Tellus (2007), 59B, 535–541

TELLUS

Assessment of the status of biogenic organic emissions and impacts on air quality in southern Africa†

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(Manuscript received 29 April 2006; in final from 16 January 2007)

ABSTRACT

Air quality management in South Africa has traditionally focused on industrial, vehicular and domestic coal burning as emission sources of air pollution. Only recently through, research initiatives such as Southern African Fire-Atmosphere Research Initiative in 2000 (SAFARI 2000) and the Cross Border Air Pollution Impact Assessment Project, have the importance of biogenic volatile organic compound (BVOC) emissions been recognized in regional atmospheric chemistry and composition, particularly relating to surface ozone formation. These projects have identified significant gaps in the understanding of BVOC emissions in southern Africa.

BVOC emissions are relatively well understood for southern African savanna and woodland plant species and landscapes. Considering that the region is home to more than 20 000 plant species, the most significant gap in the understanding of BVOC emissions is the acute lack of plant specific emission information. Equally important is an understanding of the unique local factors that control BVOC emissions.

A project has been launched in South Africa to develop capacity and technologies to address the BVOC knowledge gaps. It focuses on measurement and modelling and aims to develop a cadre of skilled scientists in BVOC sampling techniques using leaf and branch enclosures, relaxed eddy accumulation and lidar techniques in conjunction with development and application of photochemical modelling.

1. Introduction

Southern Africa is a developing region and as such, political focus has been on the provision of basic services and poverty relief. This has drawn attention away from the developing environmental problems associated with increasing urbanization and industrial growth. Increasing affluence of the region in recent years has seen tremendous urbanization and associated consumerism. This is reflected in electrification of households which has increased from 36% in 1994 to 68% at the end of 1999 (Blignaut, 2002) and new car sales have doubled over the last two years (after being static for 30 yr) (www.naamsa.co.za).

In conjunction with this, South Africa has large coal reserves which are the main source of energy in the country accounting for approximately 76% of the country's energy consumption (www.geohive.com). Coal is burnt in residential homes, in factory burners and even converted into liquid fuels. The sulphur content can range between 0.5 and 3% of the mass of the coal depending on its grade. Given that approximately 160 million tons of coal are consumed annually (Spalding-Fecher and Matibe, 2003), this naturally gives rise to significant sulphur dioxide emissions which are mostly released directly into the atmosphere with little mitigation occurring except from heavy industry. As a consequence SO_2 is the main pollutant of concern from an environmental point of view.

Under these circumstances, it is hardly surprising that other pollutants, such as photochemically reactive precursors and their sources, are only recently starting to be investigated by a handful of local researches. This is also reflected in the ambient air quality monitoring in the region. Data from ambient monitoring that is conducted by metropolitan councils and private analytical companies on behalf of major industries have in the past been difficult to obtain. Recent government legislation is moving towards making these data publicly available with the justification that the public has a right to clean air and information pertaining to this right. In this regard, the "Initial National State of Air Report" is being compiled for the period 1993 to 2005. Fig. 1 indicates a substantial growth in SO_2 ambient air quality monitoring in recent years as attention is slowly being shifted towards clean air. Simultaneously growth in O_3 and NO_2 monitoring has been relatively slower.

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†Presented at the 1st iLEAPS Conference, Boulder Colorado on 23 Jan 2006
DOI: 10.1111/j.1600-0889.2007.00276.x

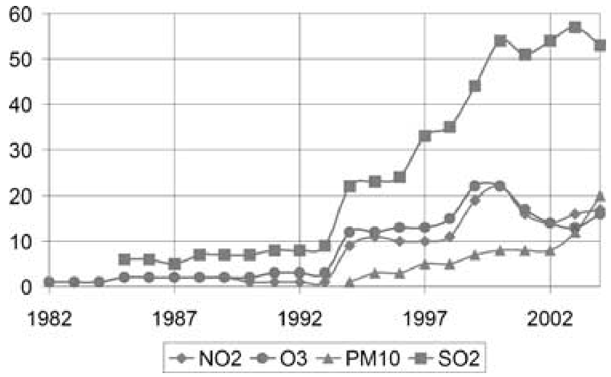

Fig. 1. Number of monitoring stations in South Africa.

During 2005, a major milestone was reached in South Africa in the environmental field with the assent of the new National Environmental Management: Air Quality Act (Act 39 of 2004) which replaced the Air Pollution Prevention Act (Act 45 of 1965). In essence, the Air Quality Act has shifted the emphasis away from permits controlling stack emission rates to the receiving environment where it is the total pollution that is of concern not the individual sources. Additionally South Africa has phased out leaded gasoline fuel and has introduced low-sulphur diesel fuel, which will have related health benefits in the ambient environment.

With the Air Quality Act in place and a national data base of both sources and monitored data, South Africa will have taken a large step forward in ensuring that air pollution is managed better and ultimately reduced wherever possible. To support this, an understanding of all pollution sources, their reactivity, transportation and reaction products (both primary and secondary) are necessary to ensure appropriate management of impacts and the implementation of mitigation strategies. This is more difficult to achieve for emissions of biogenic sources of volatile organic compounds (BVOCs). Regional factors such as unique plant species; biannual atmospheric circulation patterns; low rainfall; high temperatures and irradiance that influence emissions and atmospheric chemistry must be recognised in deriving BVOC emissions.

In order to initiate a process to address the dire dearth of BVOC information in southern Africa, the aim of this paper is to provide an overview of the current state of knowledge of emissions of BVOCs, to highlight the factors that control emissions and the potential impact of BVOC in southern Africa and particularly in South Africa. Some of the questions that are addressed are:

- what is currently known about BVOCs;
- do southern African climatic conditions and plant diversity affect BVOC emissions; and
- what are the future plans to address the knowledge gaps.

2. BVOCs and their significance

Tropospheric ozone is formed by the complex photochemical reactions involving NO_x and VOC precursors. Investigations have shown that 30%–90% of the total VOC emissions are from biogenic sources (Guenther et al., 1994). A typical average for an urbanised region in the USA is approximately 60%. In the southern African region, which is much less urbanised than the USA, this figure is likely to be higher over large areas. Furthermore, BVOC emissions are typically more reactive than anthropogenic VOC having lifetimes defined in hours as opposed for days (Carter et al., 1995; Stockwell et al., 1997). Generally, these BVOC are benign substances (found in a variety of natural products such as Camphene and Limonene (Atkinson and Arey, 2003), but they combine photochemically with NO_x to form ozone. As precursors in the photochemical reaction, it is thus vital that they are understood in order to develop management interventions to reduce the production of ozone (Karlik et al., 2002).

BVOC studies worldwide have focused within a very narrow range of latitudes with USA, France, Taiwan and Hong Kong responsible for most of the studies. With few exceptions, there is a total dearth of studies that have been performed in other regions (Solomon et al., 2000).

A typical approach to estimating emissions from plants is to utilize land use land class (LULC) data sets and matching this with vegetation class data sets. Emission estimates are based on the formula (Guenther et al., 1994) of

$$I = I_s C_L C_T, \tag{1}$$

where I_s is the reference emission rate at a standard temperature, usually 30°C and C_L is an adjustment factor based on leaf surface temperature and leaf area index (LAI) and C_T is an adjustment based on the photosynthetically active radiation (PAR) intensity.

The approach above is utilized by the GLOBEIS BVOC emissions generating program (Yarwood et al., 2002). It has information for 159 plant species and 1207 LULC classes. Taxometry methodology is used when specific species data are not available whereby all known species of the same genre are averaged (Karlik et al., 2003). Many studies have shown that this error is typically between 0.5 and 5 times the actual amount and hence this should be used only in the absence of alternative data.

Recent studies in Europe (and elsewhere) have been two-fold. First, to study emissions for the predominant species of the region that are not included in the (predominantly USA based) literature. Secondly, there have been conflicting reports of the actual values themselves with the conclusion being reached that the emission factors are region specific. Studies have shown that the age of the leaf has an effect whereby mature leaves have higher emissions. Maximum emissions occur at about the 8th node and thereafter show a gradual decline (Isebrands et al., 1999). Furthermore, results comparing emissions factors conducted at the leaf, branch, canopy and above canopy using balloon measurements and relaxed eddy accumulation techniques, differ significantly.

Emissions from plants are generally categorized as isoprene, monoterpenes and other VOC (OVC) where each class of compounds contributes roughly a third of the BVOC emissions (Chang et al., 2005). Isoprene is categorised as a secondary metabolite which are known to play a role in allelopathy (Blum et al., 1999), thermal protection, chemical defense, attraction for pollination and as phytopathic agents, although no causal role has been found per se (Fall et al., 2001). Additionally, BVOC emissions are commonly associated with plant stress and there are indications that stress factors enhance isoprene emissions.

Speciation of BVOC emissions poses additional challenges to atmospheric modellers. While isoprene is a chemical species in its own right, monoterpenes are a class of VOCs that are not necessary speciated identically for each plant species and in many cases the speciation profile is not adequately described for modelling purposes.

3. BVOC in southern African projects

A number of studies pertaining to ozone have been undertaken in South Africa. They have tended to focus on total tropospheric ozone typically using MOSAIC data and TOMS (Diab, 2004), while limited studies have evaluated the causal nature of BVOC in the formation of ozone. Recently three studies have started to make some in-roads into addressing this shortcoming, namely Southern African Fire-Atmosphere Research Initiative in 2000 (SAFARI 2000), the CAPIA and the DAPPS projects. These are reviewed here:

3.1. SAFARI 2000

The Southern African Regional Science Initiative (Annegarn, 2002; Swap et al., 2002) (SAFARI 2000) was an international science initiative with the overall objective of developing a better understanding of the southern African earth–atmosphere–human system. More specifically, the objectives of SAFARI 2000 was to identify and understand the relationships between the physical, chemical, biological, and anthropogenic processes that underlie the biogeophysical and biogeochemical systems of southern Africa. Particular emphasis was placed on:

- biogenic, pyrogenic, and anthropogenic emissions;
- their characterization and quantification;
- their transport and transformations in the atmosphere;
- their influence on regional climate and meteorology;
- their deposition, and resultant effects on ecosystems;
- Integrating remote sensing, computational modeling, airborne sampling and ground-based studies;
- The biological, physical and chemical components of the regional ecosystems.

Following on from the SAFARI 92, which focused strongly on biomass burning in the southern African region, SAFARI 2000 was one of the most significant regional projects. The main outputs of this research are captured in the SAFARI 2000 Special Edition of Journal of Geophysical Research (2003, Vol 108, D2) and the data have been drawn together in a collection of 91 regional data sets covering the following fields (see www-eosdis.ornl.gov/S2K/safari.html).

- Atmospheric and Airborne Studies (18 data sets), Meteorology Cloud Aerosol;
- Background Land Cover (11 data sets), AVHRR: land, vegetation and tree cover;
- Background Soils (seven data sets);
- Climate and Meteorology (14 data sets), Rainfall tower measurements;
- Field Based Measurements (26 data sets), Biomass burning LAI Vegetation identification;
- Hydrology Studies (two data sets);
- Regional Data (four data sets), Biomass burning and fuel estimates BVOC emissions;
- Remote Sensing (20 data sets), Satellite and airborne;

Of these, only the one data set is directly related to BVOC emissions and the work contained therein is described in more detail in (Otter et al., 2003). Using BVOC emissions from southern African savannas and woodlands from measurement campaigns during SAFARI 2000 (Greenberg et al., 2003; Guenther et al., 1996; Harley et al., 2003; Otter et al., 2002) and satellite-derived land-use and vegetation products, summer and winter isoprene emission rate data sets were generated as shown in Fig. 2. However, much of these data were generated using European and American emission factors based on species rather than regional measured data. Less than 10% of the southern African plant species were taken into consideration for this estimate (Otter et al., 2003).

The mean global isoprene emission rate is 0.55 g C m^{-2} $month^{-1}$ (Guenther et al., 2000), which implies that the southern African estimates are significantly below the global average. It is uncertain if this is due to inaccuracies in the vegetation mapping or to emission rates that are not applicable to local conditions.

3.2. CAPIA

Southern Africa is a region of abundant sunshine, significant atmospheric emission sources and a dominant anticyclonic climatology that suppresses vertical mixing and favours the accumulation of pollutants. These conditions favour the formation of ozone and suggest that ozone concentrations over southern Africa may be relatively high. Ozone is an important constituent in tropospheric chemistry (Jenkin and Clemitshaw, 2000). It is also associated with impacts to human health (Lioy et al., 1987), vegetation (Emberson, 2001; van Tienhoven et al., 2005) and

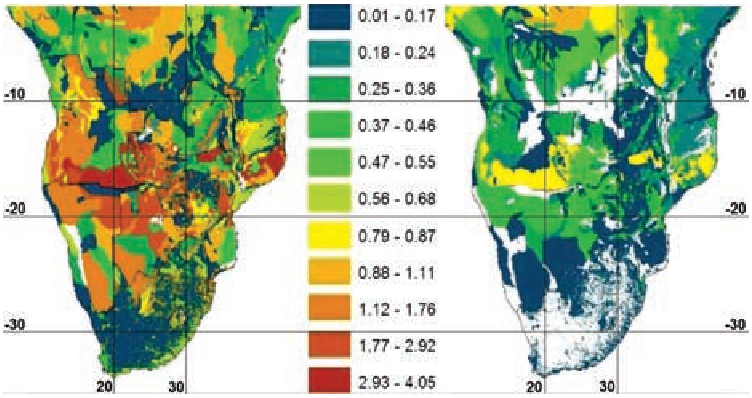

Fig. 2. January (summer) and July (winter) isoprene emission rates (gC m^{-2} *month*$^{-1}$) (Otter et al., 2003).

materials (Lee et al., 1988). Despite these potential impacts, measurements are limited to a few monitoring sites in southern Africa. In South Africa, surface ozone measurements have been made at the Global Atmosphere Watch site, situated at Cape Point (18E;34S), since 1983 (Brunke and Scheel, 1998). Background concentrations typically vary between 15 ppb in summer and 30 ppb in winter with an annual average of approximately 22 ppb. Surface ozone is also monitored at a number of sites in the industrialized north-eastern parts of the country (Annegarn and Turner, 1996) . In Botswana, monitoring is on-going at Maun where hourly average concentrations of 90 ppb and higher are not uncommon (Zunckel et al., 2006a). During the period 1991–1993 an ozone-monitoring network was in operation in the eastern highlands of Zimbabwe (Jonnalagadda et al., 2001) where the mean annual surface ozone concentrations ranged between 37 and 49 ppb. Surface ozone is also monitored at five stations as a component of the Deposition of Biogeochemically Important Trace Species (DEBITS) programme at background stations and on the central Mpumalanga highveld, where mean annual concentrations are lowest at Etosha (18 ppb) and highest on the highveld (28 ppb).

The Cross Border Air Pollution Assessment Project (CAPIA) (Zunckel et al., 2004b) was established to assess the potential impacts of ozone on maize, a staple food crop in five southern African countries. Monitoring of surface ozone over southern Africa has shown that ambient concentrations often exceed a threshold of 40 ppb at which damage to vegetation by ozone could be expected (Zunckel et al., 2006a). However, measured surface ozone data are scarce in the region so it was necessary to complement the monitoring with regional-scale photochemical modeling to achieve the objective. The Pennsylvania State and NCAR Mesoscale Model (MM5) (www.mmm.ucar.edu/mm5/) was used to produce gridded meteorological data for 5 days in each month of the maize growing season, October to April. This was input to the photochemical model, CAMx (www.camx.com). Gridded anthropogenic emissions from industry, transport and domestic burning and gridded biogenic emissions from soils and vegetation from SAFARI 2000 were input to CAMx. The model estimations indicate large areas on the sub-continent where surface ozone concentrations exceed 40 ppb for up to 10 h per day (Zunckel et al., 2006a). Maximum concentrations may exceed 80 ppb, particularly in the winter when mean ozone concentrations are higher. The areas where the 40 ppb threshold is exceeded coincide with maize growing areas in South Africa and Zimbabwe, (Fig. 3). From the results, it appears that neither anthropogenic emissions nor biogenic emissions are dominant in the production of surface ozone over southern Africa. Rather the formation of surface ozone over

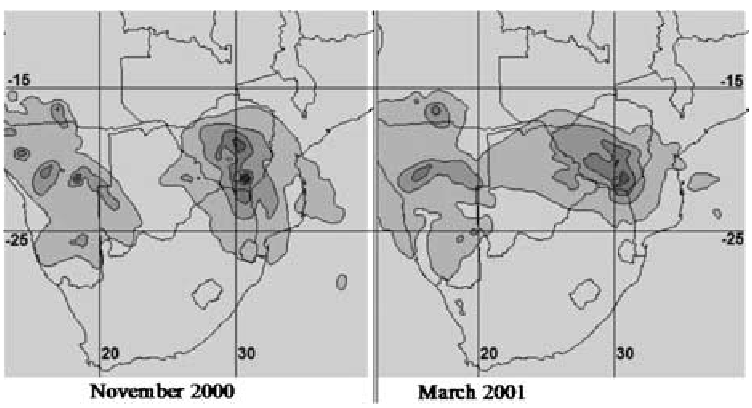

Fig. 3. Maximum modelled O_3 (ppb) (van Tienhoven et al., 2006).

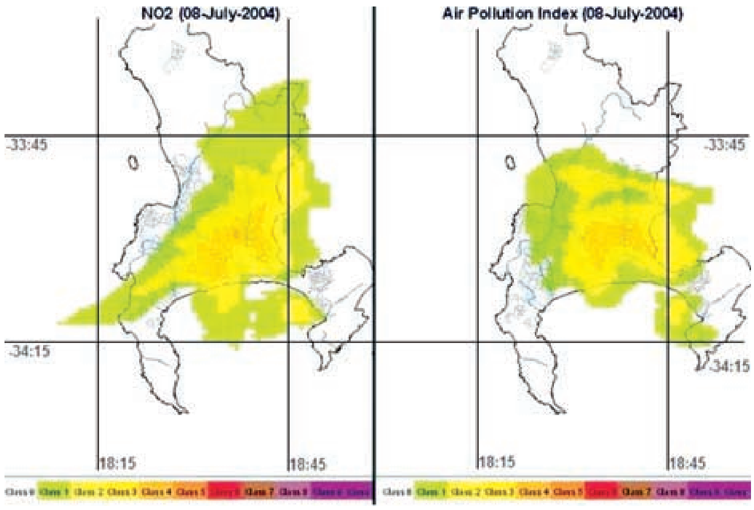

Fig. 4. Typical outputs of the air pollution index from DAPPS (http://dapps.csir.co.za).

the region is attributed to the combined contribution of precursors from these source types.

3.3. DAPPS

The development of the Dynamic Air Pollution Prediction System (DAPPS) (Zunckel et al., 2004a, 2006b), was the next significant step in the ability of southern African modelers to model emissions from biogenic sources. Where the CAPIA project evaluated a large domain at a 50 km^2 grid for mostly a rural environment, the urban-scale DAPPS project was on a 1-km^2 grid cell resolution over the City of Cape Town. Here BOVC emissions rates were crudely derived from emission factors from known vegetation species and landuse and vegetation maps. Instead of modeling using historical data the aim of DAPPS is the real-time forecasting of ozone and haze the display of results daily as a relative index on the internet Fig. 4 (Cairncross, 2003).

Preliminary results indicate that the biggest contributing factor to the high ozone concentrations in this urban environment may be related to the motor vehicle emissions when traffic flow is congested. However, in this VOC limiting scenario all biogenic emissions would quickly react to form ozone. The contribution by BVOC to the formation of ozone is compounded by the region experiencing a winter rainfall when plant growth is expected to be much higher, coinciding with the frequent occurrence of surface inversions inversions in winter and spring.

4. Biodiversity

South Africa has the richest temperate flora in the world. The South African National Botanical Institute (SANBI) has classified all plants in South Africa into: 7 assemblages (Fig. 5), 369 families, 2639 Genera, 21 817 species, 24035 taxa (Germishuizen and Meyer, 2003). This includes 10% of the world's vascular plants in less than 2.5% of the earth's land surface area. Globally the earth is divided into seven biological

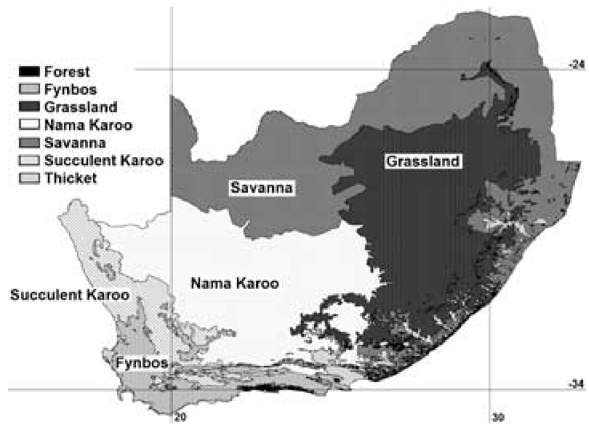

Fig. 5. SA biological zones. (Germishuizen and Meyer, 2003).

zones or biomes and South Africa's Cape Floral Kingdom is the singular biome to fall within one country. It entails most of the region marked as Fynbos in Fig. 5, and consists of 8700 plant species of which 6000 are unique to the region. With existing development in BVOC science occurring mostly in Europe and USA it is expected that only a few of the local species will be included in existing emissions inventory data bases, other than the work done by (Greenberg et al., 2003; Otter et al., 2003) and others in SAFARI 2000 on the Savanna and woodland plant species.

The effect temperature has on isoprene emissions has been studied previously (Guenther et al., 1994; Vizuete et al., 2002) and this is depicted in Fig. 6. Other researches claim that all temperatures greater than 40°C should be assumed as 40°C for modelling BVOC emissions. In this context, typical summer temperatures for southern Africa are between 35°C and 40°C with temperatures reaching 45°C not uncommon (SAWB, 1988). In comparison the "reference" temperature used in GLOBEIS is 30°C (Yarwood et al., 2002). The stresses associated with plants in southern Africa are expected to be higher than in Europe and

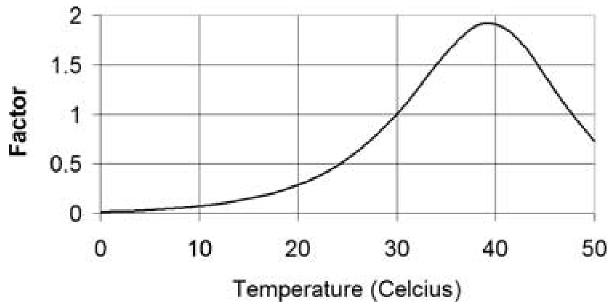

Fig. 6. Isoprene emission factors based on temperature. (Yarwood et al., 2002).

the USA due to increased heat and the occurrence of drought. It is therefore conceivable that the temperature-emission factor curve (Fig. 6) used in GLOBEIS could be significantly different in southern Africa from that applied to the American data set where temperatures are cooler.

5. Conclusions and recommendations

Estimates of BVOC emissions are necessary to improve our understanding of urban, regional and global atmospheric chemistry. Understanding BVOC emissions at the plant species level and at landscape scales allows better predictions of future BVOC emissions as land-use changes take place across the region and is valuable input to air quality management at all spatial scale.

While there is wide acknowledgment that the interaction between the biosphere and atmosphere is an area needing concerted scientific effort on a large scale, the current understanding of basic emissions from the biosphere (plants, animals and soil) is weak in southern Africa. We are therefore unable to assess whether land-use changes over the region result in fundamental changes in tropospheric chemistry, which in turn can result in a co-occurrence of emissions causing, for example, high O_3 episodes or long-term climate variations. Apart from being unable to predict and manage detrimental changes in the atmosphere, we have no understanding of the economic impact (e.g. crop damage, tourism decline due to poor visibility, etc.) associated with poor air quality. Measurement and modelling of BVOCs will contribute significantly to improve the understanding of urban, regional and global atmospheric chemistry, the global carbon cycle and climate to enable effective air quality management.

In this regard, a project was initiated in 2005 October to build capacity and technologies to address the shortcomings in BVOC science in southern Africa that have been identified in this paper. With a focus on measurement and modelling, the project aims to develop a cadre of skilled scientists in BVOC sampling techniques using leaf and branch enclosures, relaxed eddy accumulation and lidar techniques to address the dire shortage of plant specific emission factors to improve landscape emission estimates. To support air-quality management at local and regional scale it is important that the project also focuses on the continued development of photochemical modelling expertise in the region.

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