OZONE MAXIMA OFF THE EAST COAST OF SOUTH AFRICA: THE ROLE OF BIOMASS BURNING

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INTRODUCTION

Some recent studies[1,2] have shown that tropospheric ozone concentrations can be inferred from satellite data sets. Fishman[3], examined the tropospheric residual and found that at low latitudes, the highest concentrations of the tropospheric residual were off the west coast of Africa. Fishman *et al*[2], proposed that tropical biomass burning was the primary cause of this South Atlantic August-November tropospheric ozone maximum that has been observed by satellite. Furthermore, work by Andreae[4] confirms the existence of distinct fire seasons, particularly in the Southern Hemisphere, with a maximum in September and October. This seasonality has been reflected in high tropospheric ozone levels in the South Atlantic region at the same time of year[2].

A significant portion of the ozone increase according to Fishman *et al*[5], appears to be connected to biomass burning occuring in southern Africa. Ozonesonde profiles taken at Brazzaville, Congo and Ascension Island provide evidence in support of this theory. Fishman *et al*[5] propose that at these latitudes, the predominant low-level winds are trade winds (easterlies) which would carry the fire related emissions from central and western Africa to the eastern south tropical Atlantic Ocean. According to Fishman[3], the upper level winds are westerlies, hence it is likely that once the emissions and photochemically generated ozone are transported to higher elevations, they are carried long distances to the east. This, Fishman *et al*[5] and Fishman *et al*[5], argue, accounts for the elongated plume of peak ozone values that is seen to the east of Africa, which stretches across the Indian Ocean and extends as far east as Australia and New Zealand. It is this elongated plume of peack ozone values, which is the focus of biomass burning in modifying atmospheric chemistry, and secondly, to determine whether any relationship exists between the occurence of severe fires and ozone maxima off the east coast of South Africa, and to consider the role of the prevailing atmospheric circulation in such a relationship. The study area chosen lies between the Drakensberg Escarpment and the east coast of South Africa, and encompasses the province of Natal and parts of the Transvaal.

The data used in this study include: ozone, fire and meteorological data.

Ozone Data

TOMS (Total Ozone Mapping Spectrometer) Data

TOMS (Total Ozone Mapping Spectrometer) Version 6 gridded data for the period January 1979 to October 1992, for the region bounded by longitudes 20°E to 40°E and latitudes 20°S to 35°S, has been used to examine total column ozone over the study area. The TOMS satellite based equipment performs remote observations measuring the thickness of the layer or column if all the ozone directly above the surface were brought to standard pressure and temperature. This thickness is measured in Dobson Units (DU), where 1 DU = 2.69 x 10 16 molecules of ozone in a square centimetre[6]. Readings are taken once a day at local noon and the TOMS data are made available in the form of digital daily maps with a resolution of 1 latitude by 1.25 longitude by the National Space Science Data Centre (NSSDC) located at the Goddard Space Flight Centre, Maryland, USA.

TOMS data are thought to determine total ozone in a clear column to within 2% of that determined from ground based observations[7]. The presence of clouds generates some uncertainty as to the accurancy of TOMS ozone values, since TOMS cannot sense ozone below cloud tops. In the data reduction algorithm, the height of the cloud is estimated by visible reflectance. Below this height, a climatological distribution is used to correct for the column of air not seen by the TOMS satellite. This process can lead to either an overestimate or an underestimate of the true amount of ozone present, as shown in the two cases described by Fishman *et al*[8] and Fishman and Browell[9]. Fishman and Larsen[1] identified instances where the presence of cumulus clouds in the vicinity of a local source region of tropospheric ozone (i.e. biomass burning) has most likely resulted in an underestimate of the amount of total ozone reported by TOMS.

Fire Data

Sugar Cane Fire Data

Records of sugar cane fires for the 13 year period 1979 to 1992, comprising the dates and general locations of any unplanned sugar cane fires were obtained. Instances of very large, widespread accidental fires as well as cases of the occurrence of numerous fires on a particular day over a variety of sugar districts, were extracted from these records to be used as case studies. It is important to note however, that the fire data used in this study, did not include the annual planned burns which occur during harvest in the sugar industry during the winter months, as these are not adequately documented.

Forest Fire Data

Records of forest fires on both private and state owned plantations for the 13 year period, 1979 to 1992, were obtained from the Department of Forestry in Pretoria. The data set comprises the date, location, extent (in hectares) and cause of any forest fires which occurred during the 13 year period.

Meteorological Data

Radiosonde Data

Daily radiosonde data were obtained from the South African Weather Bureau in Pretoria for the period of the selected case studies, for stations in the Transvaal and Natal. The data utilised included the wind speeds and directions at the surface, 850 and 700 hPa surface pressure surfaces. The above mentioned data sets were used to produce streamline charts. Afternoon readings (approximately 12:00Z) were extracted in order to complement the TOMS readings which are recorded around noon each day. Surface synoptic charts covering the duration of the case studies were obtained from the Meteorological Office at the Louis Botha Airport in Durban.

BIOMASS BURNING

Natural fires have occurred since the evolution of land plants some 350 to 400 million years ago. The first evidence of the use of fire by human lifeforms, dates back to 1 million to 1.5 million years ago[10]. Since then anthropogenic fire has defined the relationship between humans and the lands they live on. According to Crutzen and Andreae[10], over the last decade the environmental impact of the burning of fossil fuels and biomass has been felt throughout the world, and concerns about its consequences are widespread. Although the quantities of fossil fuels burned have been well documented, most biomass burning takes place in developing countries where records of amounts burned are not often kept. Global biomass burning involved a variety of activities and practices including: the burning of forests for land clearing; the annual burning of grasslands; the annual burning of agricultural stubble and waste after the harvest; the burning of wood as fuel; the clearing of forest and brushland to control pests, insects and weeds; the prevention of brush and litter accumulation to preserve pasturelands; control of fuel accumulation in forests; nutrient regeneration in grazing and crop lands; game hunting and the production of charcoal for industrial and domestic use[11,10,12,13].

Because most biomass burning is concentrated in the Tropics and Sub-tropics, and occurs mainly during the dry season (July to October in the Southern Hemisphere and January to April in the Northern Hemisphere), it is not surprising that the emissions result in levels of atmospheric pollution that rival those in the industrialised regions of the developed nations[10]. High concentrations of hydrocarbons and CO have been observed during the burning season in the tropics[14]. The importance of biomass burning, as a significant source of atmospheric trace gases that are photochemically active in the troposphere, was first hypthesised by Crutzen[15]. Since then, a number of studies have concoluded that biomass burning contributes significantly to the global budgets of CO_2, CO[14], CH_4, NO_x[16], and NMHCs, all of which lead to the photochemical production of tropospheric ozone.

According to Crutzen and Andreae[10], the average chemical composition of dry plant biomass corresponds closely to the formula CH_2O. When biomass is burned, complete and efficient combustion will produce water vapour and carbon dioxide as the primary combustion products, according to the reaction

$$CH_2O + O_2 \rightarrow H_2O + CO_2$$

where CH_2O represents the average chemical composition of biomass material. Dry biomass matter consists of approximately 45% carbon by mass, with the remainder being hydrogen and oxygen. In general, due to incomplete and inefficient combustion of biomass matter, CO_2 accounts for about 90% of the gaseous carbon released, with CO accounting for about 10% and CH_4 and NMHC representing about 1%[11]. Thus, although the emissions from biomass combustion are dominated by CO_2, many products of incomplete combustion which play vital roles in atmospheric chemistry and climate, are emitted as well. The CO, hydrocarbons, and NO_x gases emitted proved the starting ingredients for the formation of ozone and photochemical smog. The hypothesis is that the oxidation of CO, along with methane and NMHCs, can provide an important source of tropospheric ozone when sufficient NO_x is present[13,14,16].

Biomass burning occurs frequently in South Africa throughout the winter period of every year in the form of either prescribed burns or wildfires. The southern African landscape includes vast grasslands, wooded savannas, and forest-savanna mosaics, which are prone to fire. Table 1 provides an indication of the areal extent of biomass burning in South Africa.

Table 1. An overview of the extent of biomass burning in South Africa.

Biomass Type	Total Area Occupied	Average acreage burned
Grasslands[17]	31.40 million (ha)	4.887 million (ha)
Savanna[17]	40,88 million (ha)	4.885 million (ha)
Forests[18]	1.3 million (ha)	Unknown
Sugar Cane[19]	471261 (ha)	368526* (ha)

* This value only represents the planned burning of sugar cane at harvest. Frequent unplanned burning occurs.

The burning of grasslands, savanna, forest and sugar cane areas in South Africa probably plays an important role in the production of tropospheric ozone. To examine this role more thoroughly, it is essential that the variations in ozone which occur as a result of a large biomass fire episode be examined. Because very limited records of grasslands and savanna fires exist, it was decided that this data set would not be utilised. The availability of large, accurate dats sets of both forest and sugar cane fires ensured that adequate data was available to examine the effect of biomass burning in the study region on ozone over southern Africa. To examine the role of biomass burning in the development of ozone maxima off the east coast of South Africa, a case study approach was used. Case studies were selelcted from days on which particularly large or extensive fires occurred in the study region. A minimum area burned criterion of 500ha was arbitrarily chosen.

CASE STUDY - 12 September 1985

On the morning of 12 September 1985, parts of the Eastern Transvaal Escarpment and Lowveld experienced strong north-westerly winds. A large number of forest fires broke out, with a variety of origins. The strong winds augmented the spread of the fires, resulting in the destruction of 12000 hectares of forestland[20]. Forest plantations in the Eastern Transvaal cover approximately 260000 hectares, of which 4.6% were burnt on this occasion[20]. Synoptic conditions experienced in the study region during the period 11-13 September 1985, show that the day prior to the fires i.e. 11 September 1985, was characterised by hot, dry, Berg wind conditions and were accompanied by an increase in temperature and wind speeds, together with a sharp decrease in humidity. Such conditions are typical of an intense pre-frontal Berg wind condition. There was no midday inversion at Pretoria which is the nearest synoptic measurement station to the fire region. A trough of low pressure moved across the country from south-west towards the north-east and by the early evening of 12 September, wind speeds had decreased, the wind direction had changed from north-west to southerly, and there was a sharp drop in temperature.

At 01:00 the following day i.e. 13 September, an inversion with a depth of 215m was situated at the surface at Pretoria. A strong upper air inversion based at 1241m above the surface and with a depth of 704m was also in evidence. On 13 September, the frontal system proceeded north-easterly and a low pressure cell was situated over the interior of the country. Typical post-frontal conditions were experienced throughout the region and were accompanied by the elimination of the subsidence inversion.

The low pressure system on 12 September produced considerable convergence at the surface. However, the system was shallow, for by the 850hPa level, the streamline analysis revealed south-westerly flow. The absence of an inversion on 12 September facilitated the upward penetration of ozone precursors and ozone in the buoyant smoke plumes where they would come under the influence of the south-westerly flow and move the burn products towards the north east. For the examination of the synoptic situation on the day of the fire and an examination of the general circulation trends, it is clear that conditions were favourable for the production of tropospheric ozone. Because of the concentration of pre-cursors as a result of the synoptic conditions, it is possible that the subsequent increase in tropospheric ozone would in fact have been reflected in total column ozone concentrations. An examination of the TOMS total column ozone concentrations for the period 11-13 September 1985, for the region 20° to 40° E and 20° to 40° S, shows that this does in fact occur (Figure 1).

On 11 September from the alignment of the contours and the sharp gradient, it is evident that there is a frontal system approaching from the south of the country. Barsby[21] has described the relationship between synoptic weather systems and total ozone and noted the positive departure in ozone which occurs to the rear of a frontal system. Figure 1.a depicts the TOMS total column in the region 30° to 35° S, reflecting the north-eastward movement of the front. By 13 September 1985 an anomalous equatorward extention of high total ozone has developed in the region 20° S to 25° S (Figure 1.b). It represents an increase from 290DU on 12 September to 320DU on 13 September and appears unrelated to the frontal passage which is characterised by a linearly arranged gradient increasing towards the south-west.

Futhermore, the maximum lies ahead of the front and can thus not be attributed to the positive departures of ozone which occur to the rear of fronts. The maximum is also located in the region to the north-east of the fires, which is where the

a) TOMS Ozone, 12 September 1985 **b) TOMS Ozone, 13 September 1985**

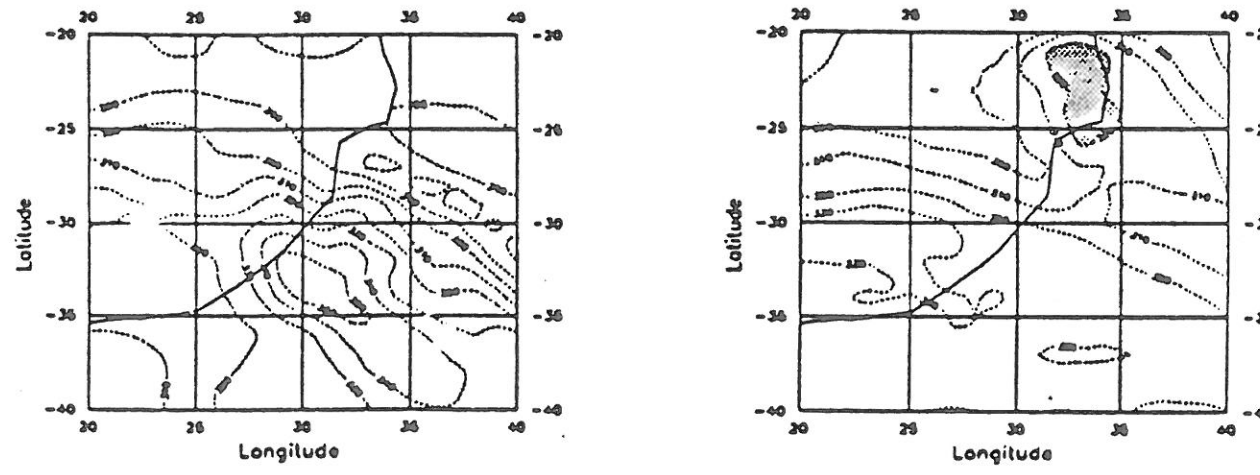

Figure 1. TOMS total column ozone concentration (DU) for the region 20° to 40° E and 20° to 40° S on (a) 12 September 1985 (b) 13 September 1985.

burn products would have been expected to have been transported according to the circulation patterns. It may thus be concluded that the maximum in TOMS total ozone seen in Figure 1.b, is produced by an increase in tropospheric ozone generated by the forest fires of 12 September 1985.

CONCLUSION

A clear relationship between the occurrence of biomass fires, the prevailing atmospheric circulation and the formation of ozone maxima was established. Ozone maxima are seen to develop when a frontal system passes along the east coast of South Africa after the occurrence of large biomass fires. The passage of frontal systems along the east coast of South Africa is a common occurrence. It results in conditions ahead of the front being highly conducive to pollution accumulation and concentration. As a result of the characteristics of atmosphere during the study period, gases from the biomass fires over the eastern Transvaal would have been lifted up into the atmosphere by the buoyant smoke plumes and subsequently transported north and east towards the ozone maximum. It is hypothesised that it is necessary for the prevailinng atmospheric circulation to be pre-frontal for an ozone maximum to develop. Hence the condition of the atmosphere following a large biomass fire is very important in determining whether an ozone maximum develops off the east coast of South Africa or not.

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