A DYNAMIC AIR POLLUTION PREDICTION SYSTEM FOR CAPE TOWN, SOUTH AFRICA

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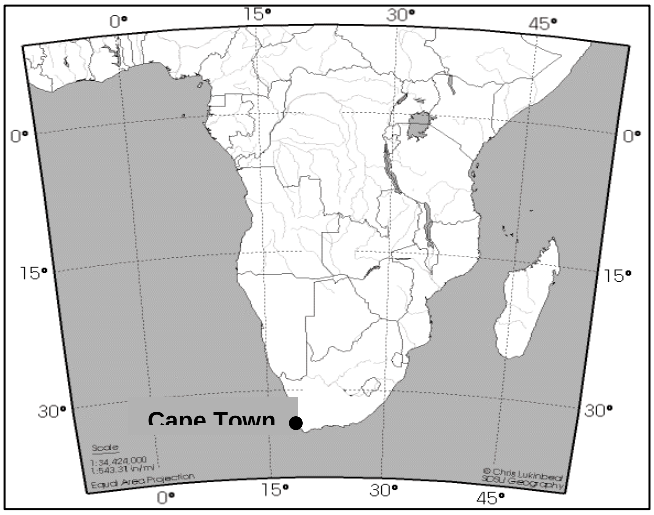
ABSTRACT

The Dynamic Air Pollution Prediction System (DAPPS) combines a comprehensive emissions inventory, a meteorological forecast model and a photochemical dispersion model to predict ambient concentration of selected pollutants on an urban scale. The Penn State/UCAR MM5 mesoscale model is nested to 1 km to develop gridded meteorological input fields for the Comprehensive Air Quality Model with Extensions (CAMx). Gridded spatially and temporally resolved emission data are also input to CAMx where atmospheric transport and chemistry are simulated to estimate air pollutant concentrations for different forecast periods. The air quality forecast information is conveyed to the users by means of an Air Pollution Index which is based on health risk of exposure to individual pollutants and to combinations of pollutants via a web site and in other forms of media. A Haze Index is used to convey forecast visibility information. A pilot system is being developed in the City of Cape Town, South Africa. DAPPS is also used to evaluate the consequences of development options

1. INTRODUCTION

New South African air quality legislation has moved away from source-based control to a philosophy of air quality management that combines emission controls and the protection of the receiving environment. This is achieved through the design and implementation of air quality management plans tiered through the various levels of government down to individual emitters. In response to the legislative needs, the Dynamic Air Pollution Prediction System, (DAPPS) is being developed by a consortium of South African institutions to assist with air quality management and planning decisions.



DAPPS is being developed as a pilot system in the City of Cape Town (Fig. 1). Cape Town is located on the southwestern tip of southern Africa. It is a harbour city with a population of approximately 3.15 million people. Some of the air quality management challenges in Cape Town are complex topography, generally poor air pollution ventilation in winter, emissions from a range of source types, poor public transport facilities and congested peak hour urban traffic flow.

Figure 1: Southern Africa indicating position of Cape Town

2. THE DAPPS MODELLING SYSTEM

DAPPS is a computer-based, modular system. The key input modules are emissions processing, meteorological processing and the definition of initial and boundary conditions. These modules prepare and provide input to the photochemical dispersion module. Output from this module is processed in the form of indicators for display on a web-based information platform. DAPPS is illustrated as a schematic in Figure 2 showing the direction of flow of information.

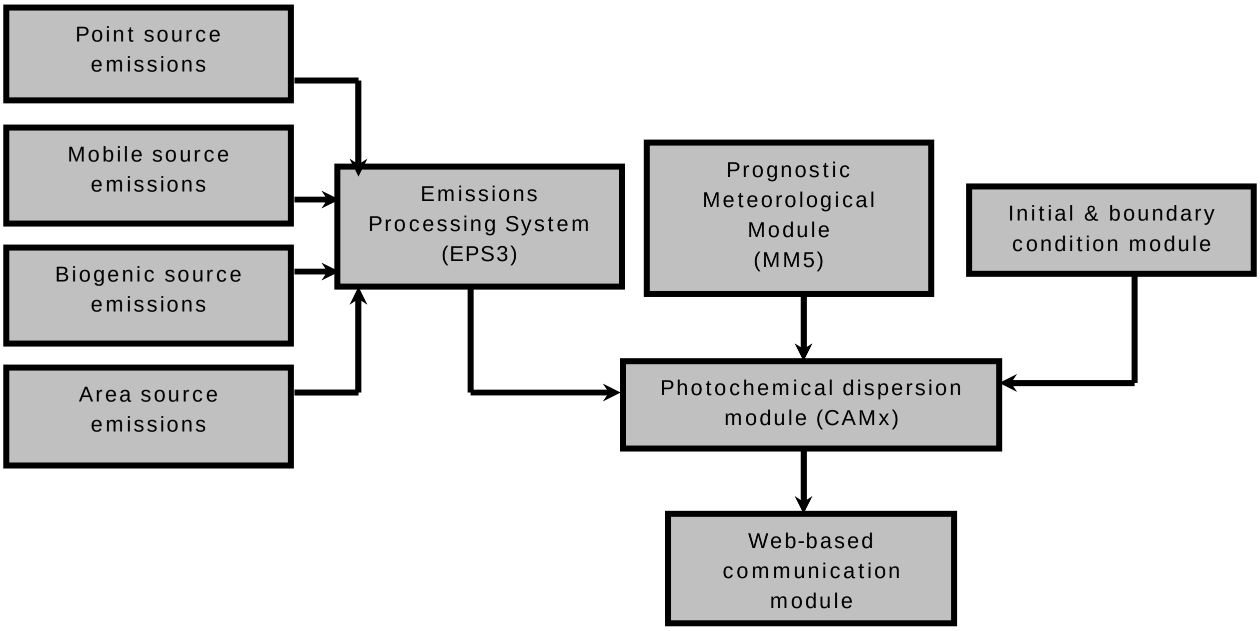


Figure 2: Schematic of the DAPPS modelling system.

2.1 Emissions Inventory

The DAPPS emission inventory for Cape Town includes temporally and spatially resolved emissions from point sources (large, medium and small scale industry), mobile sources, biogenic emissions and area sources such as emissions from wood and paraffin burning for cooking and space heating in homes in informal residential areas. The various emission types are processed using the US EPA's Emission Processing System (EPS3) [1]. Emissions input data are prepared for typical week day, typical Saturday and typical Sunday and holiday scenarios for given seasons.

2.1.1 Point Sources

Point source emissions from large and medium industry have been calculated from stack emission data, and in instances, using US EPA AP-42 [2] emission factors applied to fuel and raw material usage rates to estimate pollutant emission rates. Individual site, stack, industrial process and fuel data were collected form existing databases and through targeted questionnaires. The temporal characteristics of each source are used to derive hourly emission rates for CO, SO_2, NOx, particulate matter and total organic carbons. In most cases point source emissions are constant over time. Speciation of the organic carbons and other input compounds are performed in EPS3, based on fuel use and the specific industrial process.

Smaller point emission sources located within each 1 km^2 grid square of the modelling domain are summed and the total emissions in each grid block are represented as area sources. When grouping the smaller emitters consideration is given to similarity in process and time of operation.

2.1.2 Mobile sources

The International Petroleum Industries Environmental Conservation Association (IPIECA) Toolkit [3] has been used to generate the base case mobile source emissions inventory for Cape Town for 2001. The vehicle fleet is characterised by vehicle class and fuel type, average speeds in each class and the annual distance traveled in each class. Average speeds are assumed in IPIECA for travel on urban or rural roadways or on highways; the IPIECA pollutant emission factors, derived from the COPERTIII database, for each speed zone and for each of the vehicle classes, were applied. The Toolkit makes provision for five gasoline and diesel specification scenarios. These were configured to simulate the different phases of gasoline and diesel composition before and after the 2001 base year.

The major routes in the model domain are divided into sub sections, or links. For each link hourly emission rates are calculated for SO_2, NOx, CO, Pb and hydrocarbons. The diurnal variation in CO and NOx emissions in a selected grid block in the city centre are illustrated in Figure 3.

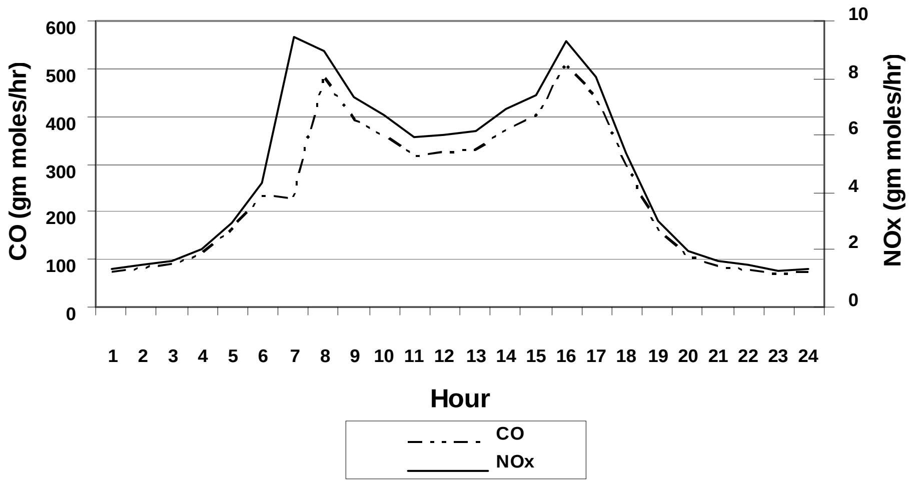


Figure 3: Diurnal variation in CO and NOx emissions from the Cape Town motor vehicle fleet in a selected grid cell in the city centre for the typical weekday traffic scenario.

Emissions from shipping and aircraft traffic will be included in an update of the mobile source inventory later in the project.

2.1.3 Area sources

Paraffin and wood are the main fuels used for heating and cooking in homes in informal residential areas in Cape Town. Emissions from these sources are treated as area source emissions. The emission rates are determined by applying appropriate emission factors to data on fuel type and quantity burnt in the defined areas. These sources have well defined seasonal and diurnal variations which are incorporated into the inventory.

Emissions of NOx and CH_4 from landfill sites are also treated as area sources by DAPPS.

2.1.4 Biogenic emissions

VOC emissions from vegetation are dominated by isoprene and light-dependent monoterpenes. They show daily and seasonal variations that peak with temperature and light intensity thus are not emitted at night. Stored monoterpene emissions are also temperature and humidity dependent with low emission rates at night and varying during the day with temperature. Emissions from areas of natural vegetation are treated as area sources in DAPPS.

2.2 Meteorology

The Pennsylvania State University / National Center for Atmospheric Research Penn mesoscale meteorological model, MM5, is used in the DAPPS system to generate gridded prognostic meteorological fields. MM5 is initially run for a larger mother domain with a grid resolution of 15 km, and then nested to 3 km and then to 1 km over the metropolitan area. The gridded meteorological fields include the following parameters in each of the 10 vertical layers: horizontal wind speed and direction; temperature; pressure and height; clouds and rain; water vapour and vertical diffusivity. The DAPPS modelling domain, from approximately 33° 30’ S to 34° S and 18º E to 19º E for the City of Cape Town, is approximately 2 500 km^2 in area.

2.3 Photochemical model

The Comprehensive Air Quality Model with extensions (CAMx) [4] is the core component of DAPPS. It is an Eulerian photochemical model that simulates the emission, dispersion, chemical reaction and removal processes in the lower troposphere by solving the chemical continuity equation for each chemical species on a system of nested three-dimensional grids. The Carbon Bond 4 chemistry mechanism [5] allows for 91 reactions and 36 chemical species, providing an integrated assessment of gaseous and particulate air pollutants.

The Cape Town modelling domain of 44 km by 54 km in the horizontal and 4 km in the vertical is effectively a three dimensional array of 1 km by 1 km grid cells in the horizontal with varying vertical cell depth. The lowest layer is approximately 70 m deep. CAMx carries pollutant concentrations at the centre of each cell, as well as the meteorological state variables supplied to the model where they represent grid cell average conditions. Wind and diffusion coefficients are carried at the cell interfaces to describe the transfer of mass in and out of each cell. In the vertical most variables are carried in the middle of the layer, besides those that describe the mass transport rate between layers. These are the vertical diffusion rate and the vertical entrainment rate which are carried at the centre of each cell horizontally, but at the top of each layer. The grid cell processes and their respective directions of flow are illustrated schematically in Fig. 4 (left) and the coupling between grid cells in the horizontal and vertical is shown schematically in Fig. 4 (right).

Mean monthly concentrations of selected trace gases measured at the Global Atmosphere Watch station at Cape Point [6] are used to set boundary conditions. Gaseous and particulate concentrations measured during the airborne Brown Haze II study [7] are also used, particularly to define concentrations at the top of the modelling domain. Initial conditions for each model are set using information from the ambient air quality network in Cape Town.

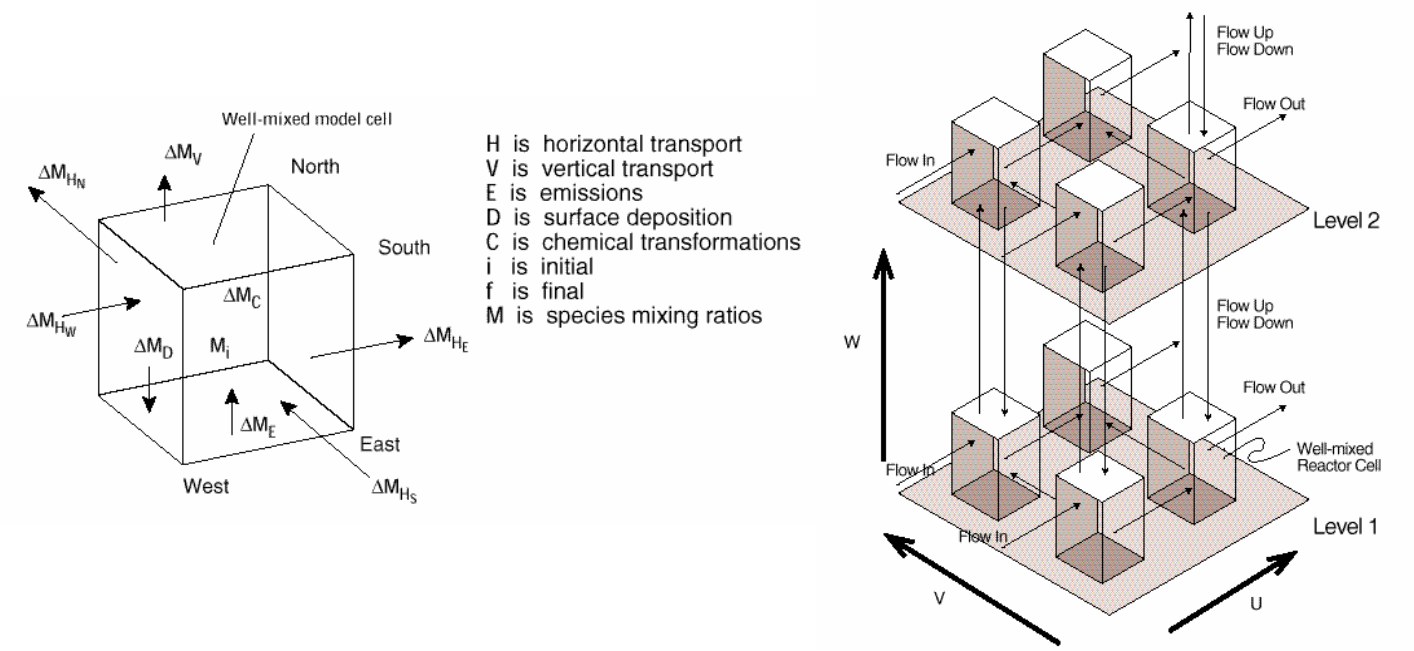


Figure 4: Schematic representation of CAMx grid processes (left) and the inter cell couplings in the horizontal and vertical [8].

2.4 Air quality indices

Air quality index systems are simplified methods to communicate potential health impacts of the prevailing air pollution levels and are based on the ambient concentrations of the classical or criteria pollutants. These systems relate ambient concentrations of air pollutants to a numerical scale and/ or colour scale. However, the use of a single-figure index system posses several difficulties. For example, different pollutants may have different health end points and information may be lost in the use of a single index. It will be difficult or impossible to translate a unified pollution index value back to the disaggregated actual pollutant concentrations. Furthermore, a comparison of the index with national or international guidelines and standards may not be possible.

The Air Pollution Index (API) [9] that has been developed for DAPPS is based on the methodology of the World Health Organisation (WHO) and the European Centre for Environment and Health (ECEH) [10] for estimating the health impacts of ambient air pollution. Predicted ambient concentrations of criteria pollutants in the lowest layer in each of the grid blocks are translated into a human health risk-based API. This provides a spatially and temporally resolved indication of the API across the Cape Town metropolitan area.

Deteriorating visibility as a result of persistent atmospheric haze is receiving increasing attention, examples being the Asian Brown Cloud and the semi-permanent African tropospheric haze layer. The Cape Town Brown Haze, apparent during the winter months from April to September, is another example and has led to the Brown Haze Study [11] in 1990 and Brown Haze II in 2004 [7]. The 1990 Brown Haze Study used a chemical mass balance technique to show that the $PM_{2.5}$ fraction of particulate matter is the most important component of the haze, with diesel and petrol vehicle emissions identified as the largest contributing sources. This (Brown Haze) study did not consider secondary particulate formation.

Haze relates to the extinction of light through scattering and absorption processes, which in turn is a function of the ambient concentration of fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), NO_2, secondary sulphates and nitrates, ozone and organic carbon. In DAPPS this functional relationship is termed the Haze Index. DAPPS calculates concentrations of the key pollutants required by the Haze Index, while the necessary meteorology is available via MM5 in each modelling cell throughout the domain. In this way the Haze Index is calculated for each cell throughout the three dimensional domain. Cells where haze will preferentially occur may therefore be identified.

3. VALIDATION

Due to the number of independent components in DAPPS, it is necessary to understand how well each component is performing in order to understand the final output. In other words, a sufficient degree of confidence must be developed in performance of MM5 as well as the representativeness of the emission inventory to have confidence in the output from CAMx and in turn, in the calculated index values.

The modus operandi for the validation of DAPPS will concentrate on selected days or periods that represent the four dominant typical synoptic circulation patterns. The MM5 prediction for these typical days will be compared with actual conditions. CAMx will be run for each of these meteorological cases with the typical emissions of each case. The outputs of the system will be compared with measured data from the Cape Town ambient air quality monitoring network. This network comprises 10 monitoring stations where SO_2, NO_2, NO, NOx, O_3 and PM10 are monitored, but not all of the contaminants are necessarily monitored at all the stations.

Improvement and maintenance of the emission inventory is an on going exercise. Currently it includes most industrial sources, motor vehicle emissions and the larger area sources such as residential and biogenic emissions. Emissions from shipping and aircraft will be included in the process of continual refinement and improvement op the existing point and mobile source data, as well as identifying and including sources that may have been omitted initially.

4. AIR QUALITY MANAGEMENT AND DAPPS

The new air quality legislation in South Africa is based on a philosophy of air quality management aimed at protecting human health and the environment. It is however true that air quality cannot be managed per se, but rather it is the activities that impact on air quality that should be managed to ensure reduced impacts on the quality of air. In the same way, exposure to air pollution can be managed to reduce the impact. By making forecast air quality information available to a wide range of stakeholders, DAPPS provides information to assist decisions regarding emitting activities and exposure choices. In a fully functional (future) operational mode the DAPPS output will be available via a web site and in the printed media in order to reach a wide range of users.

DAPPS is also configured in an off-line manner as an integrated tool to evaluate and compare the implications of development scenarios on air quality. The atmospheric chemistry capability of CAMx allows the evaluation of development options where emissions that involve reactive pollutants (for example, ozone precursors) or where photochemistry is important. Examples are the planning of urban roadways or public transport alternatives, or possibly the effects of changes in the composition of gasoline on atmospheric chemistry and ambient air quality. Conventional dispersion models do not include atmospheric chemistry modelling capabilities.

5. CONCLUSION

The Dynamic Air Pollution Prediction System (DAPPS) is a modular computer based system that has been developed by a South African consortium to assist with air quality management in urban environments. The system combines a comprehensive emissions inventory that is spatially and temporally resolved with a prognostic meso-scale meteorological model (MM5) and a photochemical dispersion model (CAMx). DAPPS is being piloted in Cape Town, South Africa and is planned to operate in real time to provide daily forecasts of air quality across the metropolitan area. The system will also operate off-line as a tool to evaluate the implications of development scenarios on air quality.

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