

# Preliminary assessment of risk of ozone impacts to maize (*Zea mays*) in southern Africa

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*Ozone impacts on crops in southern Africa are assessed using current European-based methods (AOT40 concept).*

## Abstract

Surface ozone concentrations in southern Africa exceed air quality guidelines set to protect agricultural crops. This paper addresses a knowledge gap by performing a preliminary assessment of potential ozone impacts on vegetation in southern African. Maize (*Zea mays* L.) is the receptor of interest in the main maize producing countries, i.e. South Africa, Zambia and Zimbabwe. Surface ozone concentrations are estimated for the growing season (October to April) using photochemical modelling. Hourly mean modelled ozone concentrations ranged between 19.7 and 31.2 ppb, while maximums range between 28.9 and 61.9 ppb, and are near 30 ppb over South Africa and Zambia, while in Zimbabwe, they exceed 40 ppb and translate into monthly AOT40 values of over 3000 ppb h in five of the seven months of the growing season. This study suggests that surface ozone may pose a threat to agricultural production in southern African, particularly in Zimbabwe.

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## 1. Introduction

Global near-surface concentrations of ozone in the northern hemisphere have risen from between 10 and 20 ppb at the beginning of the twentieth century to values between 20 and 40 ppb in recent times (Volz and Kley, 1988). Ozone is the most prevalent and damaging air pollutant to which plants are exposed in many parts of Europe, North and Central America and the Far East (Fuhrer et al., 1997; Mulchi et al., 1983; Ollerenshaw

et al., 1999; Smidt and Herman, 2004). In the United States of America, losses in the region of 3 billion dollars result each year from the impacts of ozone pollution on crops (Adams et al., 1988; Holmes, 1994). Agricultural damage from ozone in Europe for 1990 was estimated to be £4.3 billion (Holland et al., 2002). Effects of ozone may range from visible damage such as leaf spotting to yield or quality reductions (Ollerenshaw et al., 1999; Fumagalli et al., 2001; Fuhrer and Booker, 2003). While much research effort has focussed on ozone impacts in Europe, North America and more recently in Asia, very little attention has been directed on Africa.

The purpose of this study is to establish whether surface ozone concentrations pose a threat to vegetation in

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southern Africa. In particular, there is a need to understand whether or not ozone concentrations pose a threat to crop productivity and livelihoods, especially in regions where high ozone levels coincide with vulnerable populations. The Cross-border Air Pollution Impact Assessment (CAPIA) project was thus initiated in order to gain preliminary insights into the likely extent and scope of surface ozone impacts on maize (*Zea mays* L.). Since surface ozone monitoring data are sparsely distributed across the region, a regional modelling approach was adopted to estimate surface ozone concentrations. For the CAPIA project, southern Africa includes the countries south of 10 degrees south and for the purposes of this paper the focus is on the three provinces in Zambia, Zimbabwe and South Africa where the bulk of the maize crop is grown (Fig. 1).

## 2. Recorded ozone concentrations

In southern Africa there is growing concern that the concentrations of ozone commonly found in the lower troposphere may adversely affect natural vegetation, forests and crops (Carlson, 1994; Emberson et al., 2001; Grobbelaar and Mohn, 2002; Marshall et al., 1998; Randall, 2002; van Huyssteen, 2003; van Tienhoven and Scholes, 2003; van Tienhoven et al., 2005). Over rural southern Africa, surface ozone concentrations range between 20 and 40 ppb<sup>1</sup> (Annegarn et al., 1996; Marengo et al., 1990). Mean annual ambient ozone is 22 ppb at Cape Point, South Africa, which is an unpolluted, background measuring station forming part of the Global Atmosphere Watch network (World Meteorological Organisation, 2003). Total ozone in the lower tropospheric column (surface to 500 hPa, corresponding to an altitude of about 5 km, or about 3 km above the ground level over the high interior plateau) has been shown to range from 35 ppb (autumn 1994) to 75 ppb (spring 1992) over southern Africa (Kirkman et al., 2000). In the heavily industrialised mining and energy generation region of South Africa, maximum hourly means of 76.8 and 110 ppb ozone were measured at Verkykkop and Elandsfontein, respectively. Maximum daily means over 40 ppb were recorded at four out of five highveld monitoring stations in 1994 (Rorich and Galpin, 1998).

Zunckel et al. (2004) reviewed surface ozone monitoring in southern Africa between 1999 and 2001 and provided an indication of ozone concentrations and their variation from active and passive sampling in Botswana, South Africa and Namibia. The highest ozone concentrations were found to occur over Botswana and the

Mpumalanga highveld of South Africa. In both regions, the hourly springtime maximum is between 40 ppb and 60 ppb, but reached more than 90 ppb as a mean in October 2000. In these two regions the mean monthly minimum is between 20 and 30 ppb. The mean daytime ozone concentrations in Botswana and on the highveld reach 40 ppb as early as 10:00 h and remain above this level for up to 10 h per day. At Maun, in Botswana, a maximum hourly mean of 150 ppb has been recorded. The mean annual concentration of ozone across 14 passive monitoring sites in Zimbabwe was 42 ppb (Jonnalagadda et al., 2001) (Table 1). Measured concentrations at various sites in southern Africa thus appear to be high enough and of sufficient duration to potentially cause damage to vegetation.

Generally, ozone monitoring is limited to a few campaign studies and at a limited number of sites in southern Africa. Monitoring methods at these different sites across southern Africa vary, making comparison difficult at a regional scale. The large interannual and spatial heterogeneity in measured ozone concentrations that occur over the southern Africa region mean that these data are inappropriate for the purposes of the proposed assessment of ozone impacts on maize. A modelling approach was therefore adopted in order to obtain a representative and consistent understanding of the spatial and temporal variations of surface ozone across the region. Modelled ozone concentrations are used to investigate the potential risk of ozone damage to vegetation in southern Africa.

## 3. Ozone modelling

The Comprehensive Air Quality Model with extensions (CAMx) (ENVIRON, 2003) was used to model near-surface ozone (Zunckel et al., 2005). The modelling domain (3000 km by 3000 km) extended from 10° to 35° S and from 10° to 40° E, and included the countries of Botswana, Mozambique, South Africa, Zambia and Zimbabwe (Fig. 1). The lowest 4 km of the troposphere were divided into ten layers. The lowest layer is approximately 70 m deep. Each layer of the modelling domain was divided into a 60 by 60 grid, giving 50 km grid spacing in both horizontal directions.

Spatially resolved annual average emissions of CO, SO<sub>2</sub>, NO<sub>x</sub> and total hydrocarbons resulting from anthropogenic activities (industry, transport and domestic burning) (Fleming and van der Merwe, 2002) were input to the modelling. Biogenic emissions of volatile organic compounds (VOCs) were included (Otter et al., 2003) and hourly and seasonal variations were applied to the biogenic emissions data (Zunckel et al., 2005). Biomass-burning emissions after the onset of summer rains in October or November are relatively small (Silva et al., 2003). As a result, they are not considered in the

<sup>1</sup> ppb, parts per billion on a volume basis. It can also be written nl l<sup>-1</sup> and is equivalent to nmol mol<sup>-1</sup>. For ozone, 1 ppb is equal to about 2 µg m<sup>-3</sup>.

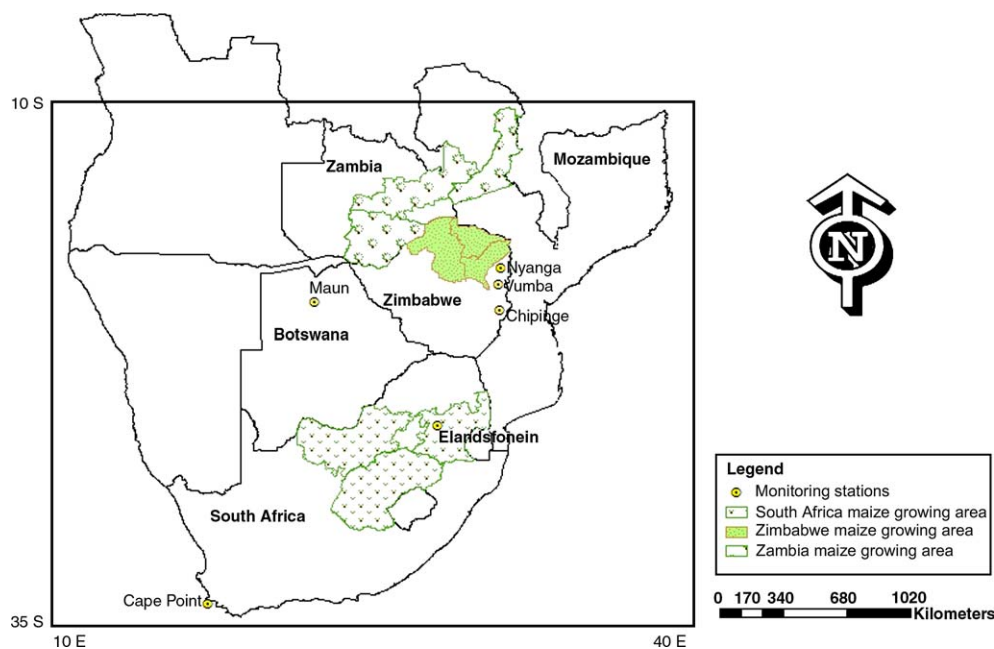


Fig. 1. Map of southern Africa showing the CAMx modelling domain, maize growing regions and locations of ozone monitoring sites.

modelling period from October to April. Further details on the modelling approach, the inputs and the comparison of the modelling results with measurements are discussed in Zunckel et al. (2005).

The CAMx modelling system, together with the meteorological processing using MM5, is intensely demanding on computing resources. This combination of models is not easily applied in long duration modelling studies (Zunckel et al., 2005). For the purposes of the CAPIA project, the ozone modelling is therefore limited to a 5 day period in each month of the growing season. The 5 day (120 h) window period in each month allows analysis of the variation in ozone concentrations across the growing season, and gives a preliminary indication of the potential for ozone damage. The spatial extent of the risk assessment focuses on the main maize growing provinces in Zambia, Zimbabwe and South Africa (Fig. 1).

Table 1  
Ambient ozone levels at remote rural sites in Zimbabwe and Botswana

Site	Altitude (masl)	Mean (minimum/maximum) ambient ozone levels (ppb)		
		1991	1992	1993
<b>Zimbabwe<sup>a</sup></b>				
Nyanga	1820	42.4 (20/57)	42.0 (21/45)	41.0 (18/62)
Vumba	1520	33.0 (22/52)	38.9 (19/55)	41.7 (15/59)
Chipinge	1130	44.8 (20/61)	44.6 (22/63)	47.3 (27/67)
<b>Botswana<sup>b</sup></b>				
Maun	929	48.9 (2.2/151) (period July 1999 to December 2000)		

<sup>a</sup> Passive sampling over 7 day periods (Jonnalagadda et al., 2001).

<sup>b</sup> Hourly ozone (data from the Ministry of the Environment in Botswana).

#### 4. Maize production in southern Africa

Agriculture in southern Africa is important for both export and subsistence purposes. Food production is essential for small-scale and subsistence farmers as large portions of the southern African population rely on self-grown foodstuffs. Urban agriculture provides a supplementary income for many city-dwellers and plays an important role in poverty alleviation and nutrition (Rogerson, 2000).

Maize was selected as the receptor of interest as it is a staple crop that is widely grown for both commercial and subsistence purposes. Although maize is not considered particularly sensitive to ozone, several studies have shown a decrease in relative yield parameters with exposure to high ozone concentrations (Mulchi et al., 1995; Rudorff et al. 1996; Holland et al., 2002).

South Africa is the biggest maize producer in southern Africa, followed by Zimbabwe (Table 2). Most of the national maize crop in Zambia and Zimbabwe is grown by small and medium scale growers rather than large scale farmers. Most of the southern African countries, with the exception of South Africa and Zimbabwe, have a negative food trade balance with food aid necessary to alleviate food shortages in times of drought or floods (Tekere, 2001). Over the past decade, Zimbabwean maize harvests have varied four-fold, largely because of droughts (Patt and Gwata, 2002).

Rainfall and soil temperature are the key factors influencing the planting of the maize crop in southern Africa. Successful germination requires adequate soil moisture and an air temperature of 10–15 °C for 5–7 days. The planting date is also influenced by the choice

Table 2  
Annual maize production (thousand tons) in selected southern African countries

	1999/ 2000	2000/ 2001	2001/ 2002	2002/ 2003	Major maize growing provinces
Botswana	5	9	2	2	No data
Mozambique	1196	1019	1143	1236	No data
South Africa	7508	10 584	7483	9099	Free State, North West, Mpumalanga
Zambia	856	1310	802	602	Central, Eastern, Southern
Zimbabwe	1520	2040	1476	509	Mashonaland East, West and Central
Total	11 085	14 962	10 906	11 448	

Source: Southern African Development Community (SADC) available on South African Grain Information Service Website. <http://www.sagis.org.za/>.

of cultivar and the likelihood of a mid-summer drought. During drought, high temperatures and low humidity reduce pollination and fertilisation during flowering, and so reduce yield (Du Toit, 1999). Harvesting times vary according to the amount of rainfall received. Maize is most likely to be sensitive to damage by ozone during and after anthesis which varies temporally across the region with climate and maize variety (Table 3).

## 5. Risk assessment

As an assessment of potential risk, the concentration-based critical level approach of the United Nations Economic Commission for Europe (UNECE) was adopted. The critical level represents an estimate of pollutant exposure above a defined threshold at which adverse effects on ecosystems or human health may be expected to occur (Bull, 1991; UNECE, 2004). For ozone, the relationship between exposure and damage is expressed using the accumulated exposure over a threshold of 40 ppb (AOT40) ozone index. Statistically, this gives a good linear relationship with yield reductions in arable crops based on pooled data from open-top chamber experiments (Fuhrer et al., 1997). The choice of this

Table 3  
Generalised production phases for the southern African maize crop

Country	Planting	Mid-flowering	Harvesting
South Africa	Mid October to mid November	January to February	March to April
Zambia	November to December	February	March to April
Zimbabwe	Late October to November	December to January	March to April

threshold does not suggest that concentrations below 40 ppb have no effect, but rather reflects a cut-off concentration that is applicable to European crops, and above which responses are likely to occur. The ozone concentrations over 40 ppb are accumulated over daylight hours. The AOT40 exposure index is one of three approaches currently adopted in Europe to define potential risk of damage (UNECE, 2004), although it is recognised that environmental factors that can modify plant response to ozone (such as high soil water stress and low atmospheric humidity) are not taken into account (Ashmore, 2003; Emberson et al., 2000). Dose–response relations for the flux-based approach to assessing ozone damage are already in use or being developed (Pleijel et al., 2000; Filella et al., 2005).

Since data for flux-based modelling are not available for southern African crops and conditions, the AOT40 approach is used in the CAPIA project. The areas in southern Africa where high ozone concentrations coincided with maize production are identified. Both daylight average and maximum concentrations during the modelling period are considered. The final step considers the applicability of the European index for ozone impacts on vegetation in southern Africa.

## 6. Results

The estimated maximum hourly ozone concentration for the 5 days in each month of the entire growing period is shown in Table 4 for each country of interest.

Maximum modelled ozone concentrations in Zimbabwe are almost double those in South Africa and Zambia throughout the growing season. Modelled maximum hourly ozone concentrations over 50 ppb are common over central Zimbabwe.

The estimated maximum hourly ozone concentration and the mean hourly ozone concentration averaged over each maize area for the growing season are illustrated in Fig. 2. Since these data are averaged over the maize areas, the hourly peaks modelled for single grid cells

Table 4  
Maximum modelled hourly ozone concentration (ppb) recorded in any grid cell within the maize region of Zambia, Zimbabwe and South Africa

Month	South Africa	Zimbabwe	Zambia
October 2000	41.5	73.3	36.1
November	<b>54.2</b>	<b>107.0</b>	52.5
December	51.8	100.9	37.6
January 2001	52.0	96.0	41.0
February	31.3	83.2	53.4
March	53.9	100.0	<b>54.8</b>
April	38.7	87.0	46.3

The highest hourly maximum over the entire growing season is shown in bold for each country.

(Table 4) are not evident. Data are also averaged over the 120 h period, so night time concentrations are included. Average hourly ozone concentration ranged between 19.7 and 31.2 ppb across the maize growing regions, while maximum values ranged between 28.9 and 61.9 ppb.

While average modelled hourly daylight ozone concentrations of 30 ppb or less occur over most of southern Africa, concentrations of over 30 ppb occur as a broken band across Botswana, Zimbabwe and central Mozambique, with occasional extensions into the most northerly part of South Africa (Fig. 3). Central and southern Zimbabwe commonly experience levels of 40 ppb or more between November and April, with the highest hourly daylight concentration of 55.6 ppb occurring in January. The high ozone concentrations occur consistently throughout the growing season, regardless of the prevailing meteorological conditions (Zunckel et al., 2005).

Estimated surface ozone concentrations exhibit different diurnal patterns. Hourly ozone concentrations are shown in Fig. 4 for a selected grid cell in South Africa, Zambia and Zimbabwe. The grid cell with the highest ozone concentration over the entire growing season and coinciding with the maize growing area of each country was selected to demonstrate the diurnal variation. Ozone concentrations in Zimbabwe show a strong diurnal cycle across the modelling periods throughout the growing season. The diurnal cycle is not as pronounced in Zambia or South Africa. The strong diurnal pattern is likely attributable to the solar cycle and the diurnal cycle associated with biogenic emissions of VOCs from soil and vegetation. Emissions of monoterpenes, isoprene and  $\text{NO}_x$  depend on temperature, soil moisture and light intensity and so follow the diurnal cycle (Otter et al., 2003). It is not clear why the diurnal fluctuations in ozone concentrations should be so distinct in Zimbabwe compared with South Africa and Zambia. It could be attributable to specific vegetation types, such as Mopane savanna. Mopane (*Colophospermum mopane*) occurs in a narrow band through the middle of southern Africa. Emissions of light-dependent monoterpenes from Mopane are an order of magnitude greater ( $1\ 770\ \text{Gg C yr}^{-1}$ ) than emissions from any other landscape type in southern Africa

and may be responsible for driving the strong diurnal variation in ozone concentrations modelled for Zimbabwe (Otter et al., 2003). It should also be noted that no diurnal variation was applied to the anthropogenic emissions (Zunckel et al., 2005).

The AOT40 values are calculated for daylight hours across the modelling domain. Ozone concentrations over 40 ppb during daylight hours are summed for the 120 h modelling period, and then extrapolated to derive the monthly AOT40 value (Fig. 5).

The critical level for the protection of crops is set at 3000 ppb h over the growing season (generally considered to be 3 months) and is based on European wheat (*Triticum aestivum* L.) (Fuhrer et al., 1997). Ozone exposure and yield relationships are available for maize (Holland et al., 2002), but sensitivity to ozone may differ markedly both between and within species (Grobbelaar and Mohn, 2002; Postiglione et al., 2000). Until locally grown maize crops are used to derive ozone exposure relationships, it is appropriate to use the European critical level aimed at protecting all crops, not only maize.

Much of southern and central Zimbabwe experience an AOT40 of 1000 ppb h or more in each month from October 2000 to April 2001, but there are no exceedances in Zambia and infrequent exceedances in the northern parts of South Africa (Fig. 5). Over a 3 month growing season, these values accumulate to exceed the 3000 ppb h threshold currently defined to protect crops by the UNECE. The critical level of 3000 ppb h, accumulated for 12 h of daylight, is exceeded for every month of the growing season except October in the central parts of Zimbabwe.

## 7. Discussion

Based on model estimates, it is apparent that the 40 ppb surface ozone concentration threshold over the entire growing season is seldom exceeded in either Zambia or South Africa (Fig. 4). In South Africa, instances of exceedance occur early in the growing season, in November and December. It is therefore unlikely to affect grain fill, which, in some grain crops species is

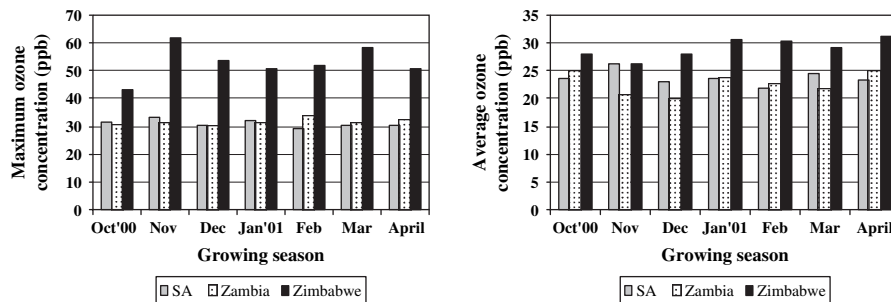


Fig. 2. Hourly maximum (left) and hourly average (right) ambient ozone concentrations modelled over 120 hours and averaged over the maize growing area of each country.

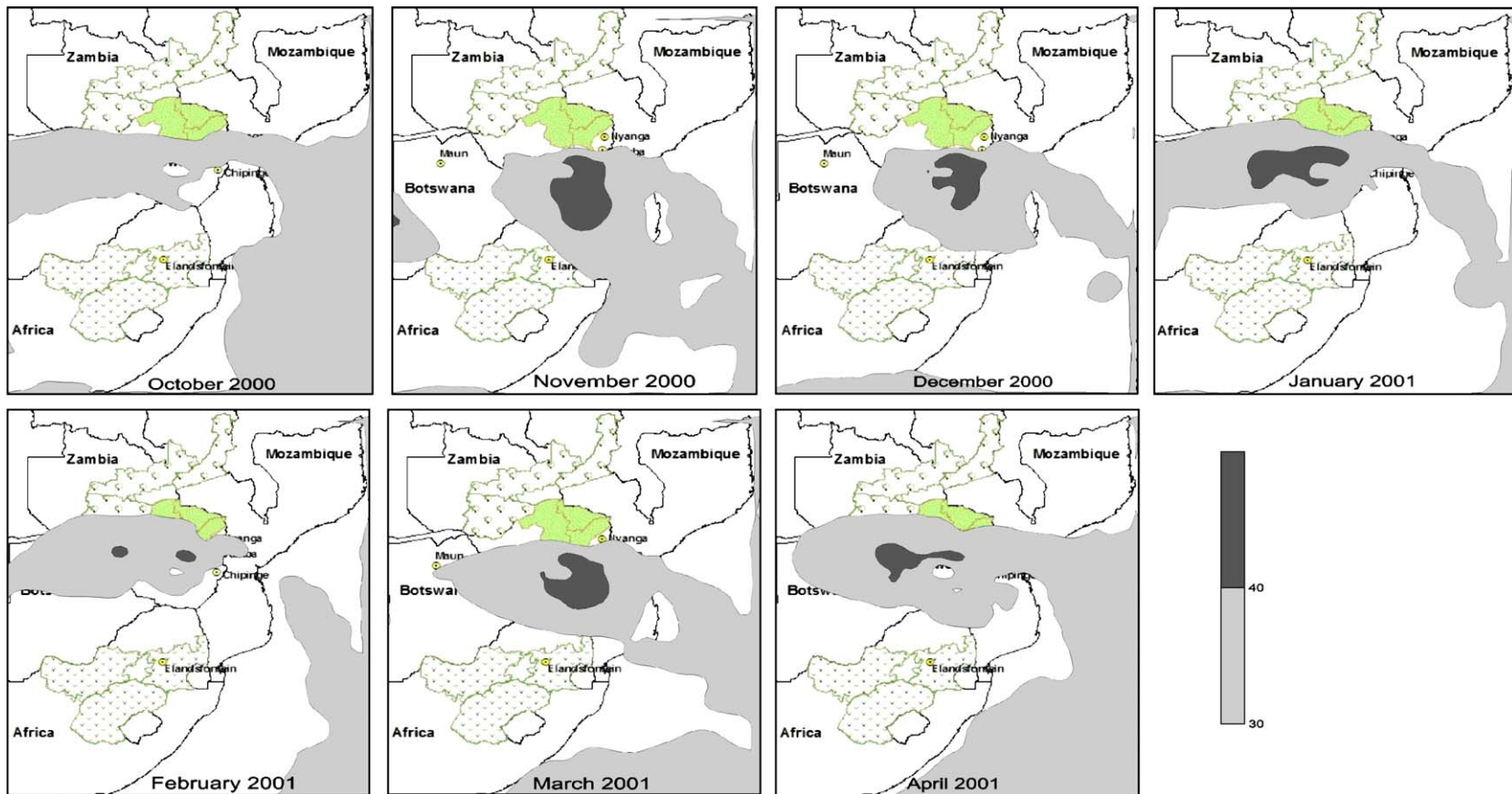


Fig. 3. Average daylight ozone concentrations in ppb over the main maize growing area in southern Africa for the 5 day period (10<sup>th</sup> to 14<sup>th</sup>) in each of the months October 2000 to April 2001.

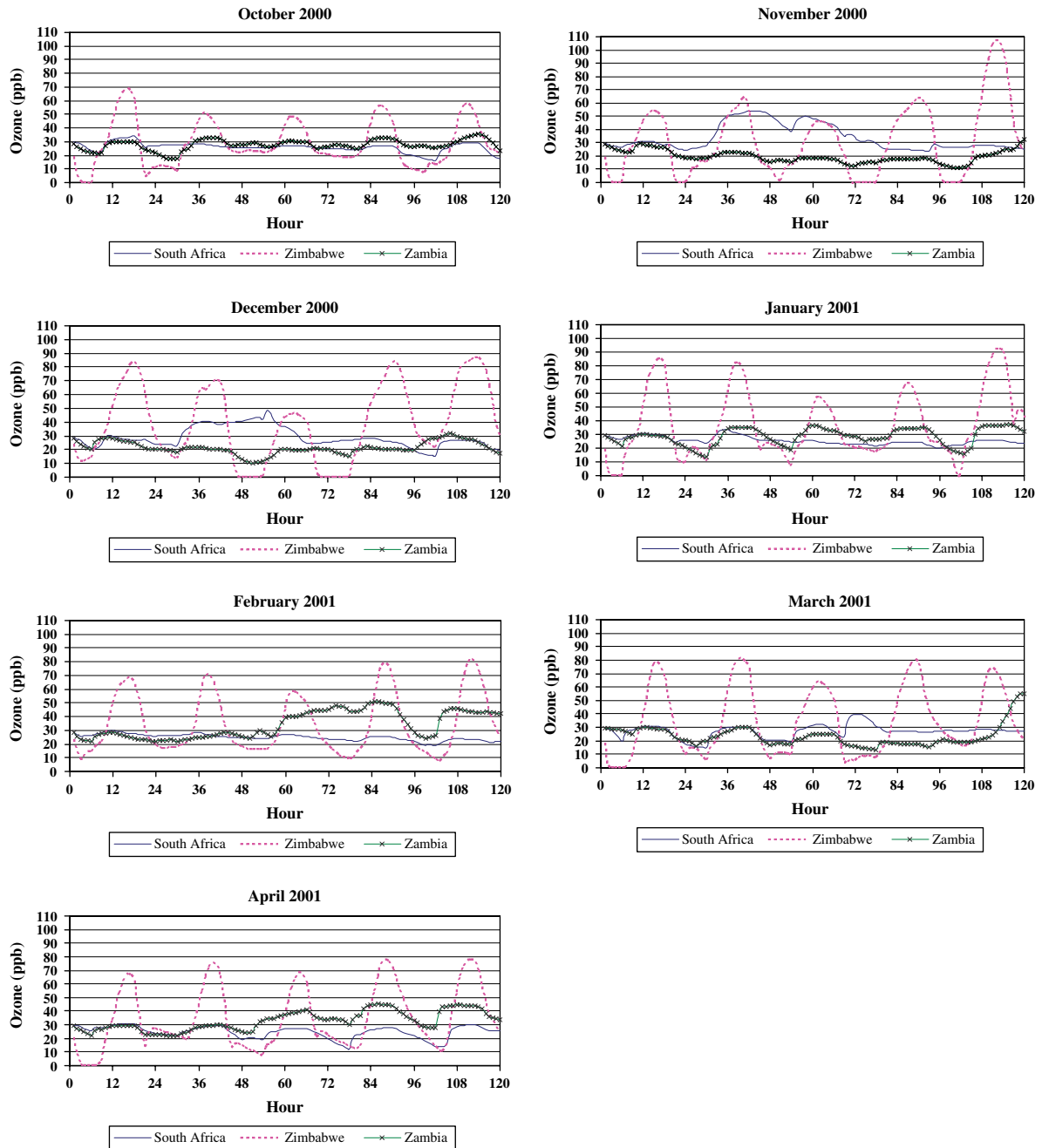


Fig. 4. Modelled hourly ozone concentrations for selected grid cells in Zimbabwe, Zambia and South Africa. Grid cells that had the highest ozone concentration at any time within the growing season were chosen (concentrations shown in bold in Table 4). (from Zunckel et al., 2005).

the most sensitive phenological period (Soja et al., 2000). The period after flowering (anthesis) is the most sensitive phase in which ozone uptake can reduce the grain yield (Lee et al., 1988). In Zambia, daylight concentrations over 30 ppb occur in January and February which coincides with the average mid-flowering period. The ozone levels estimated over Zimbabwe are the highest, with frequent exceedances of the 40 ppb threshold throughout the growing season. Mid-flowering in Zimbabwe occurs over the December and January months,

a period when ozone levels are high, and these remain high until harvesting in April.

The AOT40 approach to assess potential ozone impacts indicates that in some parts of southern Africa, specifically southern and central Zimbabwe, vegetation may be at risk from ozone damage. Although the AOT40 threshold is exceeded over parts of Zimbabwe, the areas of exceedance do not coincide with the main maize producing provinces where the bulk of the Zimbabwean commercial crop is produced.

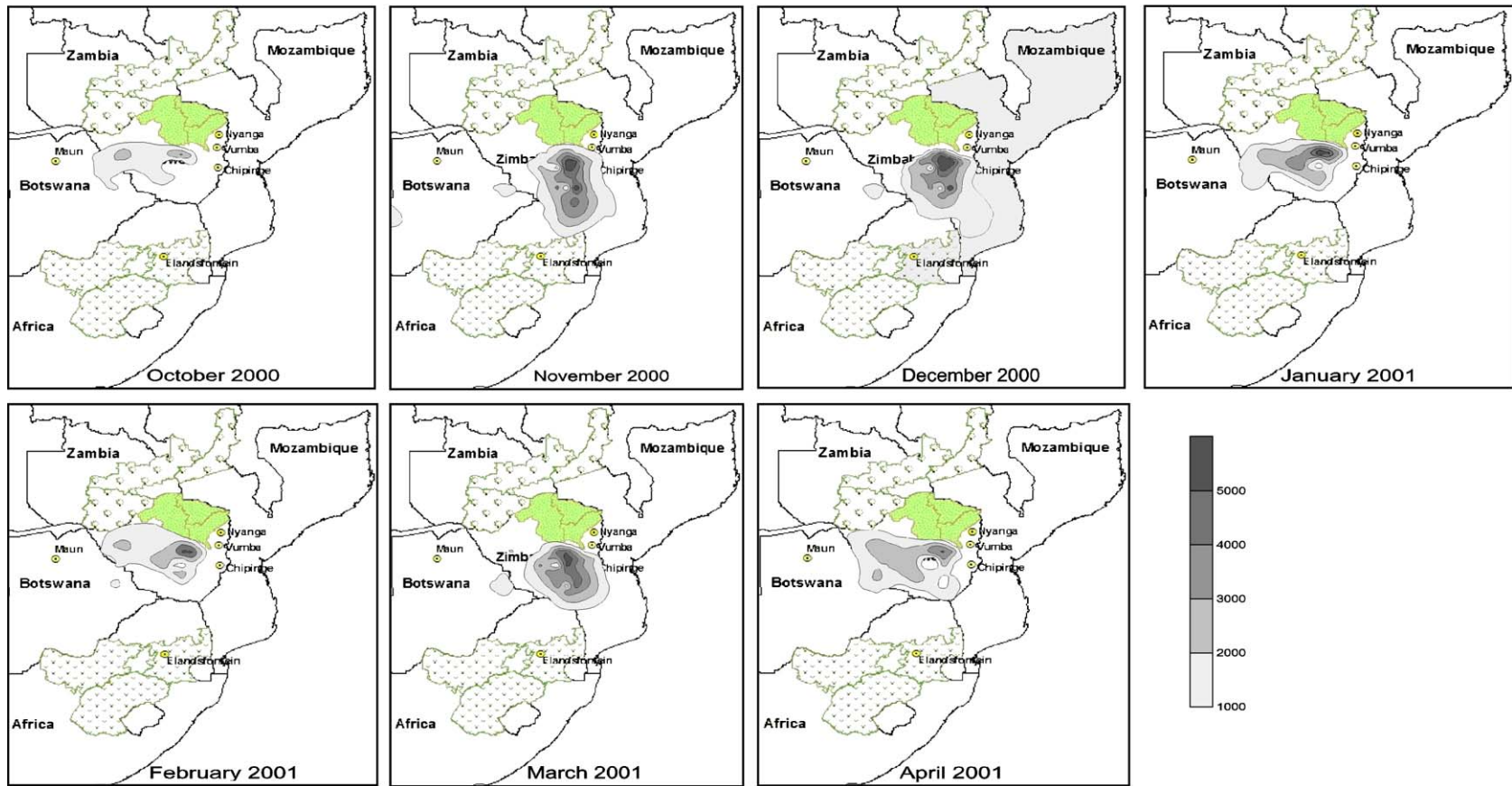


Fig. 5. AOT40 values for southern Africa for October 2000 to April 2001, based on projecting the 5-day modeled concentrations to represent a full month.



Nevertheless, maize grown in smallholdings or home-steads in the central part of Zimbabwe may be affected by high ozone levels. The highest ozone levels occur from December to April and coincide with the flowering, pollination and grain fill period when maize is likely to be most sensitive to ozone impacts (Lee et al., 1988; Soja et al., 2000).

Although there are shortcomings to the AOT40 approach to assess ozone impacts on vegetation, it has proved a useful indicator of potential damage by highlighting areas that may be most at risk. Use of the flux approach, which provides a more biologically realistic assessment of ozone damage (Emberson et al., 2000; Pleijel et al., 2000) faces two considerable challenges in southern Africa. Scarcity of key data in southern Africa is considered to be a major constraint, but more importantly, the flux approach would have to accommodate the drought episodes that frequently affect agricultural production in southern Africa. Spatial input data on soil moisture and vapour pressure deficit, and the temporal variation of these factors over the entire growing season during drought episodes, would be the greatest limitation to model performance.

To date, ozone injury assessment of plants in southern Africa has been undertaken on an extremely limited scale, using green beans (*Phaseolus* sp.) (Botha et al., 1990) and maize (van Huyssteen, 2003). The accurate assessment of visible ozone injury on plants under field conditions requires careful interpretation to ensure consistency and to avoid confusion with any mimicking symptoms (Bussotti et al., 2003). Thus, using native plants as bioindicators of ozone pollution in the field would require knowledge of species-specific plant responses to site factors such as light, soil moisture content and vapour pressure deficit as well as response to elevated ambient ozone concentrations (Bussotti et al., 2003). Additionally, plant responses to elevated ozone concentrations are influenced by the seasonal timing of ozone episodes. Sensitive woody plants, for example, may be more sensitive to ozone episodes early in the growth season (Novak et al., 2005). Such responses should ideally be measured under experimental conditions in greenhouses or open-top chambers.

The regional scale ozone maps (Figs. 3 and 5) identify central and southern Zimbabwe as an area where plant injury from ozone may occur and could be detected using sentinel bioindicators. Sentinel bioindicators are non-native genetically uniform plants that respond reliably to ozone, if well watered and cared for (Manning, 2003). Sentinel bioindicators such as the ozone sensitive variety of tobacco (*Nicotiana tabacum* L. Bel-W3) or white clover (*Trifolium repens* L. Regal NCS) could be introduced into areas to detect ozone concentrations that may cause injury to native plants. Work on ozone effects on vegetation in southern Africa should ideally start with a vegetation survey in the most likely affected

areas to determine whether damage from ozone pollution is actually occurring.

## 8. Conclusion

The main objective of the Cross Border Air Pollution Impact (CAPIA) study was to assess the potential risk that surface ozone poses to maize in southern Africa. In order to achieve this objective, ozone concentrations were estimated over the maize growing regions in South Africa, Zimbabwe and Zambia from October 2000 to April 2001, using a regional-scale photochemical model. The modelling period coincided with flowering, pollination and grain fill, the period when maize is most susceptible to damage by ozone.

Both monitored and modelled ozone concentrations over southern Africa show that the levels of ozone currently experienced are high enough to potentially damage vegetation. In this preliminary study the AOT40 index is used as an indicator of potential risk of ozone damage to crops. Throughout the growing season in central and southern Zimbabwe the modelled ozone concentrations exceed 3000 ppb h which is the critical limit set as the European guideline which accumulates ozone exposure over a 3 month growing season. Parts of Zimbabwe are identified where crop productivity may be at risk. In Zambia and South Africa modelling estimates do not exceed the 3000 ppb h level between October 2000 and April 2001.

Symptoms of ozone damage have not been reported in southern African field crops, although instances of crop disease and pest outbreaks are recorded in countries such as Zimbabwe. Farmers and extension officers must be made aware of symptoms of possible air pollutant damage to crops and native vegetation so that instances may be reported and investigated to determine whether air pollution does pose a real threat to productive agriculture. Maize has been prioritised as it is a staple crop on which many livelihoods depend, yet economically important crops such as tobacco, wheat and sunflowers, must also be considered. Apart from yield, the nutritional quality of affected crops may be reduced, and may further compromise the nutrition of poorer sectors of society who rely on self-grown crops for food.

Environmental policies and air pollution reduction strategies for the southern African region can only be effective and appropriate if they are informed by robust scientific information. This exploratory study has indicated that ozone levels may be high enough to cause concern. The key assumption that the modelled data are representative of the entire growing season needs to be validated by extending the modelling period across the growing season. More rigorous work needs to be done to determine whether or not the risk of ozone damage is real. Although the AOT40 results suggest that

Zimbabwe may be a likely starting point for ground-based validation, flux modelling in which drought effects are considered, may show contrary results.

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