Modelling transport, dispersion and secondary pollutant formation of emissions from burning vegetation using air quality dispersion models

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Foreword

Concerns regarding air quality from people living on the edge of cities and in rural towns provide an added dimension to the management of both prescribed fires and, to an extent, wildfires. In the late 1990s, the-then Department of Natural Resources and Environment (NRE – now the Department of Sustainability and Environment) and the Bureau of Meteorology began jointly developing a sophisticated ‘smoke management service’. After considerable initial success, this research project became national through the involvement of the Australasian Fire Authorities Council.

Emissions from fires depend on the type, moisture content and structure of the fuel being burned and the intensity of the fire. Once those emissions are released, the transport and dispersion of the smoke is dependent on the height of the plume rising from the fire, the wind profile, the stability of the atmosphere and the nature and properties of the smoke itself.

This report summarises the original work and details the initial outcomes achieved.

Much is yet to be learnt about the emissions from Australian vegetation and the transport and dispersion of the smoke, but enough general principles exist to allow for some guidelines to be prepared.

A number of individuals made significant contributions to this ground-breaking work. Particular credit is due, however, to Dr Orestis Valianatos whose knowledge, ability and enthusiasm contributed so significantly to not only the work described in this report, but to the significant advances that have been made in Australia in this area in recent years. Particular credit is also due to Mr Kevin O’Loughlin, the-then Regional Director, Victoria, of the Bureau of Meteorology, for the strong support he provided for the project.

With the recent establishment of a Bushfire Cooperative Research Centre, further significant advances will hopefully occur in the prediction and management of smoke. This will see not only improved benefits being realised by rural fire agencies, but also obviously by the wider community.

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Introduction

Fire in ecosystems

Fire is an integral component of many native Australian ecosystems. Periodic wildfires are essential for maintenance of biodiversity, productivity and nutrient cycling. Many native species have evolved to require the stimuli of heat to release seed from woody cones (bradyspory) and chemicals from smoke for germination. Fire is also an important element of intensive forest management. It can be used as a tool to remove slash or woody debris left after logging operations and to prepare the ground for planting or regeneration. Judicious use of fire can be used to reduce competition from saplings and undergrowth vegetation to allow existing trees to grow larger and it can be used as a means of controlling invasive weedy species. Prescribed burning can be used to reduce hazardous fuel accumulation in forests, woodlands and heathlands by lowering the potential for devastating wildfires leading to the loss of life and property.

Prescribed fires are the preferred means for achieving certain resource management objectives in native ecosystems and plantations. Alternatives include mechanical slashing or pruning and herbicide treatments but each of these forms of control are expensive, labour intensive and potentially destructive. Despite the drawbacks of alternative methods, prescribed burning is used relatively infrequently due to the costs involved, public complaints regarding smoke production and increasing landowner liability. The general public has an aversion to prescribed burning as they do not like seeing the blackened aftermath of fire and often believe that all fires are ‘bad’.

State Environmental Protection Policies (SEPP), developed under the Victorian *Environment Protection Act 1970*, set air quality objectives and goals for the whole of the State. Ambient Air Quality SEPP (No S19) sets standards, goals, monitoring and reporting protocols for a set of common pollutants, sets air quality objectives for photochemical oxidants and visibility-reducing particles and establishes the framework for managing emissions into the air environment. Air Quality Management SEPP (No S240) establishes the framework for managing emissions into the air environment in the State, including protocols for managing the potential environmental impacts of prescribed burning. Under those protocols, for instance, an administrative agreement may be set up between the Department of Sustainability and Environment (DSE) and the Environment Protection Authority to govern the timing of prescribed burning in certain regions.

The potential impacts of prescribed burning on air quality are currently being addressed in fire management practices. It is inevitable that prescribed burning will produce some smoke but the effects of these events can often be put into perspective when compared to smoke production from unplanned, uncontrolled wildfires. Careful planning and implementation of prescribed fires by landowners and state agencies can greatly minimise the severity and duration of smoke hazards. To justify prescribed burning in plantations and native ecosystems, a comprehensive plan must be developed to reliably predict smoke emissions, rates of smoke diffusion and chemical transformations and to provide a framework for risk assessment and decision making regarding management of smoke.

Fire management systems

An integrated fire management system should be based on a thorough understanding of the behaviour of fire in specific vegetation types. It requires resources to actively manage all wildfire and prescribed fire situations, to use prescribed fire to reach resource management goals and to define and manage the threshold between the desired and undesired effects of uncontrolled natural and human-caused fires. An important component of an overall fire management system is the effective management of smoke. Specific objectives of smoke management plans should be to:

- minimise the harmful effects of smoke
- provide a framework to identify and define priorities regarding smoke management
- develop and apply a comprehensive forecasting system to assess the impacts of wildfires and prescribed fires on air quality
- assist the land manager to safely and accurately accomplish the prescribed burning objectives
- help other emergency response and land management agencies to obtain information needed for day-to-day business
- provide a quality service and advice to the public
- create a mechanism for continual improvement of chemical transport models and plume modelling systems and to serve as a basis for research into advanced physical and chemical processes
- take advantage of new science and computing technology to enhance smoke forecasting techniques
- provide decision support capabilities relating to assessment of exposure to smoke, impacts on health and welfare of firefighters and the general public and formation of policy decisions.

Minimising the impacts of smoke

As suggested above, one of the major objectives of smoke management is to minimise negative impacts on air quality in order to comply with regional and state standards. Choosing specific burning patterns can minimise the impacts of smoke while still achieving burn objectives. The six basic burning patterns outlined below are used in prescribed burning operations (Schwarz 1999).

- **Back or backing fire** – slow moving, low intensity fire burning into the wind with a high residence time. The long time periods involved may allow wind shifts so an area may be divided up into sub-blocks and fired individually. Smoke dispersion from this type of fire is generally poor. However, a backing fire will produce considerably less (up to 50%) smoke per unit of fuel burned than a head fire moving with the wind (NWCG 1985, 1989). A backing fire with a slower rate of spread and longer residence time consumes a higher percentage of the fuel in the active flaming phase of combustion than other fire types.
- **Head fire** – rapid and inexpensive fire with good smoke dispersal and a short residence time. During marginal smoke dispersal conditions the most effective ignition pattern is a strip head fire. The width of strips and timing of ignition is determined from information obtained from smoke monitors located downwind. The rate of smoke production can be regulated and thus the density of smoke can be kept within acceptable concentrations by creating ‘puffs’ of smoke and allowing them to disperse prior to additional ignition. Unfortunately, head fires have the potential to escape by spotting over control lines.
- **Spot fire** – a variant of the head fire type which produces variable effects due to being a combination of localised back, flank and head fires.

- **Flank fire** – a compromise between a back fire and a head fire. A flank fire is characterised by moderate intensity and medium residence time and it can be modified to behave like a head fire, a backfire or something in between depending on spacing of the areas of ignition and the speed of which the flanks are ignited.
- **Chevron fire** – a variant of the flank fire for use in sloping areas. It may be adapted to any situation where wind and slope would interact to make a fire unmanageable with either backfires or head fires.
- **Centre ring fire** – a rapidly moving, high intensity fire that produces a large convection column. The edge of the outer ring acts as a backfire and is very easy to control along the perimeter of the burn area. The inner fire begins to interact with the outer ring in such a way that it creates its own wind pattern. The convection column produced is an excellent mechanism for smoke dispersal. Unfortunately, this technique is rarely effective. The convection column carries large quantities of smoke aloft during the active burning phase but after the flaming front has passed a large area of smouldering fuel remains and does not generate enough heat to maintain a convective column to disperse it.

In addition to careful planning and use of different types of fire for prescribed burning, other techniques for effective smoke management include:

- identification of smoke-sensitive areas for reasons of danger from reduced visibility or adverse impact on human health or welfare
- minimising the generation of smoke in sensitive areas when prescribed burning is essential for protection of life and property
- prediction, monitoring and evaluation of the impacts of smoke from each burn and development of risk assessment procedures by modelling ‘best-’ and ‘worst-case scenarios’
- development, maintenance and continual improvement of an inventory of smoke emissions from prescribed fires and wildfires for air quality modelling activities (i.e. components such as carbon monoxide, volatile organic compounds, total suspended particulate matters, particulate matter less than 10 and 2.5 microns in diameter)
- continual improvement of smoke management models and techniques
- addressing interstate smoke transport issues through enhanced communication and the development of interstate/interagency agreements
- generation of an appropriate framework for the continued use of fire for fuel reduction purposes in native ecosystems and for the use of prescribed fire as a management tool.

Monitoring smoke emissions

The extent of monitoring in an integrated smoke management system should match the size and location of the fire and the potential impacts in surrounding areas. For small fires or fires that are remote enough to result in little or no noticeable impact on the public, the following monitoring techniques may be sufficient:

- tracking the direction of the smoke plume from the ground or using aircraft
- posting personnel on vulnerable roadways to look for visibility impairment and initiate safety measures for motorists if required
- posting personnel at other smoke sensitive areas to look for smoke intrusions,
- tracking meteorological conditions during the fire
- monitoring nuisance complaints from the public.

Larger fires or fires conducted in areas close to housing or public facilities obviously require greater levels of monitoring. The above mechanisms may be implemented using a greater number of personnel involved in operational, logistic and planning tasks.

Objectives of the study

The environmental care principles set out in the Code of Practice for Fire Management on Public Land (CNR 1995) include the requirement that fire-management activities address air quality through measures that diminish the impacts of smoke generated by prescribed burning. A comprehensive system that predicts emission, diffusion, transport and chemical transformations of smoke and can provide support for risk assessment across a range of temporal and spatial parameters (used as a basis for decisions in the smoke management process) would help address the requirements of the Code.

An efficient smoke management system helps in reducing emissions by identifying and avoiding smoke intrusions into sensitive areas, monitoring and evaluating smoke impacts for each fire and by facilitating coordination among local and interstate land management agencies. In order to meet these objectives the forecasting system should include the following components:

- characterisation of fuel
- emission modelling
- plume rise modelling
- modelling of smoke transport
- dispersion and formation of secondary pollutants
- risk assessment of emissions from fires.

Each of the above components or modules of smoke management will be described in the following sections. Data generated from each module forms input information for modelling processes in other modules of smoke management and an integrated approach is therefore essential for successful application of the system. The knowledge, techniques and methods of smoke management already in place in Victoria and elsewhere will be discussed and suggestions for further research will be made. A proposal is made to develop an Air Quality Dispersion Model (AQDM) as the central core for smoke management. The final part of the report outlines the validation process of the proposed Smoke Management System (section 7). How the system will be implemented and the potential benefits that will be gained from it are discussed in section 8.

Fuel characterisation

The need for fuel characterisation

Smoke produced from burning vegetation may vary widely according to the type, amount and condition of the fuel consumed. A model with the ability to predict the quantity of fuels that are likely to be consumed by fire under specific burning conditions and for a given fuel type is required for effective smoke management. In addition, the model should have the capacity to simulate the spread and behaviour of fires under conditions of heterogenous terrain and fuels and changing weather conditions. A database with information relating to fuel types, weather and landscape patterns and fire behaviour should be developed to support smoke emission modelling within an integrated smoke forecasting system.

Accurate fuel characterisation can be used to support models developed for predicting fuel consumption, smoke production and fire behaviour during both wildfire and prescribed fires. The main objective of fuel characterisation is to develop useful and consistent classifications of vegetation that can be used to generate information from broader scale data relating to vegetation cover. If low levels of accuracy are required, aerial photos may be sufficient to make quick, easy and inexpensive determinations of quantities of fuel and stand conditions (Ottmar et al. 1998). For more accurate information requirements, a database of types of the vegetation cover should be developed from ground inventories and direct measurement of site conditions (e.g. fuel load and arrangement, vegetation composition and structure, temporal moisture variability). The characteristics of fuel required for estimating the type and volume of smoke produced are:

- type of fuel
- moisture content and size (i.e. larger fuel particles and fuels with high moisture content produce more smoke)
- arrangement (i.e. fuels that are more compact produce more smoke)
- amounts of fuel (i.e. higher fuel loadings produce more smoke).

If even more detailed information is required in relation to vegetation description a model to compute plant biomass should be used. A very straightforward software package is BIOPAK (Means et al. 1994) and is readily available from the Forest Resources Systems Institute, Alabama, USA. BIOPAK is a software package that links plant measurements to a library of documented prediction equations to estimate plant components such as leaf mass, leaf area, stem wood mass, bark mass and fuel size classes. For a given species, the program can choose appropriate equations from the library using a set of built-in assumptions based primarily on input data of plant dimensions, the geographic area sampled and seral stage of the vegetation. The main application in fire management is for calculating fuels of live plants by size classes. The software includes a library of over 1100 prediction equations, most of which were developed in the Pacific Northwest of North America, including south-east Alaska, northern Rocky Mountains and the Sierra Nevada Mountains. For Australian regions it would be necessary to use the Equation Library Editor facility to modify the prediction equation library.

The smoke produced from burning vegetation varies widely according to type, amount and conditions of the fuel consumed. Therefore, a model with the ability to predict the quantity of fuels that will be consumed in a certain fire under specific burning conditions and fuel types is the first requirement of the smoke forecasting system. In conjunction, a model that can spatially and temporally simulate the spread and behaviour of fires under conditions of heterogenous terrain, fuels and weather should be used. As suggested above, a database with standard sets of fuel types is also needed to develop fuel consumption and fire behaviour models and is required to support an emission modelling system.

Fuelbeds

Understanding the characteristics of spatial fuel layers or fuelbeds is one of the most important features of fuel and fire management decision support systems and vegetation dynamics models. Knowing the characteristics of fuelbeds has always been important to fire managers and such information is becoming increasingly important to ecologists, air quality managers and carbon balance modellers. Since fuelbeds largely determine fire behaviour and fire effects they must be characterised and mapped before any calculation of fire potential can be made. Fuel mapping, hazard assessment and evaluation of fuel treatment options and sequences all require a consistent and scientifically based fuel classification system.

Fuelbeds are complex in structure and vary widely in physical attributes, in the potential fire behaviour and effects and in the options available for fire control and use. The variation in fuelbed characteristics is not chaotic but rather the expression of ecological processes, natural disturbance events and human manipulation. Despite this, it would be prohibitively difficult to inventory all of the fuel bed characteristics necessary to predict events for making management decisions. Some method of classifying fuels and inferring fuelbed properties from a limited set of observations or data is needed. The search continues for a classification and characterisation scheme that simplifies the complexity of fuelbeds to a reasonable degree while still being informative enough to serve a variety of users. Sandberg and Ottmar (1999) presented an introduction to the characterisation of fuelbeds for the purposes of predicting and assessing fire behaviour and fire effects, for mapping fire hazard and potential fire effects and for inferring fuelbeds properties from remote sensing.

Vegetation typology

To assist in the development of a fuel characterisation scheme, an initial approach would be to use an existing system related to vegetation typology in Victoria. This system has been available for some time and is continually being updated, reviewed and reassessed as more data becomes available. The vegetation typology scheme currently in use is hierarchical with the primary vegetation unit called an Ecological Vegetation Class (EVC). An EVC is identified on the basis of broad floristic composition, vegetation structure, vegetation life histories and environmental and ecological features. Each EVC may then be composed of one or more Floristic Communities.

It is thought that an ECV exists due to a common regime of ecological processes. For example, ‘wet forest’ is a common EVC. Wherever wet forest occurs across Victoria, it is assumed to have the same structure (e.g. tall open or closed forest), to exist under certain physical environmental regimes (including rainfall, soil types, altitudinal range, aspect) and to carry the same types of plants (e.g. eucalypt overstorey, a dense layer of tree ferns, tall mesophytic shrubs, high diversity of smaller ferns and bryophytes). Floristic Communities are identified on the basis of species present (pers. comm. Cathy Molnar, Department of Natural Resources and Environment). Using the above example, wet forest may carry different suites of species in different areas of Victoria and can therefore be readily distinguished (e.g. Otways wet forest, Gippsland wet forest, Grampians wet forest).

Emission modelling systems

Defining emissions from biomass burning

Biomass can be defined as the amount of living material per unit area or volume and is usually expressed as mass or weight. Burning of vegetation biomass is part of the dynamic equilibrium between biotic production and decomposition and is the primary oxidation mechanism in most temperate zone ecosystems due to relatively slow rates of biological decomposition (Pyne 1982). The heat generated by fire and by-products of combustion have multiple atmospheric, climatic, social and ecological effects.

Biomass burning is a source of greenhouse gases such as carbon dioxide (CO_2), methane and nitrous oxide. In addition, it is a source of chemically active gases, including carbon monoxide (CO), non-methane hydrocarbons and nitric oxide. These gases, along with methane, lead to the chemical production of tropospheric ozone (another greenhouse gas) and control the concentration of the hydroxyl radical which regulates the longevity of almost every atmospheric gas. Following biomass burning, biogenic emissions of nitrous oxide, nitric oxide, and methane are significantly increased. It is hypothesised that enhanced post-burn biogenic emissions of these gases are related to fire-induced changes in soil chemistry and microbial ecology (Levine 1994).

Other compounds are produced from burning of biomass. Particulate matter less than 2.5 microns in diameter, organic carbon, hydrocarbons and inorganic carbon emissions scatter light and contribute to haze, which degrades visibility (Leenhouts 1998). While greenhouse gases produced from biomass burning have the potential to trap radiant heat, particulate matter acts to reflect solar radiation (Crutzen & Goldammer 1993).

Modelling smoke emissions

Research focussing on modelling emission rates from biomass burning would make the following contributions:

- generate methodologies and tools to collect, analyse and summarise the smoke emissions measurements to be used in the Air Quality Dispersion Model (AQDM), and
- provide a clearer understanding of the effect and accuracy of the modelled input emission rates on the proficiency of the AQDM for smoke forecasting.

The Air Quality Dispersion Model is composed of a number of inputs including the amount and nature of biomass consumed, emission source strength, combustion efficiency of fuels, chemical and physical composition of emissions, emission factors and rates of heat release. Emission source strength is the rate of production of emissions expressed in units of mass per unit time or mass per unit time per unit area. Emission source strength is the product of the rate of biomass or fuel consumption and an emission factor for the pollutant of interest and is representative of the physical and chemical fuel characteristics. Total emissions from a fire or class of fires is the source strength integrated over total time of burning and can be estimated by multiplying the emission factor by the total biomass consumed by the fire. An emission inventory is the aggregate of total emissions from all fires or classes of fire in a given period for a specific geographic area (Sandberg et al. 1999).

Combustion efficiency of fuels is defined as the ratio of carbon released as CO_2. For convenience, the modified combustion efficiency is defined as the ratio of the carbon released as CO_2 divided by the sum of the amount of CO_2 and CO released. Alternatively, dividing the amount of CO released by the amount of CO_2 released gives an approximate measure of combustion efficiency. Ratios of CO to CO_2 range from approximately 0.04 for flaming combustion to more than 0.25 for smouldering combustion.

In discussions of prescribed burning, the combustion process is divided into phases of preheating, flaming, glowing and smouldering. The different phases of combustion greatly affect the amount of smoke emissions produced (Ward & Hardy 1984, —1991). The preheating phase seldom releases significant quantities of emissions to the atmosphere. The flaming phase is the fast combustion of finer fuels and is associated with generation of large amounts of heat. The glowing combustion phase is usually associated with burning of large amounts of woody fuels such as piles of logging residue. Smouldering combustion is limited to situations where the fuel is consumed by non-flaming processes and is generally of low intensity. Smouldering combustion produces high emissions of particulate matter and CO (Schwela et al. 1999). The smouldering combustion phase represents very inefficient and incomplete combustion that emits pollutants at a much higher ratio to the quantity of fuel consumed than does the flaming combustion of similar materials.

Particulate emissions from prescribed and wildfires depend on the mix of combustion phases, the rate of energy release and the type of fuel consumed. All of these elements must be considered when selecting the appropriate emission factor for a given fire and fuel situation. In the case of wildfires, it has been hypothesised but not proven that the nature and amounts of air pollutant emissions are directly related to the intensity and direction of movement of the wildfire relative to the wind and are indirectly related to the rate at which the fire spreads. The factors that affect the rate of spread of fire are weather (wind velocity, ambient temperature, relative humidity), fuels (fuel type, fuel bed array, moisture content, fuel size), and topography (slope and profile of the area).

There are currently two approaches used by the U.S. Forest Service to monitor fuel loading, area burnt, fuel consumption and emissions produced from prescribed fires (Sandberg et al. 1999). The most accurate method of monitoring requires field measurements of fuel loading, fuel consumption and of the emissions produced (Brown 1974, Ward & Hardy 1991). A less accurate method uses visual assessment of fuel loading and these estimates are used as inputs to models to predict fuel consumption (Ottmar et al. 1993, Reinhardt et al. 1997) and emission production (Sandberg et al. 1979, Sandberg & Peterson 1984, Ward & Hardy 1991, Reinhardt et al. 1997). Logistical problems such as size of the burning area and difficulties in safely situating personnel and equipment close to fire have prevented the collection of any reliable emissions data on actual wildfires. Therefore, until such measurements can be made, the only available information has been obtained from burning experiments conducted in laboratory trials (U.S. Environmental Protection Agency – U.S. EPA 1996).

Emission models available

Models developed by the U.S. Forest Service can be used to predict particulate emission factors and source strength. These models address fire behaviour, fuel chemistry and ignition techniques and can predict the mix of combustion products at the event-scale (project level). Such models can be aggregated upward to the landscape, state and regional scales. It must be remembered that the accuracy of the results of an emission model is dependent not only on the quality of the input data, but also on the assumption underlaying the model. The characteristics of two models are described below.

A. **FOFEM 4.0** (First Order Fire Effects Model, Reinhardt et al. 1997)

This is an easy-to-use computer program, available from the U.S. Department of Agriculture, Forest Service, used to predict the effects of prescribed fire and wildfire in forests and rangelands throughout the U.S. It produces quantitative site-specific predictions of:

- tree mortality by species and size and by flame length,
- fuel consumption for duff, woody fuels and live fuel including canopy,
- smoke emissions from crown or surface fires,
- site-specific emission factors,
- combustion efficiency, and
- amounts of 2.5 and 10 micron particles and CO produced.

B. **EPM 2.0** (Emission Production Model, Sandberg & Peterson 1984)

The EPM predicts air pollutant emissions, source strength, heat release and plume buoyancy consistently for a range of fire environments and fuel types. The model requires an estimate of consumption of fuels from flaming and smouldering phases of the fire and a stylised description of ignition pattern. The EPM then calculates timed emission rates for gases, particulate matter and heat. The model, available from the U.S. Department of Agriculture, Forest Service, can provide:

- input to air quality dispersion models
- consistent predictive ability across a variety of U.S. ecosystems
- information relevant to wildland, rangeland and forest fires
- calculations for local, regional and national scales.

The EPM relies on a fuel consumption model called CONSUME 2.1 (Ottmar et al. 1993) which is the only fuel consumption model that distinguishes between combustion phases. The EPM then uses inputs of ignition pattern and theoretical equations of the various combustion processes to calculate rates of combustion from the mass of each fuel element consumed during flaming and smouldering. The ignition pattern is user-defined, and may be provided by fire spread models or estimated from land-use patterns.

Fuel loading values for fuel combustion models should include site-specific estimates of the oven-dry mass of living vegetation and dead biomass available for consumption by a fire. Ideally, these are further defined in terms of fuel size class, such as fine fuels (from 0 to 2.5 cm diameter), small fuels (between 2.5 and 7.5 cm diameter), large woody fuels (greater than 7.5 cm diameter), live vegetation and duff (partially decomposed litter). Each fuel component has a different propensity to burn in a fire and equilibrates its moisture content with the surrounding environment at a different rate. The amount of available fuel actually consumed by a fire is a complex function of many variables, however the main parameters are the fuel moisture content, fuel size class distribution and arrangement, ambient wind speed and fire intensity.

Fuel consumption models such as CONSUME 2.1 (Ottmar et al. 1993) exist for many fuel types in the U.S. If consumption models are unavailable for a given fuel type then the conservative assumption that 100% of the available fuel is consumed is used. The model predicts the amount of fuel consumption based on weather data, the amount and moisture of fuels and a number of other factors. CONSUME 2.1 can be used for most broadcast and underburns on forested lands in the western states of the U.S. if the woody fuels are relatively homogeneous and composed of Douglas fir, hemlock, alder, lodgepole pine or mixed conifer species. The model is currently being modified and the new version, CONSUME 3.0, will better predict total and smouldering fuel consumption during wildfires for national U.S. applications. The model is available from the U.S. Department of Agriculture, Forest Service.

Current international research programs

The South East Asian Fire Experiment (SEAFIRE) is a research activity currently in the planning and preparation phase and will be conducted under the scheme of the International Geosphere-Biosphere Program (IGBP). The International Global Atmospheric Chemistry (IGAC) Project is a core project of IGBP. One of the activities of IGAC Focus 2 (‘Natural variability and anthropogenic perturbations of the tropical atmospheric chemistry’) investigates the impact of biomass burning on the atmosphere and biosphere (Biomass Burning Experiment (BIBEX)). SEAFIRE will establish the fire research component within the Integrated SARCS/IGBP/IHDP/WCRP study on land-use change in south-east Asia.

SEAFIRE aims to explore the ecological impacts of fire used in forest conversion and shifting cultivation and fires in natural vegetation such as grassland and seasonally dry monsoon forests. The composition of smoke emissions, regional and global transport mechanisms and the chemical impacts of atmospheric pyrogenic emissions will be studied. Biogenic and marine sources of trace gases and aerosols will be considered, along with anthropogenic sources (e.g. fossil fuel burning, secondary chemical products). Special emphasis will be laid on inter-annual climate variability (*El Niño* Southern Oscillation—ENSO versus non-ENSO) and the role of the ‘warm pool’ in global distribution of smoke emissions.

This research program should provide many benefits to the user community including forest and other land management authorities and various environmental agencies. The research has potential application in management systems including remote sensing and GIS applications for decision support systems in fire management.

Completed BIBEX projects include:

- Southern Tropical Atlantic Regional Experiment (STARE),
- Transport and Chemistry near the Equator – Atlantic (TRACE–A),
- Southern Africa Fire-Atmosphere Research Initiative (SAFARI),
- Southern African Atmosphere Research Initiative (SA’ARI–94),
- Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO).

Ongoing BIBEX projects include:

- SAFARI-97 field campaign in Kenya implemented in September/October 1997,
- the Zambian International Biomass Burning Experiment (ZIBBE),
- Africa Biofuels/Emissions Research Programs (AB/ER),
- update on the Southern African Regional Science Initiative (SAFARI 2000),
- Fire Research Campaign Asia – North (FIRESCAN),
- South East Asia Fire Experiment (SEAFIRE),
- Large scale Biosphere-Atmosphere experiment in the Amazon (LBA).

Future research on emission modelling

It is obvious that current models used to predict emissions from fires are inadequate in coverage and incomplete in scope. Emission production models need improvement to include a greater range of fire and fuel types and to model multiple sources of emissions. Outputs should, but do not yet, include a complete array of chemical and physical components and initial plume buoyancy. Research needs to be conducted to link emission models to fire behaviour, air quality and dispersion models in a geographically resolved system and to have the capacity for scaling up to greater spatial scales (Sandberg et al. 1999).

For evaluation of existing emission models and development of models more suitable to Australian conditions a number of features of the input data must be taken into account. These include detailed characterisation of fuel types and loads, the chemical and physical composition of emissions, types and rates of combustion and heat release. In addition, the anticipated use of these data that will dictate the level of complexity and accuracy required. Emission modelling should also (Sandberg et al. 1999):

- support efforts to develop uniform minimum recording standards for prescribed fires
- provide real time inputs in order to continually validate transport and smoke dispersion models to estimate impacts on visibility and compliance with national air quality standards
- integrate fire behaviour models with emission production and smoke dispersion models
- support efforts to compare fuel consumption and emissions from prescribed fire and wildfire
- support research, development and refinement of fuel loading, fuel consumption, and emission production models
- provide tools for improved smoke management planning and operations.

The development of a smoke emission model that uses outputs from the fuel characterisation module (described in the previous section) and has the ability to incorporate a range of fire and fuel types is essential. The outputs from such a model would be in the form of predictions relating to fire effects and would allow planning recommendations for a range of burning conditions, fuel types and ignition patterns. In addition to estimating the production of gaseous and of particulate pollutants, the model would be required to provide rates of heat release, an important parameter for plume rise modelling (see next section).

Plume rise modelling

Calculating the pattern and effect of plume rise from fires is an important step in determining the contribution of smoke emissions to climate systems and the impact of smoke on human health and visibility. Buoyant plumes can carry emissions high into the atmosphere where long residence times are possible. This increases the potential for additional chemical changes that can create ozone and change visibility. Less buoyant plumes cause emissions to remain relatively close to the ground thereby compounding air quality issues (Ferguson et al. 1998).

The first approach in simulating smoke plume rise from fires is to use the plume rise model developed by the Commonwealth Scientific and Industrial Research Organisation Division of Atmospheric Research (Physick et al. 1994). This model is based on a description of a 'bent-over' plume and is therefore a more complete description of mean plume rise. It is in turn based on the model of Glendening et al. (1984) and has recently been more fully developed by Hurley and Manins (1995).

Input data for plume rise calculations includes ambient meteorological conditions, emission factors for each gas species and particulate size class produced, an average value for the fuel loading of the area and data from the fire relating to total burnt area and the mean rate of heat release. The rate of particulate emissions and plume rise heights can then be calculated and are imported into emission dispersion models (section 5). A more detailed description of the available literature on the plume rise module is given in Valianatos (1999). In order to develop a unified smoke plume model with the ability to calculate plume rise from buoyant sources of aerial emissions associated with biomass fires, the differences in formulas and assumptions made in existing plume rise models need to be analysed (Sandberg et al. 1999).

Modelling of transport, dispersion and secondary pollutant formation

Pollutants in the atmosphere

Air quality and land management planners lack spatially explicit planning and real-time systems for assessing impacts of fire on air quality. Appropriate models have to be based on air quality dispersion models (AQDM) to accurately simulate plume behaviour, dispersion, chemical transformations and deposition for a wide range of fire, topographic and climatic conditions. Until recently, these so-called 'research-type models' were considered unsuitable for practical application because of their high computational requirements. However, with the rapid development of computer hard- and software, the situation is changing and models of this type may be used for compensating for gaps in simpler dispersion models. More complex systems that are currently in use involve a dispersion and transport model (HYPLIT) but they do not take into account chemical transformations of smoke.

Pollutants emitted to the atmosphere from physical and biological processes, fires and anthropogenic sources affect ambient air quality. Background air quality is also affected by dispersion due to atmospheric movement and turbulence, removal processes (e.g. leaching by rain) and by secondary chemical reactions such as photochemical processes. Ambient air quality can be measured at a single point or as a source distributed over any area and length of time of interest. Atmospheric conditions and emission source strength can change rapidly and almost always change diurnally. Plume rise, plume trajectory and dispersion of smoke from fire may last from one to several days and must therefore be modelled as a series of separate events each lasting only a few hours. It is clear that comprehensive data sets and complex modelling systems are needed to predict, measure and monitor the effects of air pollution from fires to compare with pollutants from other sources.

A new approach for smoke management activities is proposed here. Instead of using simple dispersion models, a complex Air Quality Dispersion Model with state-of-the-art components and good records of successful validation studies is suggested. Such a forecasting system would require input of a minimum number of parameters describing the sources of smoke to be monitored (as described in Valianatos 1999, — et al. 1999*a*, —— et al. 1999*b*, — 2000, — et al. 2000) and outputs would need to be displayed in some form of user-friendly interface. This study aims to assess the suitability of current AQDMs for biomass smoke modelling and to highlight additional work that may be required to make these models more useful for smoke management.

Air Quality Dispersion Models

The aim of an AQDM is to provide a means of calculating air pollution concentrations based on a series of mass continuity equations. These equations describe the relationship between the concentration of a given pollutant in the atmosphere arising at a chosen location and the release rate, dispersion and dilution associated with it. Mass continuity equations are resolved by coupling chemistry with advection and diffusion processes. Predictions of transport and dispersion of smoke over long distances must also include spatial and temporal variability of winds, the presence of various terrain and weather features, chemical transformations and rates of chemical deposition. After formation of a smoke plume, the highly dynamic mixture of combustion compounds is transported from the emission site. During transport, the compounds change their chemical composition, physical characteristics and concentration in the air. The residence time of the combustion compounds in the air depends on the nature of the processes they are involved in and may vary from seconds or minutes to days or weeks.

The use of an AQDM that incorporates detailed chemistry of atmospheric aerosols and gases (anthropogenic and otherwise) generates an appropriate framework for a cooperative effort between atmospheric modellers and analytical chemists in addressing the problem of smoke management. Visibility impairment (the impact of the smoke plume on human vision) and regional haze (due to the presence of fine particulate matter less than 2.5 microns diameter) are just two of the adverse effects of smoke presence in an area. Atmospheric aerosol particles are of particular concern because of their impact on air quality over a range of spatial scales. Recent studies have shown that particles less than 2.5 microns are potentially harmful to human health. These particles are most often produced by chemical transformations taking place in the atmosphere rather than being emitted directly as smoke particles. The proposed AQDM will help in the understanding atmospheric aerosol processes and the relationship of ambient particulate concentrations to biomass burning.

If an AQDM is used for forecasting smoke dispersion and composition, the background or existing concentration of a certain pollutant must be taken into account. At any given time a particular pollutant may be present in the atmosphere due to release from natural and anthropogenic sources rather than from fire. If the background concentration of a pollutant is not taken into account, the concentration calculated at the receptor does not accurately reflect the amount of pollutant in the atmosphere and the validation process of the AQDM becomes inaccurate.

Estimating the impact of emissions from an individual source is best accomplished using a Lagrangian dispersion model. This model ‘follows’ the emissions as they are transported downwind. The Lagrangian framework sits within the HYSPLIT model (the smoke forecasting system used by the Department of Natural Resources and Environment) and provides direct assessment of impacts of emissions from a variety of sources. However, there are some physical processes, such as non-linear chemical transformations, that can be more completely and explicitly characterised using Eulerian grid modelling techniques. The computational demand of non-linear chemical transformations using a Lagrangian modelling framework is too high at present and therefore impractical for routine use. Furthermore, smoke management strategies are designed and evaluated by analysing ‘what if’ scenarios. The AQDM therefore has to accurately reflect the complexity of physical, chemical and biological processes being simulated to be able to provide better support for environmental decision-making.

Assessing AQDMs

Based on the above, the following selection criteria can been used to choose models that are most appropriate for this activity. An investigation and analysis of the characteristics of the available AQDMs and supporting data is needed in order to better understand their limitations. The following questions were asked of current AQDMs.

- Are calculations for secondary pollutant concentrations included?
- Can more than one type of emission source (e.g. point, area and volume sources) be incorporated?
- Does the model incorporate a sub-grid scale Plume-in-Grid (PinG) algorithm?
- Does the model contain a chemical mechanism compiler with a fast and accurate chemistry solver?
- Can input from multiple sources be used?
- Does the model accommodate multiple map projection and two-way grid nesting?
- Are there options for using more accurate solvers for transport and diffusion of emissions?
- Does the model include a component to describe aerosol dynamics in the atmosphere?
- Does the model treat cloud dynamics and chemistry by simulating the physical and chemical processes of clouds that are important in air quality simulations?
- Does the model incorporate CB-IV (Carbon bond-IV) and SAPRC (Statewide Air Pollution Research Centre) photochemical mechanisms?

According to positive responses to all or a majority of the above criteria, a list of models potentially suitable for smoke management is provided in Appendix 1. The application of each model in relation to smoke modelling is also described in detail. Several AQDMs appear to be potentially suitable for smoke modelling however, since validation data for biomass burnt during wildfires is largely unavailable, recommending the use of one model over another is not yet possible. In order to effectively assess the impact of a smoke pollutant it is necessary to use an air quality dispersion model with modules describing the chemical transformation of pollutants during transport and dispersion from the source to the receptor. A simple dispersion and transport model does not describe the effects of air chemistry on the final plume characteristics.

Preliminary recommendations for the AQDM to be adopted by DSE should be based on:

- meteorological and topographic complexities of the area
- the level of detail and accuracy needed for the analysis
- computing resources available
- the detail and accuracy of the database (i.e. emissions inventory, meteorological data, air quality data).

The following characteristics of the model should also be considered:

- **performance:** the time required for a complete forecasting loop to be completed
- **model implementation:** the effort required to adapt the AQDM to incorporate data from other agencies or systems (e.g. data provided by the Bureau of Meteorology meso-Limited Area Prediction System)
- **sensitivity and uncertainty:** the level of testing required to assess discrepancies between predictions from a model and observations. Some discrepancies are normal when using a mathematical model to describe complex atmospheric processes but it is important to determine the level of confidence or uncertainty associated with the model. Validation is generally based on existing data and continual assessment of new data.
- **scientific issues:** the possibility of including new modelling techniques addressing specific smoke-related issues
- **visualisation:** the workload required for the output of a model to be presented graphically and to be analysed statistically
- **human-computer interaction:** the number of people required to perform tasks associated with the system
- **data management**: the space required for archiving procedures and data processing.

After selection of an appropriate AQDM there are some immediate issues that need to be addressed in order to quantify the accuracy of the model. The following tasks should be performed:

- a comprehensive assessment of performance of the model and sensitivity to input data and how this affects the accuracy of results
- a study of the contribution of different modules and the impact of choosing alternative parameterisation schemes for different processes
- perform a preliminary evaluation of the capabilities of the model under Victorian conditions using data from previous studies
- document uncertainties in assumptions and parameters of the model and areas requiring further research and development
- develop methodologies for identifying the extent to which the model simulates reality by comparing model predictions against appropriate field measurements and statistically analyse the observed deviations
- design specific measurement campaigns for the validation of the model as part of the process for adapting the model to existing infrastructure
- tailoring of existing data sets and software to the application of a specific model
- evaluate the performance of the model to ensure that potential users can assess the reliability, consistency and accuracy of the model for themselves.

The AQDM ultimately adopted for smoke management by the DSE will have to satisfy the above criteria and considerations while being robust enough for extensive testing.

Risk assessment of emissions from fires

Predicting smoke intrusions

Risk assessment should aim to address the risk of emissions from fires by predicting the probability and severity of potential smoke intrusions into smoke sensitive areas. Smoke sensitive areas include highways, airports, communities, residences of asthmatics, hospitals, schools, chicken farms, recreation areas, factories and high tension lines. An automatic warning system based on such risk assessment and on output from smoke forecasting systems could then be designed. This warning system would need to incorporate current monitoring guidelines and protocols for source strength, air quality, visibility and nuisance impacts from fires.

As outlined elsewhere in this report (section 3), the issues to address when dealing with emissions from biomass fires include:

- characterisation of the magnitude and composition of the emissions and their transformations during transport
- quantification of resulting concentrations of ambient air pollutants
- evaluation of likely exposure scenarios for affected populations (both indoors and outdoors).

In case of wildfires, the concentration of smoke at ground level at distances from the source is the most important parameter in determining whether the source imposes a significant risk of exceeding an air quality standard or objective.

Visibility

Visibility is usually defined as the furthest distance at which an object can be identified. In a perfectly clean atmosphere composed of non-absorbent gases the only process restricting visibility during daylight is the scattering of solar radiation from gas molecules. This is known as ‘Rayleigh Scattering’ and is usually represented by a scattering coefficient. The visibility in an atmosphere in which Rayleigh scattering is the only optical process active may be used as a reference. If absorption of solar radiation is occurring in addition to scattering, an absorption coefficient may also be defined. The sum of the scattering and absorption coefficients is called the extinction coefficient. The only light-absorbing gas that is normally found in the atmosphere is nitrogen dioxide. The extinction coefficient increases as particle and gases are added to the atmosphere and visibility is reduced due to increased scattering and absorption by an increased number of particles. The most effective light scattering particles are within the range of 0.4 to 0.7 microns diameter with fine particles less than 2.5 microns affecting light scattering more than particles greater than 2.5 microns diameter. A useful index for quantifying the impairment of visibility by the presence of atmospheric aerosol particles is the deciview (Pitchford & Malm 1994).

Visual air quality is a term used to describe visibility aspects of air pollution. Overall visibility is influenced by non-pollution factors such as clouds, snow cover and the angle of the sun. The distribution and extent of pollutants in the atmosphere relative to the sight path of the observer has a large effect on the degree of visibility impairment. For example, if pollutants are distributed uniformly across the horizon and vertically from the ground to a height well above the highest terrain it is known as a uniform haze. If the top edge of the pollution layer is visible, as is often the case when a pollution layer is trapped below an inversion layer, it is referred to as a surface layer haze. A layer of pollution that is not in contact with the ground is an elevated layer. A smoke plume can be thought of as a special case of an elevated pollution layer, though from many vantage points it may not be possible to distinguish a plume from an elevated layer of pollution. It is possible to have combinations of distribution of pollutants such as multiple elevated layers of smoke superimposed upon a uniform haze (U.S. EPA 1999).

Visibility models available

One popular plume visibility model is the Reactive and Optics Model of Emissions (ROME). This model includes potential effects of light scattering by size-resolved particles (Seigneur et al. 1997, Gabruk et al. 1999). The modelling of aerosols in the Community Multiscale Air Quality (CMAQ) System also provides the capability to predict visibility (Byun 1998).

Verification and validation of the Smoke Management System

Verification and validation

The following plan defines the methods to be used for verification and validation of the proposed Smoke Management System. There should be three main steps in this process as suggested by Byun (1998):

- **evaluation** – assessment of the adequacy and correctness of the science represented in the models by comparison against empirical data
- **verification** – determination of consistency, completeness and correctness of the computer code and the adequacy of the system design
- **validation** – review of the accuracy of the predicted data and hence acceptance of the model with respect to the needs and requirements of the user.

Four basic activities are associated with this process:

- **inspect** – review products, processes and strategies for conformity with established project standards
- **analyse** – compare draft products against an established baseline
- **test** – exercise software code using written test plans and procedures
- **demonstrate** – show the presence or absence of functional capabilities as outlined in design specifications.

In addition, continual feedback from fire practitioners to the research community regarding weaknesses and strengths of the Smoke Management System will result in new and improved management products.

These verification and validation activities of the Smoke Management System and its components will be performed in conjunction with, rather than independent of a number of phases including the:

- concept phase
- prototype phase
- requirements definition phase
- design phase
- coding phase
- acceptance test phase
- maintenance phase.

Visibility-related characteristics that can be used to assess the accuracy of the visibility predicted by the smoke forecasting system can be partitioned into three groups. These groupings essentially describe and define the visual characteristics of the atmosphere (U.S. EPA 1999). Aerosol and optical characteristics depend only on the properties of the atmosphere through which light passes and can therefore be used to describe visual air quality. Scene characteristics are dependent on lighting conditions.

- **Aerosol** – the physical properties of particles in the ambient atmospheric including particle origin, size, shape, chemical composition, concentration, temporal and spatial distribution.
- **Optical** – the ability of the atmosphere to scatter or absorb light passing through it. Extinction, scattering and absorption coefficients plus an angular dependence of light scattering known as the normalised scattering phase function describe the physical properties of the atmosphere. Optical characteristics integrate the effects of atmospheric aerosols and gases.
- **Scene** – the appearance of a scene viewed through the atmosphere. Scene characteristics include the visual range of the observer, contrast of the scene, colour, texture and clarity. Scene characteristics change with illumination and atmospheric composition but are more closely aligned with the simple definition of visibility than aerosol or optical characteristics.

Sampling information

When establishing the level of resources required for undertaking research associated with the adopted Smoke Management System it is necessary to identify what data will be needed and where it will be applied. The impact of emissions, meteorology and smoke must be recorded over time to obtain quantitative data on plume dimensions, particulate size and density and emission factors. Pollutant sampling can be an instantaneous snapshot, such as a satellite photo or can represent temporal averages at a fixed location or a spatial average, such as a sample collected on an aircraft. Physical samples of smoke, regardless of the mode of collection, can share certain characteristics such as collection height, location, time and duration. Satellite photos on the other hand, are a rather unique product and may be a source of subjectivity due to different kinds of information that may be extracted and variable user interpretation.

The performance of the smoke forecasting system needs to be evaluated by comparing the modelled data with experimental studies. Airborne sampling by small aircraft and ground observations using a sampling network can be used to document the chemical composition of plumes from biomass burning for the duration of active combustion of an experimental fire. Qualitative assessments of the smoke forecasting system can also be used identify constraints of the system, end-user needs, operational efficiency and the architecture of the user interface. This task will be implemented using the sampling approaches outlined below.

Ground-level sampling

Ground-based instrumentation will be used in an observational network to measure ground-level smoke concentrations, radiation (e.g. direct solar flux, shortwave irradiance), photosynthetically active irradiance (PAR), ultra-violet irradiance (UV-A and UV-B) and size-dependent aerosol chemistry (Jensen et al. 2000). The ground-sampling matrix should also include sensors for particulate matter, temperature and combustion gas velocity. Gas samples can be made by taking ‘grab samples’ (bagged samples of smoke for chemical analysis of combustion gases), canister samples for trace gas analysis, adsorption tubes and instrumentation for ‘real-time’ gas analysis.

Aircraft sampling

Recent advances in aircraft instrumentation and technology have considerably improved detection limits and measurement accuracy for sampling of many atmospheric gases. The chemical composition of plumes from biomass burning in a variety of environments can now be studied through aircraft-based sampling programs.

Smoke plumes from burning biomass cool rapidly as they mix with the local atmosphere and are then transported away from the fire by the prevailing winds. Small aircraft passing through the plume at successive distances from the burn site can be used to document the chemical composition of a plume. Such studies can provide key information for evaluating the rates of chemical transformations within plumes. Ancillary meteorological measurements and photographs documenting the spread of the plume over time must also be collected to support the chemical analysis. Several research groups have already used aircraft to make measurements of the chemical composition of smoke plumes from biomass burning. These research efforts should be viewed as being preliminary and further research using this technique of collection should be undertaken.

Aircraft instrumentation for collection of samples of trace gases and aerosols should include a means to evaluate the following parameters (Jensen et al. 2000):

- thermodynamics and wind
  - static and differential pressure
  - attack and sideslip
  - dry-bulb, wet-bulb and dewpoint temperature
  - liquid water content
- aerosol, cloud and precipitation particles
  - isokinetic inlet
  - single particle analysis
  - elemental carbon
  - giant nuclei
  - aerosol particles and concentration
  - cloud droplet spectra
  - precipitation images
  - nephelometers operated at 15% and 85% relative humidity
- trace gases
  - sulfur dioxide (SO2)
  - ozone (O3)
  - nitrogen oxide (NOx)
  - carbon monoxide (CO)
  - carbon dioxide (CO2)
  - hydrogen (H2)
- radiation
  - remote temperature
  - short wave and long wave radiation
- aircraft navigation
  - aircraft position, speed, acceleration and attitude angles
  - latitude and longitude
- other features
  - still and video cameras.

Chemical characterisation has typically been limited to a few components and data is lacking for some potentially important species including aerosols. Process models must be developed to describe the chemical transformations occurring in the fresh biomass burning plumes and during the post-burning phases (Goldammer & Penner 2000).

Remote sensing measurements

Remote sensing methods provide an important means for compiling geographical statistics of fire frequencies. An example is the AVHRR (Advanced Very High Resolution Radiometer) sensor carried on board the NOAA (National Oceanic and Atmospheric Administration) series of satellites which is suitable for studying fires and vegetation characteristics. Unfortunately, the AVHRR is limited to a spatial resolution of only 1-4 km. In the future, using other Earth Observation Sensors (EOS) such as HIRIS (High Resolution Imaging Spectrometer) and MISR (Multi-angle Imaging Spectro-Radiometer) will significantly reduce this limitation. New satellite sensors such as the BIRD satellite of the Deutsches Zentrum für Luft- und Raumfahrt (DLR, launched 22 October 2001), the FOCUS instrument designed for the International Space Station, Phase A, and the recently designed FIRESCAR-S (FIRe Events, SCars, and Atmosphere Reconnaissance Satellite) of the DLR. These sensors are dedicated to detect and identify fire events caused by burning vegetation, volcanic activity, industrial hazards and burning oil wells and to quantify the effects of fire and monitor fire emissions.

Ground-based data compilations are essential components to remote sensing efforts. Collaboration with the FAO (Food and Agriculture Organisation) will be initiated to compile biomass burning practices on a country-by-country basis. From this study, on-site investigations will be targeted in selected areas (e.g. the savannas of Africa and South America, Goldammer & Penner 2000).

There are no automated smoke detection schemes associated with remote sensing currently available. Much of the difficulty of detection is due to the bright background over which smoke is generated. Other concerns are the lack of spectral separability between clouds and smoke and the limited number of spectral channels available from AVHRR imagery. Most studies can provide only a qualitative view of smoke plumes, as there is no comprehensive quantitative information available on the spatial information of smoke.

There are several problems associated with using satellite photos. These include difficulties in retrieval from archives, use of multiple channels, large volumes of data per photograph and subjective quantitative interpretation of pollutant cloud dimensions. Images should be converted to a standard geographic projection that can be easily matched to smoke forecasting system outputs. In general, data from satellite photos would only be used for verification of volcanic eruptions and smoke from large-scale fires and there are still many uncertainties associated with the use of these data. For instance, how should modelling outputs be quantified and compared with satellite images, how will models define the edges of images and how should satellite images be processed saved to the archive? New satellites will provide more quantitative aerosol measurements and could potentially provide sufficient complementary information to utilise the older archives (Schwela et al. 1999).

Non-conventional measurements

For some documented experiments only limited data such as plume widths may be available. Other information such as chemical deposition may have been derived from many different methods of measurement and over different periods of time at a number of locations. These experiments will have to be evaluated on a case-to-case basis to determine their suitability for inclusion in a larger archive (Schwela et al. 1999).

Application, implication and benefits

Research benefits

Quantitative and qualitative predictions regarding smoke from burning biomass require unified outputs from modelling of burning conditions, vegetation type, atmospheric chemistry and fire behaviour. The process of validation of the Smoke Management System therefore provides valuable feedback to all other modules. Ideally, the process of design, application and verification of the system will result in a comprehensive but flexible forecasting mechanism suitable for a combination of management objectives across many temporal and spatial scales. The target Smoke Management System will account for the combustion of fuels, emission of combustion products to the atmosphere and dispersal of smoke.

The research described in this report will allow better understanding of the fundamental physical, chemical and meteorological processes related to smoke emission from fires. How these emissions change with meteorological variability, land-use and climate change perturbations will also be identified. This research will also:

- identify current strengths and limitations in the application of atmospheric transport models to smoke forecasting
- compare the sensitivity of model-based smoke management strategies to the accuracy of modelled emission rates
- offer an appropriate framework for understanding chemical processes in plumes from biomass burning
- determine the research needed for theoretical studies to provide better analytical or numerical solutions to extremely complex equations representing the physics of pollutants
- help to establish an efficient operational approach towards smoke management by combining observational methods and modelling techniques to reduce uncertainty and risk
- recognise the linkages between smoke and other atmospheric pollutants and diagnose the relationships between the control strategies designed to manage each pollutant.

This system will provide an approach for balancing the use of prescribed fire with the need to meet air quality objectives and visibility goals. This will be achieved by evaluating the potential impacts of smoke on air quality and by controlling emissions from prescribed burns in an area before, during and after a specific burning event. It will also generate a framework for interstate or regional coordination for prescribed fire activity.

Industry links and interests

Reliable smoke forecasting will allow fire managers to more safely and accurately accomplish their fire management activities. The Smoke Management System will be developed for use by fire and land managers and can therefore potentially be adapted for use in other states of Australia. The air quality forecasting system used by the CSIRO and the Bureau of Meteorology Research Centre (BMRC) can utilise certain output information from the Smoke Management System to improve the quality of their input data. It will also be able to provide scenarios of smoke dispersion to assist insurance companies in the estimation of costs and effects of potential smoke intrusions into sensitive areas. In addition, an accurate smoke forecasting system can be used by the Environment Protection Agency to provide public notification of smoke exposure in the event a of wildfire.

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Appendix 1

Chemical transport model used by the CSIRO Division of Atmospheric Research (DAR)

Name: SARMAP Air Quality Model (SAQM)

1. **Developer/owner**: developed by State University of New York
2. **Availability**: arrangements to be made with CSIRO DAR for access to the model code and related documentation
3. **Recommendation for use**: to simulate the processes of three-dimensional transport and dispersion, wet and dry deposition and chemical reaction for a range of air particles, selected air toxics, sulphates, photochemical smog precursors and secondary photochemical smog products (including ozone and nitrogen dioxide)
4. **Input requirements**: three-dimensional wind, temperature, and humidity, rainfall, terrain and land-use data, regional scale emission and local scale emission data
5. **Adaptability to the existing systems**: the model is already coupled to the meteorological component of CSIRO' s air quality model TAPM (The Air Pollution Model)
6. **Output**: concentration for specified averaging times at receptor points or on an output grid; averages of concentration over a specified period and percentiles of these averages; short- and long-term averages of wet, dry and total deposition radioactive activity
7. **Type of the model**: Nested Eulerian prognostic model; three-dimensional model based on the numerical solution of the coupled advection/diffusion for an arbitrary number of reactive species; the model is fully nestable within itself and suited to operate in connection with a non-hydrostatic meteorological model on high resolution grids; transportation and chemistry are the two major changes for a pollutant in SAQM; the model has a Plume-in-Grid and an aerosol module
8. **Dynamics**: it describes three-dimensional transport with diffusion in compressible flows; vertical mixing is accounted for using a first-order closure
9. **Chemistry**: CB-IV (Carbon-bond-IV) photochemical mechanism; 32 species represented in subclasses which include inorganic, organic explicit, organic carbon bond surrogate, organic molecular surrogate; SAPRC (Statewide Air Pollution Research Centre) 1990 mechanism is anticipated to be implemented in the near future
10. **Surface exchange**: the calculation of wet deposition uses a washout/wet scavenging model driven by grided rainfall estimates from the meteorological model; surface resistance is species, radiation and moisture dependent; correction is made for effect of layer averaged concentration in the deposition calculation.
11. **Numerics**: Horizontal and vertical advection is solved using Bott's scheme (flux from adjacent cells computed using polynomials of arbitrary order; flux corrected to maintain positive-definite solution); exponential predictor corrector with lumping of steady-state species groups to solve the chemistry
12. **Grid**: Lambert conformal projection coordinate in the horizontal and terrain following in the vertical. Non-uniform layer thickness in the vertical enables high resolution near the surface; horizontal grid nesting enables multi-scale process to be modelled; horizontal grid resolution may range from 0.5 km to >20 km

13. **Future developments**: SAQM will be developed to include:

- the capability of efficiently modelling the transport and transformation of size-segregated primary and secondary aerosol species
- treatment of sub-grid scale emission sources
- sensitivity analysis

14. **Evaluation studies**:

- 170 experimental data sets from the University of North Carolina and University of California-Riverside smog chambers facilities were simulated to evaluate the performance of the CB-IV mechanism
- the model was applied in central California including the San Joaquin Valley and surrounding air basins to prepare the 1994 State Implementation Plan
- the model was extensively tested and evaluated using the rich database of the San Joaquin Valley Air Quality Study
- the model passed the model evaluation criteria of U.S. EPA and the California Air Resources Board

15. **References**:

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16. **Comment**:

Also available soon is a CTM developed at CSIRO Atmospheric Research. This model will be the atmospheric chemistry model within the Australian Air Quality Forecasting System. It is a fully modularised system in which the model equations are formulated in general coordinates, enabling it to be interfaced with a variety of meteorological drivers and chemical solvers. It is similar in philosophy to the MAQSIP system described under point 16 in the following section on U.S. EPA models.

Another dispersion model (with chemistry included) available from CSIRO is The Air Pollution Model (TAPM) which predicts three-dimensional meteorology and air pollution concentrations. The model consists of coupled prognostic meteorological and air pollution concentration components, eliminating the need to have site-specific meteorological observations. Instead, the model predicts the flow important to local-scale air pollution, such as sea breezes and terrain induced flows, against a background of larger-scale meteorology provided by synoptic analyses.

The meteorological component of TAPM is an incompressible, non-hydrostatic, primitive equation model with a terrain-following vertical coordinate for three-dimensional simulations. The model solves the momentum equations for horizontal wind components, the incompressible continuity equation for vertical velocity and scalar equations for potential virtual temperature and specific humidity of water vapour, cloud water and rain water. Explicit cloud microphysical processes are included. A vegetative canopy and soil scheme is used at the surface, while radiative fluxes, both at the surface and at upper levels, are also included.

The air-pollution component of TAPM, which uses predicted meteorology and turbulence from the meteorological component, consist of three modules. The Eulerian Grid Module (EGM) solves prognostic equations for concentration and for cross-correlation of concentration and virtual potential temperature. The Lagrangian Particle Module (LPM) can be used to represent near-source dispersion more accurately, while the Plume Rise Module is used to account for plume momentum and buoyancy effects for point sources. The model also includes gas-phase photochemical reactions based on the Generic Reaction Set, and gas and aqueous-phase chemical reactions for sulphur dioxide and particles. Wet and dry deposition are also included (Hurley 1999).

Appendix 2

A chemical transport model used by the U.S. Environmental Protection Agency

Name: Community Multiscale Air Quality (CMAQ) Modelling System - Chemical Transport Model

1. **Developer/owner**: developed under the leadership of the Atmospheric Modelling Division of the U.S. EPA (United States Environmental Protection Agency) National Exposure Research Laboratory in Research Triangle Park
2. **Availability**: arrangements to be made with the U.S. EPA for the model code and with the University of Alabama in Huntsville and the U.S. EPA for related documentation.
3. **Recommendation for use**: to support air quality modelling applications ranging from regulatory issues to science inquiries on atmospheric science processes. The CMAQ system can address tropospheric ozone, acid deposition, visibility, fine particulate and other air pollutant issues in the context of 'one' atmosphere perspective where complex interactions between atmospheric pollutants and regional and urban scales are confronted.
4. **Input requirements**: The Meteorology-Chemistry Interface Processor (MCIP) links a meteorological model with the CTM by performing the following tasks:
    - reads-in meteorological model output files (including additional files containing detailed PBL, cloud and surface parameters
    - extracts the meteorological data for the CTM sub-domain
    - interpolates the coarse meteorological model output for a finer grid
    - performs a mass-weighted averaging of data in the vertical direction if coarse vertical resolution data is requested
    - passes through surface and PBL parameters simulated by the meteorology model or diagnoses them using the mean wind, temperature and humidity profiles, surface data, and detailed land-use information available
    - diagnoses cloud parameters (i.e., cloud top, base, liquid water content and coverage) when important parameters required for processing cloud effects in the CCTM are not provided by the meteorological model
    - generates coordinate-dependent meteorological data for the generalised coordinate CTM simulation
    - writes the bulk of its two- and three-dimensional meteorological and geophysical output data in a transportable binary format.

5. **Adaptability to the existing systems:** the model is currently coupled to the MM5 output. Two more output files are required for air-quality modelling. One includes additional two-dimensional boundary layer parameters and flux values and the other contains detailed Kain-Fritsch cloud data file, which describes locations and cloud lifetimes of convective clouds. In addition, the emission data from the Inventory Data Analyser (IDA) together with the meteorology data are loaded in the Models-3 Emission Processing and Projection System Input Processor (MEPS). The Biogenic Emission Inventory System 2 and Mobile 5a models are used in modelling hourly biogenic emissions and mobile sources, respectively.

6. **Output**: concentration for specified averaging times at receptor points or on an output grid; averages of concentration over a specified period and percentiles of these averages; short- and long-term averages of wet, dry and total deposition and radioactive activity. CMAQ predicts hourly grided concentrations of fine particles mass whose size is equal to or less than 2.5 microns in diameter (PM 2.5), speciated to sulphate, nitrate, ammonium, organics and aerosol water. CMAQ model output includes number densities for both fine and coarse modes. The modelling of aerosols in CMAQ also provides the capability to handle visibility, which is another CMAQ output. CMAQ can also provide the basis for modelling the atmospheric transport and deposition of semi-volatile organic compounds (SVOC) with parameterisations for their rates of condensation to and/or volatilisation from the modelled particles.

   In order to assure and understand the results from the model, sensitivity tests are required to detect problems in model formulations and to determine if the model is credible for assessing emission control strategies. There are two powerful tolls provided with the CMAQ:

   - Process Analysis techniques used to quantify the contributions of individual physical and chemical atmospheric processes to the overall change in a pollutant's concentration, revealing the relative importance of each process (this is particularly useful for understanding the effects from model or input changes)
   - Aggregation (a statistical procedure) techniques used to estimate seasonal or annual concentrations for pollutants from CMAQ simulations which are usually performed for shorter time periods due to time and computational limitations.

   (If the Plume-in-Grid module is invoked, the plume information is another output. The model uses IO/API and produces the outputs in netCDF format and therefore it is easy to modify the code to output any other information that may become necessary).

7. **Type of the model**: Eulerian model; three-dimensional model based on the numerical solution of the coupled transport/chemistry for an arbitrary number of reactive species; the model allows only static grid nesting and is suited to operate on high resolution grids; transportation and chemistry are the two major changes for a pollutant in CTM; the model also includes the following modules:

   - Plume-in-Grid (PinG): to more realistically treat dynamic and chemical processes impacting selected pollutant plumes from Major Elevated Point Source Emitters (MEPSE) in the CMAQ modelling system. The PinG modules simulate plume rise and growth and the relevant dynamic and chemical reaction processes of subgrid plumes. PinG can be used for simulations at 36 km and 12 km resolutions; it is not invoked at 4 km resolutions and the MEPSE emissions are directly released into the CTM 3-D grid cells
   - aerosol module: designed to be an efficient and economical depiction of aerosol dynamics in the atmosphere - the modelling of fine and coarse mode particles, with the use of the fine particle model described in Binkowski and Shankar (1995), is included. The approach taken represents the particle size distribution as the superposition of three log-normal sub-distributions, called modes; the process of coagulation, particle growth by the addition of new mass, particle formation, etc. are included; the module considers both PM 2.5 and PM 10 and includes estimates of the primary emissions of elemental and organic carbon, dust and other species; secondary species considered are sulphate, nitrate, ammonium, water and organics from precursors of anthropogenic and biogenic origin; extinction of visible light by aerosols is represented in the module by two methods: a parametric approximation to Mie extinction and an empirical approach based upon field data.

- cloud dynamics and chemistry treatment: this module simulates the physical and chemical processes of clouds that are important in air-quality simulations; it includes parameterisations for sub-grid convective precipitating and non-precipitating clouds and grid-scale resolved clouds. CMAQ models deep convective clouds and shallow clouds using the algorithms as implemented in RADM for 36 and 12 km resolutions. At 4 km resolution, the clouds are generally resolved and explicit type clouds dominate.
- Meteorology-Chemistry Interface Processor (MCIP): to link the meteorological model with the CTM in order to provide a complete set of meteorological data needed for air-quality simulations
- Photolysis Rates: the photochemistry of air pollutants is initiated by photodissociation of smog precursors, which are driven by solar radiation. Within CCTM temporally-resolved three-dimensional grided photolysis rates are interpolated from a lookup table generated by the photolysis processor and corrected for cloud coverage

8. **Chemistry**: CMAQ includes both the RADM2 and CBIV gas phase mechanisms; the CMAQ version of CBIV includes the most recent representation of isoprene chemistry and two additional variants of the RADM2 mechanism also contain the newer isoprene chemistry at two levels of detail. In addition, CMAQ provides the capability to edit these mechanisms or to import a completely new mechanism by means of a generalised chemical mechanism processor. CMAQ also accounts for the formation of secondary aerosols and the reactions of pollutants in the aqueous phase; aqueous reactions are simulated by means of the aqueous chemical mechanism incorporated in RADM; all CMAQ gas-phase mechanisms are linked to these processes to provide the capability to simulate multi-phase interactions. Two chemistry solvers are available - the Sparse Matrix Vectorised Gear (SMVGEAR) algorithm developed by Jacobs and Turco (1994) and the Quasi-State Approximation (QSSA) method used in the Regional Oxidant Model

9. **Surface exchange**: This includes emission fluxes both from surface for the primary species and the dry deposition of both primary and secondary species. Emissions can be included either in the chemistry module or in the diffusion module as part of the lower boundary condition. Dry depositions are calculated for each species based on both surface and aerodynamic resistances. Surface resistance mainly depends on the species and the surface type, while the aerodynamic resistance depends on the meteorological conditions (such as winds and atmospheric stability) and the surface properties.

10. **Numerics**: horizontal and vertical advection can be solved using one of the following methods implemented in the CMAQ: the piecewise parabolic method (PPM - Collela & Woodward 1984), the Bott (1989) scheme and Yamartino-Blackman cubic algorithm; options for computing subgrid vertical transport include eddy diffusion, and the Asymmetric Convective Model (ACM) (Pleim & Chang 1992); horizontal diffusion is modelled using a constant eddy diffusion coefficient; numerical methods differ in the handling of advection of concentration fields

11. **Grid**: The model can use several different map projections in the horizontal and terrain-following in the vertical. Non-uniform layer thickness in the vertical enables high resolution near the surface; horizontal grid nesting enables multi-scale process to be modelled. Horizontal grid resolution may range from 4 km to 80 km (the assumptions for the parameterisations are valid in this range).

12. **Future developments**: CMAQ CTM will be developed to include:
    - SAPRC-97 gas-phase mechanism will soon be incorporated into CMAQ, in addition to the current CB-IV and RADM2 mechanisms available. The SAPRC mechanism will be incorporated with a fixed subset of the approximately 100 organic species contained in the semi-explicit version of the SAPRC mechanism
    - the Sparse Matrix Operator Kernel Emissions modelling system (SMOKE) will also be incorporated into CMAQ. The SMOKE model formulates emissions modelling in terms of sparse matrix operations which require considerably less time to perform than current systems
    - modelling atmospheric toxic pollutants - with the ability to simulate toxic pollutants processes in addition to the current photochemical oxidants and particulates, it is planned to transport the CMAQ model to a finer-than-urban scale to link with human exposure models
    - new linkages with global models: to bridge the information from the urban and regional CMAQ applications and from global modelling applications.
    - modelling ecosystems – efforts are needed to combine environmental modelling techniques to encompass an entire ecosystem to address issues including (a) nutrient cycling through the atmosphere, water bodies and soil and (b) acidic wet and dry deposition into sensitive ecosystems, including critical load analyses. With this ecosystem modelling approach, air quality issues can be studied in combination with other aspects of environmental health.
13. **Evaluation studies**: The development team is engaged in a substantial program for evaluation. The scope of the effort includes analyses of the performance and veracity of each individual process module as well as the integrated air quality system. The degree and rigour of this evaluation provides the basis for understanding the strengths or weaknesses of the current state-of-science in CMAQ. The evaluation of the initial release version of CMAQ is underway for three nested grids with 36, 12, and 4 km grid resolutions. With these results, CMAQ's performance can be evaluated on both the regional and urban scales. Diagnostic evaluation will continue using databases from different regional studies such as the 1995 Southern Oxidant Study conducted in the vicinity of Nashville, TN and the 1995 NARSTO-NE study
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15. **Comment:**

The EPA's Models3/CMAQ model is part of the ‘third generation’ air quality modelling systems developed recently to address multiscale, multipollutant problems. The MCNC's Multiscale Air Quality Simulation Platform (MAQSIP) can be included in the same class.

In the case of MAQSIP, atmospheric scientist and chemist have worked in collaboration with computational scientists and mathematicians to create a modular flexible system. By coupling of MAQSIP, the Sparse Matrix Operator Kernel for Emissions (SMOKE) and the PSU/NCAR MM5 Mesoscale Model it is possible to make timely, quasi-operational real-time atmospheric chemical forecasts (during summer 1998 this tripartite system was used to produce once-daily, experimental, real-time 48-hour numerical air quality predictions on a nested 108–36 km grid). This platform (MAQSIP) is part of the Environmental Decision Support System (EDSS) - an advanced decision support framework developed under a cooperative agreement between U.S. EPA National Exposure Research Laboratory (NERL) and MCNC.

MAQSIP is a fully-modularised three-dimensional system with various options for representing the physical and chemical processes describing regional- and urban-scale atmospheric pollution. The governing model equations for tracer continuity are formulated in generalised coordinates, thereby providing the capability of interfacing the model with a variety of meteorological drivers.

The model employs flexible horizontal grid resolution with multiple multi-level nested grids with options for one-way and two-way nesting procedures. In the vertical, the capability to use non-uniform grids is provided. Current applications have used horizontal grid resolutions from 18–80 km for regional applications and 2–6 km for urban scale simulations, and up to 30 layers to differentiate elements in the vertical domain.

The aerosol module of MAQSIP is based on the EPA's Regional Particulate Model (RPM). The model employs the chemistry, transport mechanisms and full array of aerosol- and gas-phase species of the RADM2 mechanism and includes the response of aerosol-size distributions to chemistry and dynamics.

The model has been applied to the domain covering the eastern United States and parts of south-eastern Canada to study the production and distribution of sulphate aerosols. The MAQSIP framework with the detailed gas-phase and aerosol model provides a modelling system that can be used to investigate the various processes that govern the loading of chemical species and anthropogenic aerosols at various scales of atmospheric motions from urban, regional to intercontinental scales. MAQSIP is used to support the Southeastern States Air Resources Management (SESARM) project to produce seasonal simulations of ozone over eastern United States.

Table Status of development of the MAQSIP module

Function	**Algorithm**	**Status***
Horizontal advection	Bott	R
	Smolarkiewicz	R
	ASD (Accurate Space Derivative)	D
	FCT (Flux-Corrected Transport)	D
	PPM (Piecewise Parabolic Method)	D
	SLT (Semi-Lagrangian Transport)	D
Vertical advection	Bott	R
	Smolarkiewicz	D
Vertical turbulent mixing	K-theory	R
	ACM (Asymmetric Convective Mixing)	R
	TKE (Turbulent Kinetic Energy)	D
	TTP (Transilient Turbulence Parameterisation)	D
Chemical mechanism	CB-IV	R
	RADM2	D
Photolysis	Table lookup	R
	TUV (Tropospheric Ultraviolet and Visible Radiation Model)	D
Solver	MQSSA (Modified Quasi Steady State Approximation)	R
	MYB (Modified Young & Boris)	D
	RADM	D
	SMV Gear	D
Cloud processes and aqueous chemistry	RADM-cloud	R
	Kain-Fritsch	D
Aerosol dynamics	Bimodal, Two-Moment (Whitby)	D
Thermodynamics	Modified MARS	D
Secondary organic yields	Pandis or Odum	D
New particle formation	Kerminen-Wexler	D
Size-dependent dry deposition	Surface Layer Resistance	D
In-cloud scavenging and wet removal	Slinn's Two-step Method	D
Regional visibility	Empirical Method	D
	Mie Scattering	D

*R: Released; D: developed but not released

15a. **References:**

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