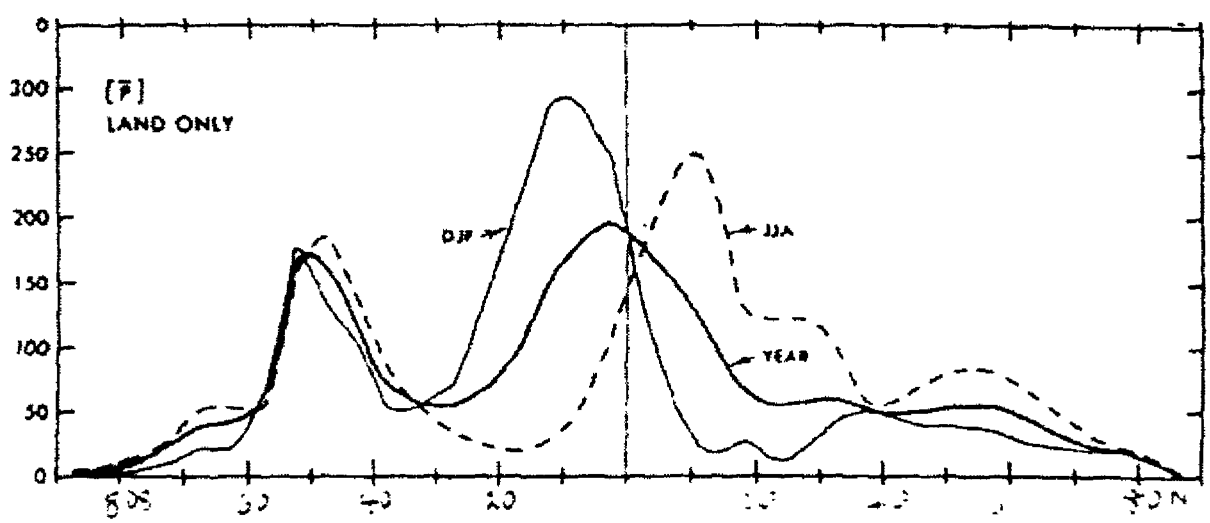


Figure 5

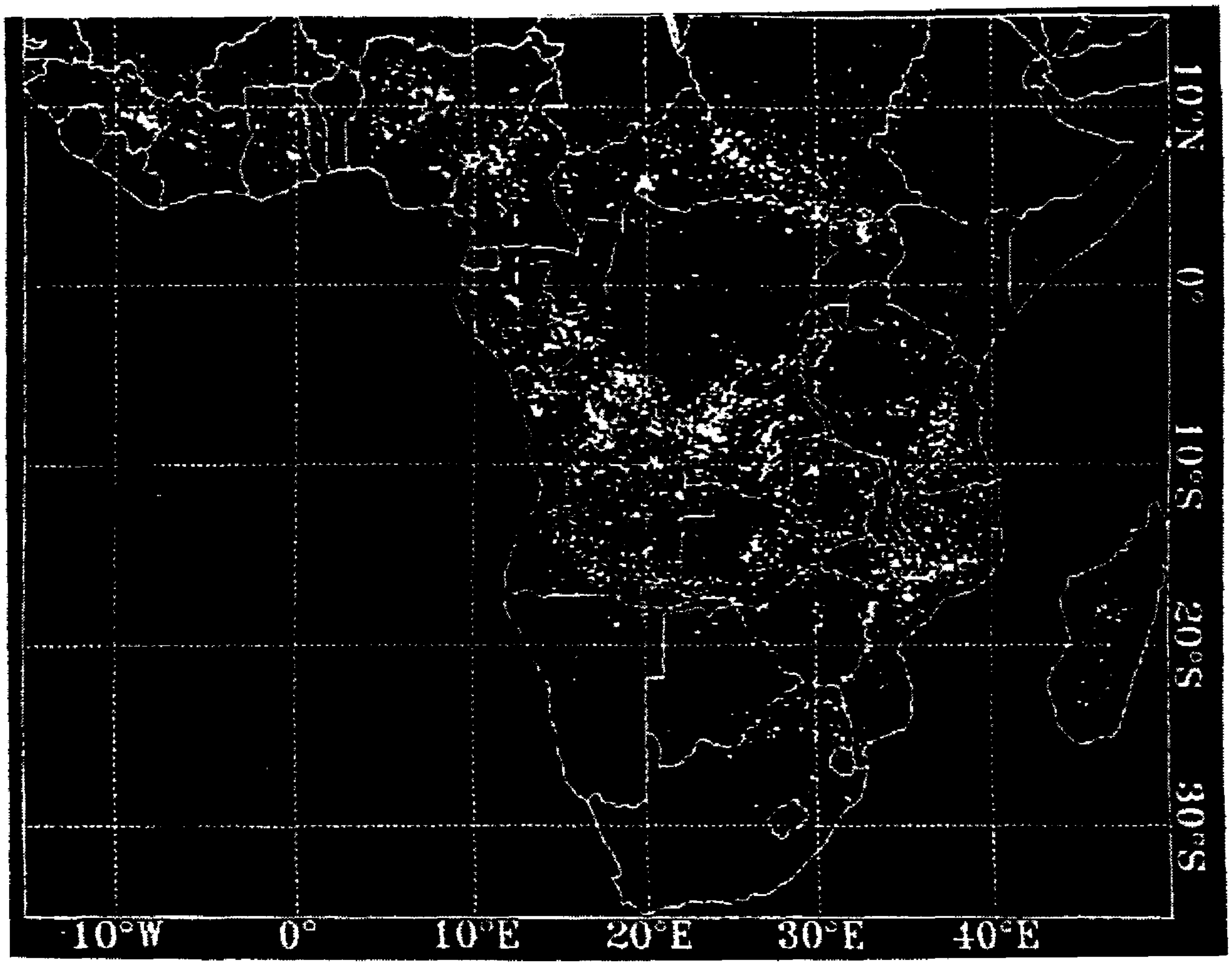


Figure 6

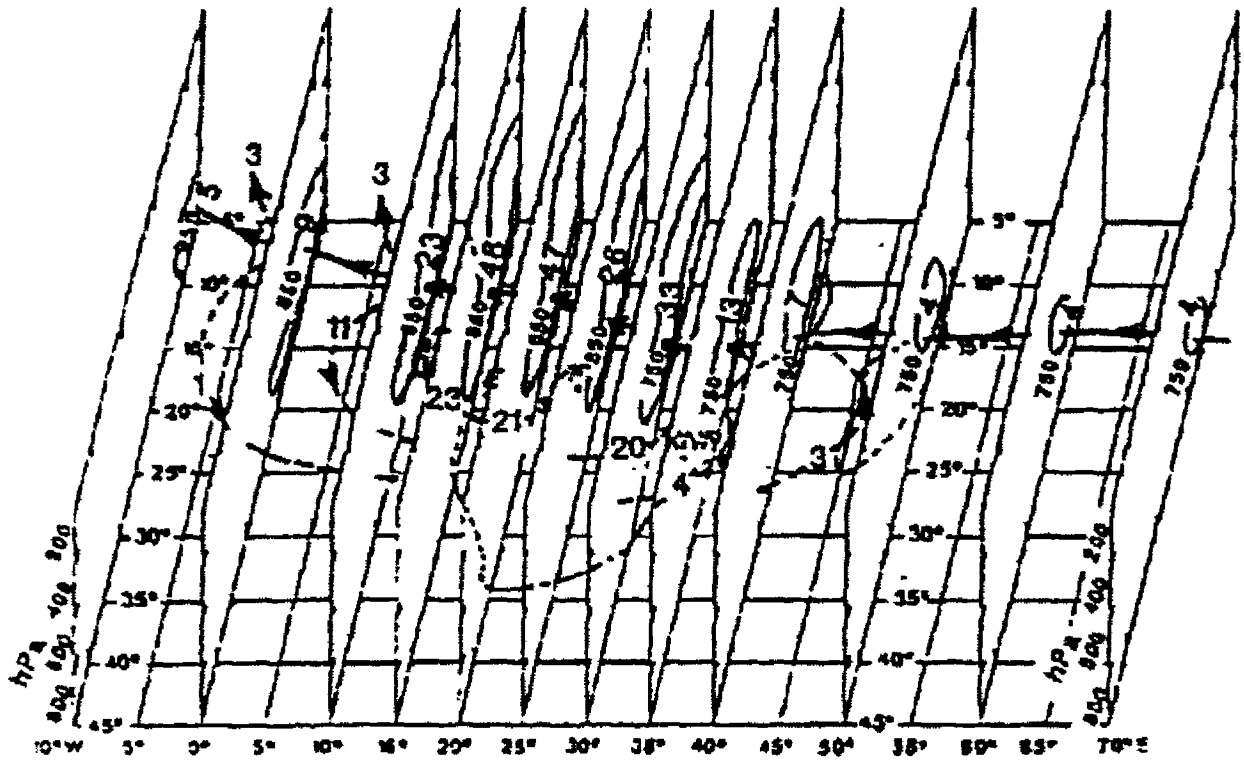
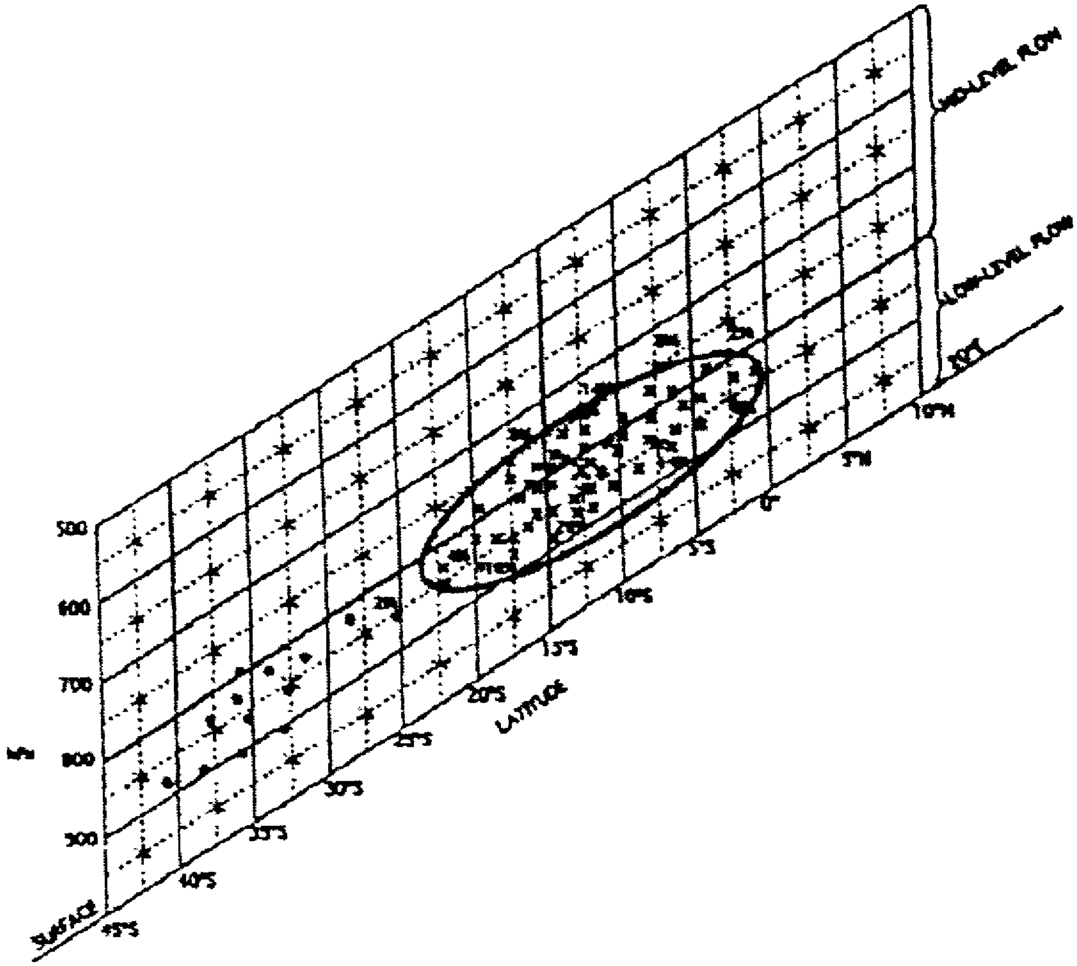


Figure 7



MID-LEVEL FLOW
LOW-LEVEL FLOW
LATITUDE
SURFACE
hPa
500
600
700
800
900
45°S
40°S
35°S
30°S
25°S
20°S
15°S
10°S
5°S
0°
5°N
10°N

FOREST FIRE EMISSIONS DISPERSION MODELLING FOR EMERGENCY RESPONSE PLANNING: DETERMINATION OF CRITICAL MODEL INPUTS AND PROCESSES

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INTRODUCTION

The last two years have seen many countries in South East Asia, Central and South America severely affected by transboundary smoke haze originating from uncontrolled forest fires, burning mainly in tropical forests severely affected by drought. The magnitude of these events was largely unpredicted and unprecedented, and understandably governments were anxious for advice about health impacts on their populations along with steps that could be taken to mitigate the problems. In the absence of global guidelines for dealing with such emergencies, the WHO is currently faced with the difficult task of developing workable guidelines for dealing with forest fire emissions and their impact on human health and well-being.

Almost certainly, implementation of guidelines relating to health effects of exposure to emissions from biomass burning will involve the use of atmospheric transport models (ATMs) that allow the ability to predict impact areas and pollution concentrations downwind of forest fire source areas. Current ATMs utilising numerical weather prediction (NWP) model outputs have been developed to a high level of sophistication and can be initialised and run at a range of resolutions for any location on the globe. They can be used in the analysis and understanding of past events as well as in forecasting. Many countries affected by regional smoke haze from forest fires lack meteorological and air quality monitoring and modelling infrastructure. Atmospheric transport modelling based on NWP is clearly the most useful approach to determine the local and regional impacts of forest fires, particularly if the predictions are made readily accessible, most likely through specialized meteorological centres located strategically around the globe.

Since the Chernobyl nuclear accident in 1986, there has been a growing interest in the long-range transport and dispersion of atmospheric pollutants. The International Atomic Energy Agency (IAEA) coordinates the response to nuclear accidents or radiological emergencies. Meteorological support for these environmental emergencies is given through a network of centres of the World Meteorological Organization (WMO), known as Regional Specialized Meteorological Centres (RSMCs). There are now eight centres (Toulouse, France; Bracknell, UK; Montreal, Canada; Washington DC, USA; Melbourne, Australia; Tokyo, Japan; Beijing, China; and Moscow, Russian Federation). Each centre is responsible for the provision of advice in the form of a basic set of products, which includes the prediction of trajectories for releases at specified heights, atmospheric exposure and surface deposition.

Volcanic ash is an environmental problem that is a significant hazard to aircrafts. In a similar fashion to the response for nuclear emergencies, the prediction of the long-range transport and dispersion of volcanic ash is performed at centres coordinated by the International Civil Aviation Organization (ICAO).

Within the next year, all of the RSMCs will be able to respond to an emergency situation located anywhere in the world. In addition to these centres with global or hemispheric capability, there are many more centres that can respond regionally, that is, use limited area meteorological models to provide input data for ATMs, and an even larger number of organisations that possess ATMs. For example, the European Tracer Experiment (ETEX) (1) evaluated 47 models, while in a previous evaluation, 22 ATMs were applied using Chernobyl data (2).

A recent WMO Workshop (3) identified a range of meteorological and other requirements to support the forecasting of smoke and haze that could be divided into long-term and short-term. Long-term forecasts are associated with improved predictions of climate variability, such as that due to the El Niño Southern Oscillation (ENSO). Short-term forecasts are closely linked to daily and shorter time-scale smoke trajectory and dispersion forecasts. A number of limitations on the short-term forecasting of smoke from ATMs were identified at that meeting; many of these are elaborated later in this paper.

In this paper, we will focus on meteorological and emissions data available during forest fire episodes for input to ATMs, the output of which could be made available to health agencies for emergency response planning and decision making. Although ATMs can handle gaseous emissions, we concentrate here on the particulate matter emitted from forest fires since this apparently provides the greatest environmental and health impacts. It is emissions from tropical forest fires that have been most problematic in recent years.

Nature of current atmospheric transport models (ATMs)

The work of the RSMCs has demonstrated the value of two modelling techniques for planning purposes (4). The first technique is to compute the trajectories of air parcels. A "trajectory" is the path that an air parcel takes as it is transported by the winds. The computation assumes that the three-dimensional wind field is known accurately from NWP models, and that the parcel follows the wind (that it is neutrally buoyant). Earlier work relied on rawinsonde (instrumented balloons providing vertical soundings of atmospheric thermodynamics and winds) data alone, but the accuracy of the computations has been improved by the better temporal and spatial resolution of NWP models. The use of NWP models to provide the data input for ATMs also permits forecasts of trajectories whereas the use of rawinsondes does not. The trajectory technique is conceptually simple and requires only modest computer resources. Trajectories can be run forward in time to determine receptor areas, or backwards in time to determine the pollutant source areas. In general, multiple trajectories are required because of the variability of the wind field (e.g. the presence of vertical wind shear). RSMCs use trajectories released at three heights (500 m, 1500 m and 3000 m) above the source location. In regions of sparse data or atmospheric complexity, the determination of the wind field is uncertain. The spread of the end points of a number of trajectories released under nearly identical (spatial and temporal) initial conditions is a measure of atmospheric predictability. The larger the spread, the less predictable the atmosphere is.

The second technique is to use an ATM. This type of model is based on the conservation of mass for the pollutant. The movement of the pollutant through the atmosphere as a result of the mean wind field (provided by the NWP model) and turbulent mixing processes (parameterized in the ATM) is balanced by the difference between the emission inputs and pollutant losses due to deposition by wet (precipitation) and dry processes (also parameterized in the ATM). For species other than smoke, losses could also include radioactive decay or change of chemical species.

There are two main modelling approaches used in ATMs; Lagrangian models that follow the trajectories of segments, puffs or particles and Eulerian models which solve the diffusion equation at every point on a fixed grid. In Lagrangian models, the dispersion is accomplished by Gaussian (or an equivalent probability function) diffusion for segments and puffs and by Monte Carlo (Langevin-Markov) techniques for particles. For Eulerian models, the dispersion is usually performed by first order turbulent closure (transfer down the gradient), but higher-order turbulent closures could be used.

For long-range transport, both the Lagrangian and Eulerian modelling techniques provide similar results. The accuracy of the predictions is highly dependent on the NWP model input, particularly the moist convection and precipitation fields, atmospheric stability (the intensity of turbulent mixing depends on this quantity), the boundary-layer height (the value of this quantity reflects the spatial distribution of turbulent mixing), and surface roughness and topographical influences. Improving the NWP model data input, initialization and physical parameterizations improve these factors. In addition, the transport model requires good knowledge of the area of emissions, the amount of material released, the initial height over which the release occurs, and the equivalent particle size. For more sophisticated modelling, knowledge of the emissions of a spectrum of particle sizes would be required as well as information about coagulation and other physical processes affecting deposition processes in complex ways.

For emergency applications, ATMs are run off-line. For daily predictions of events which have emissions over a long period of time, such as the fires in SE Asia in 1997 and 1998, the ATMs may need to spin-up for initialization. Questions of what spin-up time to use for the initialization of the ATM and what averaging time to use can only be determined empirically through model calibration and verification.

The use of limited area NWP models (LAMs) allows increases in the model resolution of wind field. In general, meteorological centres possess a suite of models of different domain sizes and resolutions. Increased model resolution input data for ATMs can produce better results, provided that the frequency of input data is increased as well as its spatial resolution. For very high-resolution NWP models, the physics of ATM turbulent mixing processes change as the atmosphere goes from being quasi two-dimensional in nature to three-dimensional. Also, the treatment of the rainfall changes from being parameterized at larger spatial scales, to being explicit at smaller spatial scales. A third change in moving to higher horizontal resolution is that the LAM must then account for vertical accelerations and become non-hydrostatic.

Verification of the general smoke pattern predicted by ATMs can be performed using satellite and aircraft data. This is sufficient for relative (qualitative) modelling. However, for health applications, quantitative modelling may be needed. In this case, determination of emission rates as a function of particle size, emission area, height extent and measurements of airborne concentrations and surface depositions need to be performed, in addition to smoke patterns derived from satellite measurements, in order to initialize, calibrate and verify the model. Typical forest fire smoke deposition velocities should also be determined experimentally.

Meteorological inputs for ATMs

The input necessary to drive ATMs comes from NWP models. These data are available on grids at regular temporal intervals in the form of direct-access, fixed-length records, one record per variable per level. Some pre-processing of the data is required. The data usually arrive in a compressed form and must be unpacked. The map projection and the vertical coordinate systems of the ATM and the NWP models often differ and interpolation to the ATMs coordinates may be required.

The basic fields required are the wind components (u, v, w) (although the vertical velocity could be derived from the continuity equation if it was missing, for example if rawinsonde data were used instead of NWP data), temperature, height or pressure, and the surface pressure. For smoke applications, it is also necessary to have the moisture and rainfall fields to be able to compute the wet deposition. Other fields that are desirable, but not essential, are the surface fluxes of momentum, heat and moisture.

Additional information is required to initialize the ATM. The starting time, run duration time, number and location of sources, height of emissions, emission rate, hours of emission, averaging interval, and the diameter, density and shape factor of the particles or their deposition velocity are all required. For applications other than smoke, a number of other quantities may also need to be specified.

NWP models rely on data from a variety of sources, including the synoptic surface network (wind, temperature, humidity, pressure, precipitation), the ship surface network, pilot balloons, rawinsondes, dropsondes, buoys, pilot reports (AIREP), wind and temperature profilers, automatic sensing of winds and temperatures from commercial aircraft (ACDAR, ASDAR, AMDAR), satellite-derived temperatures (SATEM, TOVS), moisture (HUMSAT), cloud-drift winds (SATOB), scatterometer winds (ERS-2) and sea surface temperatures (SATOB-SST).

A data assimilation and analysis procedure is then employed which accounts for the raw observations, their reliability (instrument error) and representativeness and the state of the atmosphere (all the atmospheric variables must be mutually compatible and must satisfy certain balance conditions). The data are then analyzed onto a regular spatial grid at fixed times. Even with all of these sources of data, there are still regions of the atmosphere that are sparsely covered, such as at the equator. The introduction of pseudo-observations (PAOBS) and tropical cyclone bogussing offers some help here.

The RSMCs, outside the South East Asia - Western Pacific region, have the following suite of models that could be used to drive ATMs (1, 5, 6). It should be noted that:

1. Model resolution is not a static quantity; Centres will increase their model resolution as computer resources improve.

2. Specification of the resolution for spectral models is ambiguous. We have used a linear grid estimate and have given the equatorial resolution for the non-stretched global spectral models.

Canada:
Global, 21-level, T199 spectral model (resolution about 0.90 degrees, or about 100 km); LAM, 28-level, variable resolution, uniform resolution of 0.33 degree (or about 35 km) over North America and adjacent oceans; ATM (7), Eulerian model, 11-levels, 150 km, 50 km and 25 km resolution options.

China:
Global, 19-level, T106 spectral model (resolution about 1.7 degrees, or about 189 km); LAM, 19-level, 1 degree model (resolution about 91 km); ATM, details not available.

France:
Global, 3-10 day forecasts, 31-level, T213 spectral model (resolution about 0.84 degrees, or about 93 km); Global, 0-96 hour forecasts, 27-level, variable resolution, T521.5 spectral model over France (about 20 km), T42.5 over New Zealand (about 250 km); LAM, 27-level, E66 model (resolution about 10 km); ATM (8), Eulerian model, 15-levels, 0.5 degrees (resolution about 40 km).

Japan:
Global, 30-level, T213 spectral model (resolution about 0.84 degrees, or about 93 km); LAM, 36-level, 20 km resolution; ATM (6), Lagrangian particle model, resolution about 0.84 degrees, or about 93 km.

Russian Federation:
Hemispheric, 15-level, T40 spectral model (resolution about 4.5 degrees, or about 350 km); LAM, 11-level, 50 km resolution; ATM, details not available.

United Kingdom:
Global, 19-level, 0.83 degrees latitude and 1.25 degrees longitude or about 111 km; LAM, 19-level, 0.44 degrees (resolution about 31 km); LAM, 31-level, 0.15 degrees (resolution about 11 km); ATM (9), Lagrangian particle model, variable resolution.

United States:
Global, 28-level, T126 spectral model (resolution about 1.43 degrees, or about 159 km); Global, 42-level, T170 spectral model (resolution about 1.06 degrees, or about 117 km); LAM, 38-level, 48 km resolution; LAM, 50-level, 29 km resolution; ATM (10), hybrid Eulerian-Lagrangian model using particles and puffs, variable resolution. (This model can be run via the internet: http://www.arl.noaa.gov/ready/ hysplit4.html)

Australia

The Australian modelling suite is illustrated in Figure 1. The NWP models available include the global model (GASP), which is a 19-level, T79 spectral model (resolution of about 2.25 degrees, or about 250 km at the equator); the tropical limited area model (TLAPS) which is a 19-level finite difference model with resolution of 0.75 degrees, or about 83 km at the equator; the mid-latitude limited area model (LAPS) which is a 19-level finite difference model with resolution of 0.75 degrees, or about 83 km at the equator; and mesoscale limited areas models (meso-LAPS) which are 19-level, finite difference models with a resolution of 0.25 degrees, or about 25 km.

Because of increased computer resources from October 1998, the resolution of all of the above models will be increased substantially. GASP will become 29 levels, T239 (resolution about 0.75 degrees, or about 83 km at the equator); TLAPS and LAPS, 29 levels, 0.375 degrees (resolution about 42 km at the equator); and meso-LAPS, 29 levels, 0.125 degrees (resolution about 12 km). The domain of meso-LAPS will be expanded to include all of Australia in a single forecast (55 S - 0 S latitude, 90 E - 170 E longitude). The ATM used in the Melbourne RSMC is a hybrid Eulerian-Lagrangian model which uses puffs in the horizontal and particles in the vertical, and it can be driven by any of the operational models described above (9). The resolution of the output concentration grid can be varied to suit the application.

In addition to the RSMCs, a number of other countries possess global meteorological models or LAMs. Some of these include:

The common ECMWF model:
Global, 31-levels, T213 spectral model (resolution about 0.84 degrees, or about 93 km)

The common Nordic-Dutch-Irish-Spanish model called HIRLAM:
LAM, 31-levels, 0.5 degrees resolution, or about 50 km

Germany:
Global, 19-level, T106 spectral model (resolution about 1.7 degrees, or about 189 km); LAM, 20-level, 0.5 degree (about 50 km); LAM, 30-level, 0.125 degrees (about 12 km)

Brazil:
Global, 28-level, T62 spectral model (resolution about 2.9 degrees, or about 322 km); LAM, 42-level, 40 km

South Africa:
Global, 28-level, T62 spectral model (resolution about 2.9 degrees, or about 320 km); LAM, 17-level, 80 km

India:
LAM, 16-level, 0.5 degrees (resolution about 50 km)

Republic of Korea:
Global, 21-level, T106 spectral model (resolution about 1.7 degrees, or about 189 km); LAM, 23-level, 40 km resolution

Hong Kong:
LAM, 13-level, 1 degree (resolution about 100 km)

Singapore:
Global, 16-level, T63 spectra model (resolution about 2.8 degrees, or about 312 km); LAM, 12-levels, 127 km resolution; 13-levels, 63.5 km resolution

Emission rate inputs and deposition rates for ATMs

Previous sections of this paper discussed the meteorological inputs for ATMs in some details. To provide reasonable predictions of particulate concentrations for assessment of health impacts, ATMs also require knowledge of the area and location of emissions, the amount of material released, the height of that release, and the equivalent particle size. In addition, for more detailed understanding of health impacts and processes such as settling velocity for deposition calculations, detailed particle size distributions should be obtained. Unfortunately, it is in these areas that the greatest uncertainty in air quality modelling for forest fires occurs.

Since the discovery of the importance of biomass burning, particularly in the tropics, for global atmospheric chemistry (11), there has been a great deal of work done on the nature and impacts of biomass burning in many parts of the world. This is reflected in the very comprehensive review edited by Joel Levine (12). Much of the work has been concerned with characterizing emissions, emission factors, impacts and measurement systems at the global, sub-global (eg. tropics), regional (eg. Amazonia, Southern Africa) and local level. However, there is very little discussion of emission rates from biomass burning in the literature. Our ability to reliably predict ground level particulate concentrations using ATMs running with NWP input is likely to be severely constrained without such information. Whilst it is possible to broadly characterize area emission rates based on published estimates of total emissions over a period of time (for example a season or year) and area burnt, this is likely to be very imprecise. Unfortunately, there are major difficulties in overcoming this because emission rates are hard to characterize, being dependent on many factors including fuel type, climatic conditions and fire intensity (13).

Recently, the NOAA Air Resources Laboratory (ARL) (Web page mentioned above under the United States ATM) has used published data for tropical biomass burning (14,15) to calculate the amount of particulate emitted per hectare of forest burning. This was then used in the HYSPLIT_4 ATM (10) for prediction of particulate concentrations downwind of fires in South East Asia, Mexico and Florida. When the ARL ATM is operated for a major fire, source locations and areas are updated on a daily basis from satellite imagery. ARL acknowledges the uncertainty of emission rates and calibrate their ATM predictions of concentrations by balancing their emission rate and their deposition velocity (particle size, density and shape) assumptions to give approximately the same order of magnitude for predicted concentrations as those determined by PM_{10} (sub-10 micron sized particles which are of significance for human health) measurements at 10 m height. They also compare predicted patterns and concentrations to satellite-observed quantities. The quantitative predictions by ARL are the only use of forest fire emission rates in a regional ATM that we know of.

Although local burning experiments (16-18) can provide more precise emission characteristics and rates, such information is of only limited use for atmospheric modellers wishing to predict air quality downwind of a forest fire, anywhere on the globe, in real time. The development of new satellite remote sensing techniques based on improved sensors provides probably the best possibilities for developing real time estimates of particulate emissions. Kaufman et al (19) describe a promising method for estimating the rate of emission of aerosol and trace gases from fires based on the thermal radiation emitted from the fires. It is assumed that the emitted thermal radiation is proportional to the biomass consumed, and hence also to the emission rates of aerosols and trace gases. The method therefore can distinguish between smouldering and flaming fires, processes that are known to have different emission ratios (13).

There is relatively little experimental information available about the time evolution of particles in smoke plumes, including processes such as coagulation and deposition. Hobbs et al (18) provided some results from airborne remote sensing of a prescribed burn in the Pacific Northwest of the USA. Taking HYSPLIT_4 as an example of a state-of-the-art ATM, the dry deposition is determined either by a deposition velocity, or for particles, it may be computed as being the equivalent to the gravitational settling velocity, or it may be computed using the resistance method and information about the surface (10). In the simulation of the South East Asian fires, they used a deposition velocity of 0.004 m/s, typical of a 2.5

micron particle. Wet removal for soluble gases and particles is also defined in HYSPLIT_4, where particle wet removal is defined by a scavenging ratio within the cloud and by an explicit scavenging coefficient below cloud base.

EXAMPLES OF THE USE OF ATMS IN REGIONAL FIRE SITUATIONS

During August-October 1994, significant wildfires burning in Borneo and Sumatra produced heavy smoke haze across much of Borneo and Peninsular Malaysia, including Singapore. Particularly large fires occurred in the area around Pangkalan Bun in Indonesian Kalimantan. Figure 2a shows a composite of daily trajectories (each starting at 00Z) for the period 10 September - 15 October, initialized at 950 hPa (500 m) above Pangkalan Bun. These trajectories show the 3-day forward motion of individual parcels of air, with no attempt to show smoke dispersion or concentration patterns. There appears to be two families of trajectories, with ~ 50 per cent of the total moving northwest over Singapore, Peninsular Malaysia and Sumatra, and the remainder recurving in monsoon flow towards the Philippines. It would appear that smoke entrained above Pangkalan Bun had a significant impact on the observed severely degraded air quality of Singapore, Peninsular Malaysia and Sumatra, although the latter location had forest fires of its own at this time. Equivalent backward trajectories from Singapore (Figure 2b) provide confirmation that the trade wind circulation is bringing smoke-laden air from fire regions, with more than 50 percent of trajectories passing over Kalimantan during their 3-day track.

Plots such as those produced in Figure 2 suggest that monthly or seasonal trajectory climatologies could be of value for risk assessment in regions known to suffer regularly from forest fire smoke (eg. South East Asia, Amazonia), especially if they could be tied to cyclical drought occurrences such as that due to the El Niño Southern Oscillation (20).

In Figure 3, we present a calculation of the transport and dispersion of smoke from the fires burning in Kalimantan, Sumatra, Irian Jaya and Papua New Guinea during October 1997. This figure is intended to show the kind of forecast that can be made when little information about the initialization is known. The emissions rate and the height over which the emission occurred were unknown. The emissions rate was set to unity (thus the resulting concentrations will be relative, not absolute values). The smoke was assumed as being released uniformly from the surface to 1000 m. The sources were located by determining "hot spots" from images of the fires produced by the NOAA-14 satellite. A deposition velocity of 0.001 m/s was used. No spin-up was employed, but instead the concentrations were averaged over 48 hours. The ATM was driven by the LAPS NWP model data.

Figure 4 shows a schematic diagram produced by the Singapore Meteorological Service, resulting from their analysis of the smoke pattern given by NOAA-14. The satellite images differentiate between the smoke and convective (water/ice) clouds to some degree, but often it takes careful analysis by an experienced person to see the smoke pattern clearly. Comparing the patterns given in Figures 3 and 4 shows agreement in the major patterns. This agreement occurs in spite of the fact that the calculations were averaged over 48 hours and the satellite scan was of the order of 20 minutes. The pattern of the surface deposition of smoke particles was similar to that for the airborne concentrations and is not shown.

Another comparison of predicted and observed smoke patterns is shown in Figures 5 and 6. In this case, the model was spun-up for a day as part of the intialization process. An attempt was made to produce absolute, rather than relative predictions. The emission rate/hectare was estimated from Levine (15) and the fire area estimated by NASA from satellite imagery. It was assumed that the smoke was released uniformly between the surface and 500 m. The resulting concentrations were averaged over 6 hours. Again, the airborne concentrations and the surface deposition patterns were similar. This time, we present the surface deposition pattern. The ATM in this case was driven by the US global model data. Particles were assumed to be 2.5 micrometers in diameter to simulate $PM_{2.5}$, and Stokian gravitational settling was computed. The predicted smoke concentration at 10 m over Kalimantan was several hundred micrograms per cubic metre. We also show the aerosol index determined by TOMS in Figure 7. The predictions give reasonable agreement with the limited observations that were available to us. The relatively minor differences