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

By

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CHAPTER ONE: INTRODUCTION

1.1 Background

Some recent studies (Fishman, 1987; 1990) have shown that tropospheric ozone concentrations can be inferred from satellite data sets. The distribution of tropospheric ozone can be determined from the analysis of data sets obtained independently from two different instruments: the Total Ozone Mapping Spectrometer (TOMS) and the Stratospheric Aerosol and Gas Experiment (SAGE). Data from SAGE may be used to determine the amount of ozone in the stratosphere, while total column ozone amounts are provided by TOMS - enabling the tropospheric residual to be calculated. From the analyses using the tropospheric residual, conducted by Fishman in 1987 and 1990, plumes of ozone emanating from the Asian, North American, and African continents are depicted (Figure 1.1). Subsequent analysis suggested that high amounts of ozone originating from Africa may even be influencing the ozone concentrations measured over Brazil during certain times of the year (Fishman, 1991).

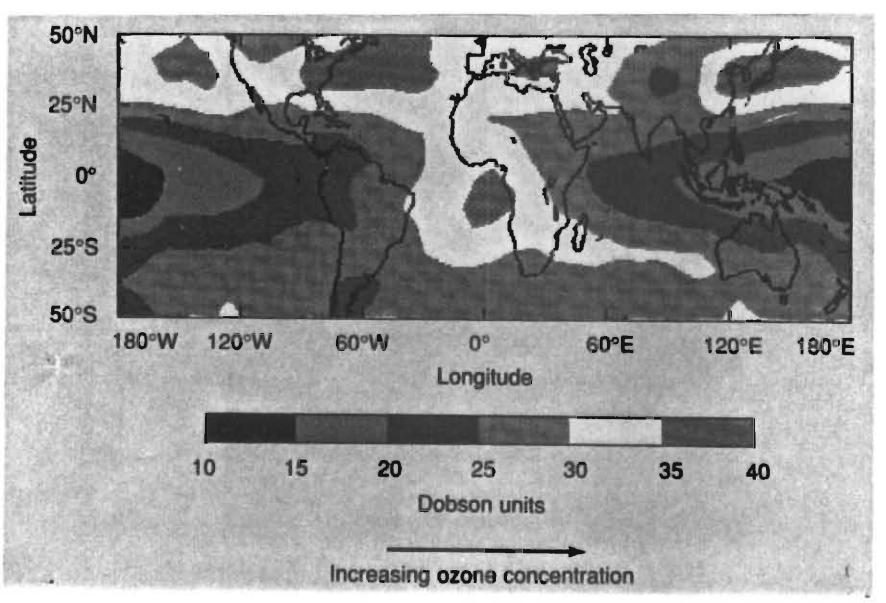


Fig. 1.1 The distribution of the tropospheric residual using annual average data, 1979-1989. After Fishman (1991).

Fishman (1991), examined the tropospheric residual using annual average data, 1979-1989 and found that at low latitudes, the highest concentrations of the tropospheric residual are off the west coast of Africa. Fishman *et al.* (1990) propose that tropical biomass burning is the primary cause of the South Atlantic August-November tropospheric ozone maximum that has been observed by satellite (Figure 1.1). Work by Andreae (1993) confirms the existence of distinct fire seasons, particularly in the Southern Hemisphere, with a maximum in September and October. This seasonality is reflected in high tropospheric ozone levels in the South Atlantic region at the same time of year (Fishman *et al.*, 1990).

A significant portion of the ozone increase appears to be connected to biomass burning occurring in southern Africa. This is evidenced by ozonesonde profiles taken at Brazzaville, Congo and Ascension Island (Fishman *et al.*, 1991). 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 (1991), 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 (1991) and Fishman *et al.* (1991), argue, would account for the elongated plume of peak ozone values (Figure 1.1) i.e. the "long yellow tail" 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 "long yellow tail" of peak ozone values, which is the focus of this study.

The MAPS (Measurement of Atmospheric Pollution from Space) experiment, undertaken in 1981 and 1984, produced two somewhat limited data sets, however the results obtained are still interesting. Over the period 5-13 October 1984, 85 hours of data were gathered by a MAPS instrument. The highest concentrations of carbon monoxide were found over the east coast of southern Africa (Reichle *et al.*, 1990). This detection of very high carbon monoxide levels in the tropics, verified the hypothesis put forth by Crutzen *et al.* (1979), that tropical biomass burning was a source of carbon monoxide comparable to fossil fuel combustion at northern temperate latitudes. It has been estimated that trace-gas emissions from biomass

burning account for about a quarter of the global source of carbon monoxide and nitrogen oxides, and about a third of the anthropogenic non-methane hydrocarbon emissions (Lindesay, 1992). An investigation of the annual cycles of carbon monoxide and methane by Brunke *et al.* (1990), at four locations in the Southern Hemisphere, demonstrates that the concentrations of these trace gases also displays seasonality with a distinct maximum during September and October.

Crutzen *et al.* (1979) suggest that biomass burning in its various forms represents a major perturbation of atmospheric chemistry. Pyrogenic emissions are believed to contribute strongly to the increase of trace gases such as methane (CH_4), carbon monoxide (CO), non-methane hydrocarbons (NMHC) and nitrogen oxides (NO_x) in the global atmosphere, which have a strong influence on the chemistry of ozone and OH, and thus the oxidative state of the atmosphere. Because much of the burning is concentrated in limited regions and occurs mainly during the dry season (July to September in the Southern Hemisphere), it is not surprising that the emissions result in levels of atmospheric pollution that rival those in the industrialised regions of the world. It is obvious from these considerations that an investigation of the role of biomass fires in atmospheric chemistry, climate change and ecology is necessary.

The TRACE-A/SAFARI (Transport and Atmospheric Chemistry near the Equator - Atlantic/Southern African Fire-Atmosphere Research Initiative) 1992 experiment was designed in response to these considerations. It involved ground based and airborne measurement of ozone, meteorological variables, atmospheric particulate matter and trace gases, in an attempt to determine whether indeed, biomass burning in Brazil and southern central and tropical west Africa, does produce the precursors which lead to the formation of the west coast tropospheric ozone maximum described by Fishman (1991). As part of SAFARI 1992, and as a forerunner to forthcoming experiments, some exploratory flights were undertaken over the east coast of southern Africa. Preliminary results reported at the SAFARI Data Workshop in May 1993 suggest that high tropospheric ozone levels are evident over the southern African subcontinent.

1.2 Contextualization and Objectives

In view of the well established role of biomass burning in tropospheric ozone levels, it is proposed in this study to focus on the possible existence of such a link on the east coast of South Africa. Fishman (1991) has briefly referred to the existence of an east coast tropospheric ozone maximum but to date there has been no investigation of its frequency or characteristics.

The objectives of the current study are:

1. To review the role of biomass burning in modifying atmospheric chemistry.

2. To describe the characteristics of the ozone maximum situated off the east coast of South Africa.

3. To undertake an inventory of fires which occur to the east of the Drakensberg Escarpment in the Transvaal and Natal using forestry and sugar cane fire records.

4. To determine whether any relationship exists between the occurrence 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.

CHAPTER TWO: DATA AND METHODOLOGY

2.1 STUDY AREA

South Africa is situated in the Southern Hemisphere sub-tropical latitudes between approximately 20°S to 35°S. The country is located between the South Atlantic and Indian Oceans. The major part of the South African interior is situated at altitudes greater than 1000m and is separated from the narrow coastal plains by an abrupt escarpment, particularly in the east. 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 (Figure 2.1).

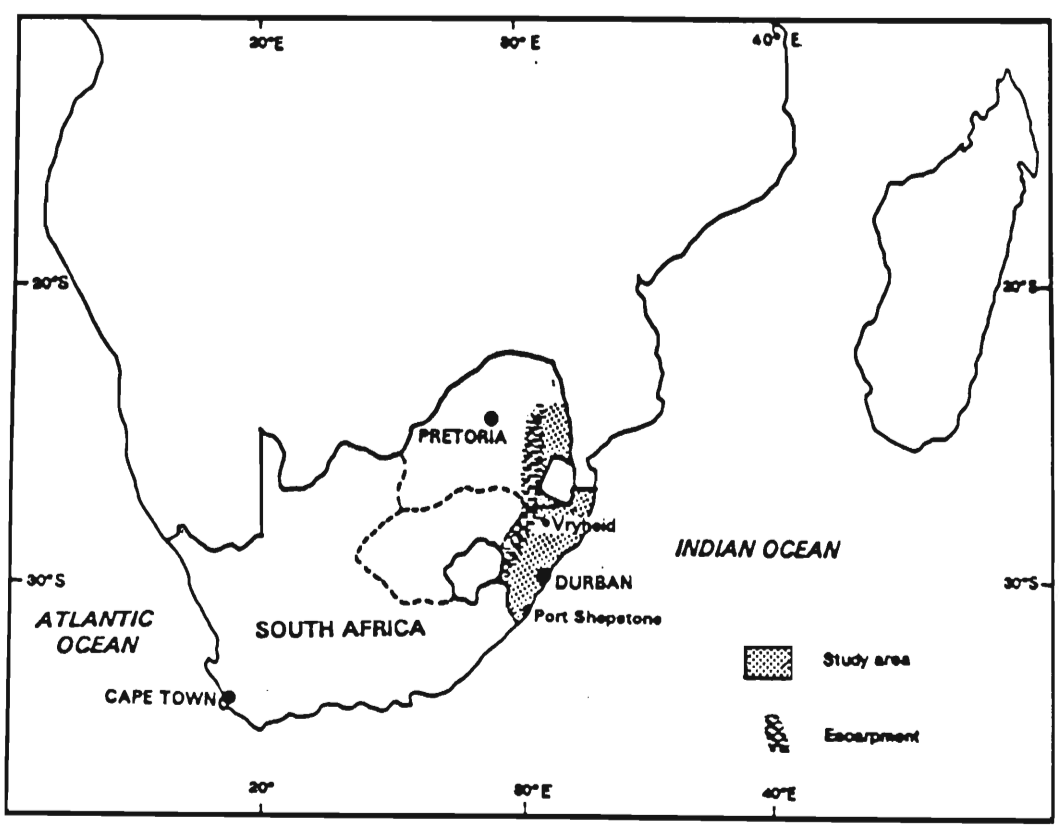


Fig. 2.1 Location map of South Africa depicting the area under investigation in this study.

2.2 DATA

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

2.2.1 Ozone Data

2.2.1.1 TOMS (Total Ozone Mapping Spectrometer) Data

TOMS (Total Ozone Mapping Spectrometer) data have been used to examine total column ozone over the study area. The TOMS instrument was sent into orbit aboard the sun-synchronous polar orbiting Nimbus 7 satellite in 1978 and has been taking daily total ozone measurements on a global scale ever since. Readings are taken once a day at local noon and the data are released by the NASA/Goddard Space Flight Centre.

The TOMS satellite based equipment performs remote observations i.e. it measures the thickness of the layer or column that would result if all the ozone directly above an observer at the surface were brought to standard pressure and temperature. This thickness is measured in Dobson Units (DU), where 1 DU = 2.69×10^{16} molecules of ozone in a square centimetre (Rodgers *et al.*, 1990). Another way of interpreting these measurements would be to express them in terms of the thickness the ozone layer would have if all the ozone in the column were brought down to standard sea level pressure (1013,3 hPa) and temperature (0°C or 273 K). One Dobson Unit is then equivalent to one hundredth of a millimetre of ozone (Gribbin, 1988).

The TOMS instrument measures backscattered solar ultraviolet radiation at wavelength bands: 312.5nm, 317.5nm, 331.3nm, 339.9nm, 360.0nm, 380.0nm. Of these only the four shorter bands are sensitive to atmospheric ozone. The two longer bands are used to estimate the scene reflectivity necessary for deriving total ozone (Fleig *et al.*, 1986). The TOMS instrument uses the six wavelengths from 312.5 - 380.0nm to separate the effects of ozone absorption, molecular scattering and surface (including cloud) reflection. The TOMS

instrument provides daily maps of total column ozone over the entire sunlit portion of the globe. Because the TOMS instrument measures backscattered solar radiation, no measurements can be made during the polar night.

TOMS data are thought to determine total ozone in a clear column to within 2% of that determined from ground based observations (Chesters *et al.*, 1989). The presence of clouds generates some uncertainty as to the accuracy 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 prescribed to correct for the column of air not seen by the TOMS satellite (Figure 2.2). Total ozone is corrected in cloudy regions by assuming a tropospheric climatological profile of ozone mixing ratio below the cloud top and a climatological estimation of cloud top height. This procedure 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.* (1987) and Fishman and Browell, (1988). Fishman and Larsen (1987) 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.

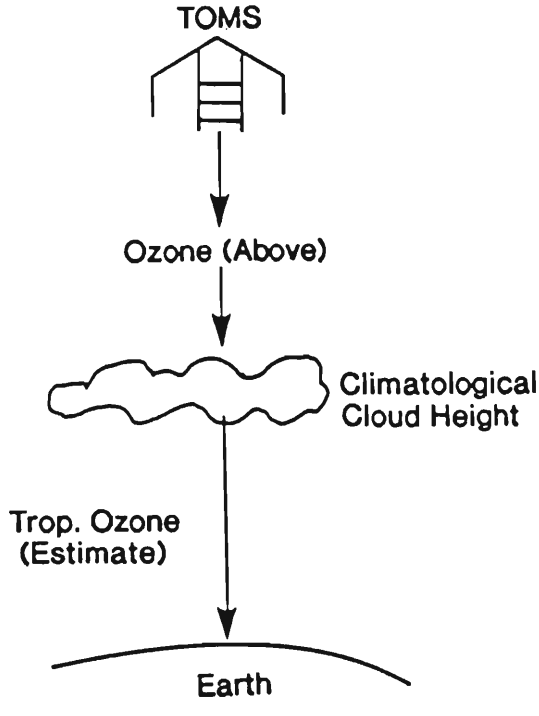


Fig. 2.2 TOMS determination of total ozone when clouds are present. After Thompson *et al.* (1992)

According to Fishman *et al.* (1987), the TOMS instrument can underestimate the amount of ozone below 5 km by 40% under representative clear-sky conditions, but this underestimation effect is only a few percent for tropospheric ozone between 5 and 10 km. Hence it becomes important to note that Delany *et al.* (1985) have shown that most of the ozone produced from biomass burning is well mixed throughout most of the troposphere (i.e., from the surface to above 10 km). Thus the underestimation effect for ozone produced from biomass burning will probably be negligible. Therefore TOMS is capable of capturing most of the increase in total ozone that is the result of relatively higher tropospheric concentrations (Fishman and Larsen, 1987).

Furthermore, Stolarski *et al.* (1988) in Krueger *et al.* (1989), report that the TOMS instrument is affected by long-term drift and that after approximately 10 years, measurements may be 3-4% below those of the Dobson network observations. However TOMS data have been reprocessed to take into account the long-term drift observed in the measurements between 1978 and 1987 due to the degradation in the reflectivity of the aluminium diffuser plate on the TOMS instrument (Bhartia *et al*, 1984). This reprocessed data set (TOMS Version 6) has been used in this study.

Despite the existence of possible errors in the TOMS data, the TOMS data set is widely used. This is perhaps because in principle, satellites are believed to provide a better global coverage than a ground-based network of Dobson spectrophotometers (Warneck, 1988).

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. The data are accessed by direct electronic link between the Space Physics Research Institute at the University of Natal in Durban, South Africa and NSSDC.

The following data have been utilised in this study: daily gridded Version 6 TOMS 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.

2.2.1.2 SAGE (Stratospheric Aerosol and Gas Experiment) DATA

Measurements of stratospheric ozone, overlapping much of the TOMS observational period, were obtained by two similar satellite experiments, SAGE and SAGE II (Fishman *et al.*, 1990). The Stratospheric Aerosol and Gas Experiment (SAGE) instrument was launched on February 18, 1979 and operated until November 18, 1981, obtaining some 13 000 ozone profiles. SAGE II was launched on October 5, 1984 and is still operating. The ozone

measurements performed by the SAGE instruments provide a vertical distribution of ozone in the stratosphere. For each SAGE profile, the amount of ozone above 100 hPa was vertically integrated and the average values of these integrated amounts calculated for each 5° longitude box (Fishman and Larsen, 1987).

The SAGE data contain many gaps due to a variety of problems experienced. A data gap of two years exists in the time period between the end of SAGE and the launch of SAGE II. Also, since 1991, SAGE data have become flawed as a result of the anomalous particulate input into the global atmosphere due to the Mt. Pinotuba eruption (J.L. Richardson, *pers. comm.*). Other gaps in data have occurred because spacecraft-sun geometry precluded an occultation from occurring as well as due to processing and reprocessing techniques (Fishman *et al.*, 1990).

The SAGE data enable the tropospheric ozone residual to be estimated. This measure has been used extensively by Fishman *et al.* (1987; 1988; 1990; 1991), and is defined as the column of ozone in the troposphere or the integrated amount of ozone between the surface and the tropopause. It is derived by subtracting the integrated amount of ozone above the tropopause derived from SAGE profiles from the concurrent amount of total ozone present observed from the TOMS measurements (Fishman *et al.*, 1990).

The tropospheric residual data used in this study have been derived from eight years (1979 to 1981 and 1984 to 1990) of TOMS, SAGE and SAGE II data. The tropospheric residual data set used was obtained from Jack Fishman at NASA Langley. This data set was calculated from Version 5 TOMS data. For the purpose of this study, only the calculated tropospheric residuals between 0°S to 50°S and 50°W to 50°E were used.

Despite the limitations of the tropospheric residual data set, it proved adequate for the requirements of this study as it provided a long term perspective of changes in tropospheric residual ozone over the study area.

2.2.2 Fire Data

2.2.2.1 Sugar Cane Fire Data

Records of sugar cane fires for the 13 year period 1979 to 1992 were obtained from the GROCANE Fire Insurance Corporation. The data comprise the dates and general locations of any unplanned sugar cane fires on the farms of clients of the insurance company. The GROCANE Fire Insurance Company insures 87% of all sugar cane farmers (B. Sugden, *pers. comm.*). 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.

2.2.2.2 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. Because of the immense magnitude of the data set as well as the assumption that only large fires can in fact make any substantial contribution to tropospheric ozone production, only instances of planned and unplanned fires in excess of 500 hectares were extracted and examined.

2.2.2.3 AVHRR and Meteosat 2 Data

NOAA-AVHRR (National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer) and Meteosat 2 data, were obtained from the Satellite Applications Centre of the CSIR in Pretoria, for the case studies discussed in this study. A NOAA-AVHRR false colour image for 12/09/85 and monochrome Meteosat 2 images for 05/10/89 and 08/08/92 were obtained. These images were used to verify the existence of fires.

NOAA-AVHRR data have been found useful for the location and monitoring of both smoke and fires because of daily observations, the large geographical coverage of the imagery, the spectral characteristics, and the spatial resolution of the instrument. They have been successfully utilised for fire detection and monitoring by a variety of researchers including Kaufman *et al.* (1990) and Brustet *et al.* (1991), Setzer and Pereira (1991) and Thompson *et al.* (1992),

The instrument has flown on several NOAA polar-orbiting meteorological satellites which have been operational since 1978. The AVHRR instrument provides medium resolution imagery, 1 kilometre at nadir, has a swath over 3 000 km, and has a sampling frequency of every 12 hours (Brustet *et al.*, 1991). Imagery can be obtained up to 4 times daily using 2 satellites that are offset by 6 hours. This provides the instrument with the potential for more cloud-free scenes of a geographical region to monitor burning.

2.2.3 Meteorological Data

2.2.3.1 Radiosonde Data

Daily radiosonde data were obtained from the South African Weather Bureau in Pretoria for

the periods of the selected case studies viz. September 1985, October 1989 and August 1992 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. Temperature data sets were also extracted and these were utilised to calculate inversion heights and intensities for the various case studies. 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.

2.3 Computer Packages

Computer packages used in this study include, *SURFER, MICROCAM, SLIDEWRITE, HARVARD GRAPHICS,* and *AUTOCAD*. The package Surfer was used to generate grids, contour maps and surface plots. The Microcam and Autocad programmes were used to generate the base topographical maps on which the streamline charts were produced. Slidewrite was used to produce plots of TOMS ozone. Harvard Graphics was used to generate histograms.

CHAPTER THREE: BIOMASS BURNING

3.1 Introduction

Natural fires have occurred since the evolution of land plants some 350 to 400 million years ago. Before natural fire regimes had been altered, or replaced by anthropogenic fire regimes, wildland fires were common and exerted strong evolutionary pressure on the development of terrestrial life. However, according to Pyne (1993), the capture of fire by the genus *Homo* changed forever, the natural and cultural history of the earth. Nothing else empowered humans, and no other human technology has influenced the planet for so long and so pervasively.

The first evidence of the use of fire by human lifeforms, dates back to 1 million to 1.5 million years ago (Crutzen and Andreae, 1990). Since then anthropogenic fire has defined the relationship between humans and the lands they live on. Fire has been used for hunting purposes, to improve grazing conditions for animal husbandry, to keep forest lands open for reasons of security (improved visibility) and accessibility and in general has become a dominant factor influencing global vegetation. Crutzen and Andreae (1990), make reference to measurements of charcoal in dated sediment cores which show clear correlations between increases in the rate of burning and increased human settlement.

According to Crutzen and Andreae (1990), 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 prominent in the public mind. 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 involves 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 (Seiler and Crutzen, 1980; Crutzen and Andreae, 1990; Levine, 1990; Andreae, 1991).

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 unexpected that the emissions lead to levels of atmospheric pollution which rival those in the industrialised regions of the developed world (Crutzen and Andreae, 1990; Crutzen and Carmichael, 1993). The importance of biomass burning, as a significant source of atmospheric trace gases that are photochemically active in the troposphere, was first hypothesised by Crutzen *et al.* (1979). Since then, a number of studies have concluded that biomass burning contributes significantly to the global budgets of carbon dioxide (CO_2), carbon monoxide (CO) (Logan *et al*, 1981; Connors *et al.*, 1991), methane (CH_4), nitrogen oxides (NO_x) (Logan, 1983; Dignon and Penner, 1991), and non-methane hydrocarbons (NMHCs) (Bonsang *et al.*, 1991), all of which lead to the photochemical production of tropospheric ozone. Figure 3.1 provides a schematic overview of the atmospheric processes influencing the impact of fires on the atmospheric environment.

According to Levine (1990) it has become increasingly apparent in recent years, that the trace gas composition of the atmosphere is changing with time. These changes include increasing concentrations of atmospheric greenhouse gases (CO_2, CH_4, nitrous oxide - N_2O, the chlorofluorocarbons - CFCs and tropospheric ozone - O_3), which have global consequences eg. global warming, the depletion of stratospheric ozone and acid rain. Another very important consequence is the increasing concentration of chemically active gases such as nitric oxide (NO) and carbon monoxide (CO) in the troposphere. This has very important implications for the photochemical generation of ozone in the troposphere.

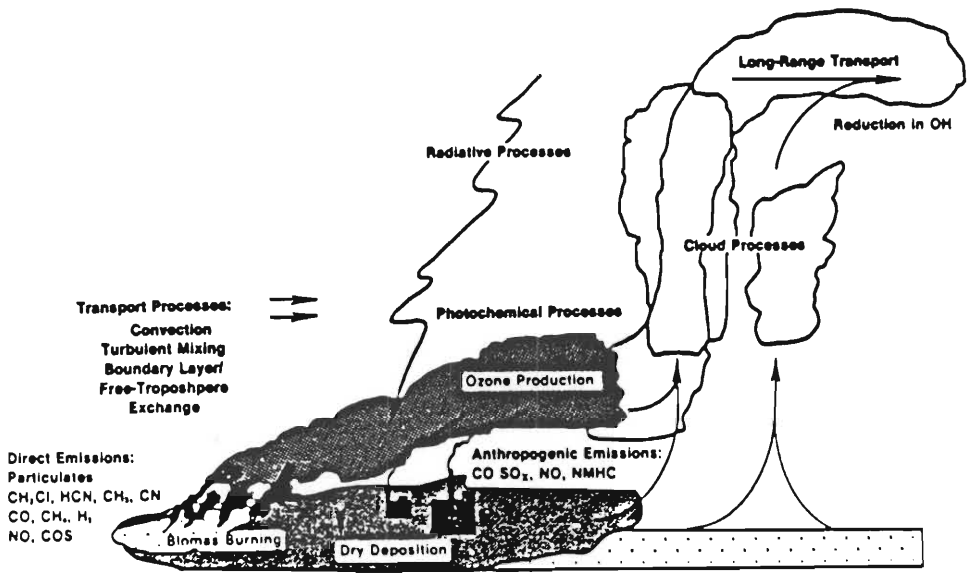


Fig. 3.1 A schematic overview of the atmospheric processes influencing the impact of fires on the atmosphere. (After Crutzen and Goldammer, 1993)

According to Crutzen and Andreae (1990), the average chemical composition of dry plant biomass corresponds closely to the formula CH_2O. The nutrient element content varies according to seasonal growth conditions but on a mass basis it is relatively low, about 0.3 to 3.8% **N**, 0.1 to 0.9% **S**, 0.01 to 0.3% **P**, and 0.5 to 3.4% **K**. 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 NMHCs representing about 1% (Seiler and Crutzen, 1980). 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, CH_4, NMHCs and NO emitted, belong to the group of gases that are the main actors in atmospheric photochemistry. They have a strong influence on the chemistry of ozone and lead to the photochemical production of ozone in the troposphere when exposed to sunlight. Thus, tropospheric ozone is considered a secondary product of biomass burning.

There are growing indications that emissions from fires can significantly influence the oxidising efficiency of the troposphere by affecting concentrations of the hydroxyl radical (Crutzen and Andreae, 1990). The hydroxyl radical, OH, is the primary oxidant in the troposphere responsible for the removal of most major pollutants released into the atmosphere by anthropogenic and natural processes. The accumulation of hydrocarbons in the atmosphere is prevented by a self-cleaning mechanism, whereby the substances are slowly "combusted" photochemically to CO_2. The fundamental molecule responsible for this oxidation process is OH. The reactions which occur are such that OH is consumed when the concentration of NO_x in the atmosphere is low. In a NO_x poor environment - as is the normal condition of most of the unpolluted troposphere, increases in ambient CO and CH_4 concentrations results in a decrease of OH and HO_2, while in a NO_x rich environment, such increases result in an increase in tropospheric O_3 formation (Crutzen, 1973). In view of the observed increase of atmospheric pollution and corresponding increase of CO and CH_4, it has been proposed that global decreases in OH, the primary sink for CH_4 and CO, could lead through a feedback mechanism to a further increase in CO and CH_4, and that this situation could produce an unstable chemical condition. Because approximately 75% of the OH radicals in the background air react with CO, biomass burning can significantly lower the oxidative efficiency of the atmosphere, and thus cause the concentrations of many trace gases to increase (Crutzen, 1973; Crutzen and Andreae, 1990).

3.2 Photochemistry of Biomass Burning

Evidence for the impact of fires on atmospheric chemistry comes from chemical measurements by satellite-based instruments, field observation programmes and ground-based monitoring. According to Crutzen *et al.* (1985) as well as Andreae *et al.* (1988), high ozone concentrations are produced in the plumes that extend over major parts of the tropical and subtropical continents during the dry season. In regions affected by tropical biomass fires, the highest O_3 concentrations are found in the range of 50 to 100 ppb, and are generally found in distinct layers at altitudes between 1 and 5 km, in keeping with the transport mechanisms of the burning plumes (Browell *et al.*, 1988). Ozone episodes with ground-level concentrations of 80 to 120 ppb must be expected to occur particularly during the dry season, when photochemically reactive air becomes trapped under a subsiding inversion layer.

3.2.1 Photochemical Production of Ozone

It was traditionally believed that the abundance of tropospheric ozone was governed by mixing rather than by photochemical processes i.e. the background ozone observed in the troposphere is produced in the stratosphere and transported down into the troposphere (Junge, 1962; Reiter, 1975 and Singh *et al.*, 1978). However, contemporary findings (Levy *et al.*, 1985; Levine, 1990) show that a variety of photochemical processes control the trace constituents of the troposphere and that it is photochemistry, rather than mixing, which plays the major role in the production and destruction of tropospheric ozone. The oxidation of CO, along with CH_4 and NMHCs, can provide an important source of tropospheric ozone when sufficient NO_x is present (Fishman *et al.*, 1979; Logan *et al.*, 1981).

The CO, hydrocarbons and NO_x, emitted during biomass combustion constitutes the starting ingredients for the formation of ozone. Once this mixture is exposed to sunlight, the hydrocarbons, are oxidised photochemically first to various peroxides, aldehydes, and so forth, then to CO. This CO is added to the amount directly emitted from fires and is finally

oxidised to CO_2 by reaction with OH. High concentrations of hydrocarbons and CO have been observed during the burning season in the tropics (Andreae *et al.*, 1988 and Crutzen *et al.*, 1985). In the presence of high levels of NO_x, as will be the case in smoke plumes, the oxidation of CO and hydrocarbons is accompanied by the formation of ozone.

The photolysis of NO_x thus represents the most important process in the photochemical production of tropospheric ozone. This process of tropospheric ozone production according to Wayne (1985), may be written as follows:

$$NO_2 + h\nu \rightarrow O + NO$$
$$O + O_2 + M \rightarrow O_3 + M$$
$$OH + CO \rightarrow H + CO_2$$
$$H + O_2 + M \rightarrow HO_2 + M$$
$$HO_2 + NO \rightarrow OH + NO_2$$
$$\text{----------}$$
$$\text{Net} \quad CO + 2O_2 + h\nu \rightarrow CO_2 + O_3$$

According to Chatfield and Delany (1990), the efficiency of O_3 formation, i.e., the amount of ozone formed per molecule of hydrocarbon oxidised, depends on the spread of the smoke plume and the chemical mix of hydrocarbons, NO_x, and O_3 present in the reaction mixture, and thus on the history of transport and mixing of the air mass. Increased concentrations of ozone promote high concentrations of OH radicals and thus increase the overall photochemical activity of air masses produced by biomass burning.

3.3 Estimates of Global Biomass Burning

To describe the impact of biomass burning on the atmospheric environment, it is necessary to understand the processes involved in the combustion of natural biomass. Current estimates of emissions from biomass burning are based on empirical data and observations from natural and experimental fires (Crutzen and Andreae, 1990). Levine (1990), talks of work done by

M.O. Andreae at the Max Planck Institute of Chemistry in Germany. Andreae estimated global emissions from biomass burning based on the total amount of biomass burned (in Terragrams of dry material (dm) per year) and the amount of carbon released to the atmosphere (in Terragrams of carbon). Andreae's estimates are summarised in Table 3.1 reproduced from Levine (1990).

Table 3.1 Global estimates of annual amounts of biomass burning and of the resulting release of carbon to the atmosphere. (After Levine, 1990).

Source	Present-Day Biomass Burned, Tg dm/yr* (Andreae)	Present-Day Carbon Released, Tg/yr (Andreae)	1850 Carbon Released, Tg/yr (Houghton)
Tropical Forest	1260	570	175(100-250)
Temperate and Boreal Forests	280	130	250(200-300)
Savanna	3690	1660	1850 (1000-2700) includes agricultural waste
Agricultural Waste	2020	910	
Fuelwood	1430	640	500(400-600)
Shifting Cultivation			450(300-600)
World Total	8680	3910	3225 (2000-4500)

* Tg dm/yr - Terragrams of dry material (dm) per year

The biomass actually burned is a critical parameter that has to be accurately assessed in order to derive trace gas fluxes at local or regional scales. Today, it is generally accepted that

Africa is the continent where biomass burning occurs most frequently. Its widespread, frequently burned savannas bear ample witness to this. In South Africa, several different types of burning have to be considered: savanna fires - which constitute the most extensive burns, forest fires, agricultural waste burning and the use of wood fuel.

Generally, the amount of biomass burned per year may be estimated by (Seiler and Crutzen, 1980):

$$M = A \times B \times \alpha \times \beta$$

where M denotes the estimated amount of dry biomass burned, A the burned area, B the biomass density (g dm/m^2), α the aboveground biomass burned, and β the fraction of aboveground biomass burned. Parameters B, α and β vary with the ecosystem and are determined by assessing the dry biomass matter before and after a fire. The complete and efficient burning of biomass produces water vapour and carbon dioxide as the primary combustion products (Seiler and Crutzen, 1980). The total mass of compound species (M(C)) produced by biomass burning is related to the mass of the burned matter M by

$$M(C) = 0.45M$$

To quantify the production of gases other than CO_2 and H_2O produced by biomass burning, the "emission ratio" (E.R.) for each gas must be determined (Seiler and Crutzen, 1980). The E.R. for a gas is defined as

$$E.R. = \frac{\Delta X}{\Delta CO_2}$$

where ΔX is the concentration of species X produced by biomass burning and is defined as

$$\Delta X = X^{*} - \overline{X}$$

where X^{*} is the measured concentration in the biomass burn plume and $\overline{X}$ is the background atmospheric concentration of the gas, and

$$\Delta CO_2 = CO_2^{*} - \overline{CO_2}$$

where ΔCO_2 is the concentration of CO_2 produced by biomass burning, CO_2^{*} is the measured concentration in the biomass burn plume and $\overline{CO_2}$ is the background atmospheric concentration of CO_2.

It is important to emphasize that the emission factor of a species will vary depending on the ecosystem that is burning. The species emission factor depends on the nature and chemical composition of the burning biomass material and the temperature of the fire. These parameters vary from ecosystem to ecosystem. Hence the parameters B, α, β, and E.R. are all ecosystem dependent (Levine, 1990).

The estimates made by Andreae (1991) (see Table 3.1), indicate that biomass burning is a significant global source of carbon dioxide (40% of all global sources), ozone (38%), carbon monoxide (32%), hydrogen (25%), NMHC (24%), NO_x (21%) and particulate organic carbon (39%). As already noted, while ozone is not produced directly by biomass burning, the gas mixture of carbon monoxide, hydrocarbons, and nitrogen oxides produced by biomass burning leads to the photochemical production of ozone when exposed to light. The chemistry leading to ozone production in the smoke plume is identical to urban smog photochemistry. Smoke plume concentrations of ozone in the range of 50-120 ppbv (parts per billion by volume) often exceed concentrations associated with highly industrialised areas.

3.5 Summary

The use of fire by humans as a tool to manipulate the environment has been instrumental in human conquest and domination of the earth. Biomass burning i.e. the intentional burning of forests, grasslands, agricultural stubble, agricultural waste and wood as fuel, etc. has been recognised as having a significant detrimental impact on the environment (Seiler and Crutzen, 1980; Crutzen and Andreae, 1990; Levine, 1990; Andreae, 1991).

Biomass fires emit much the same gases as fossil fuel burning in industrial regions: CO, hydrocarbons, and NO_x, the starting ingredients for the formation of ozone and urban photochemical smog. Once such a mixture is exposed to sunlight, the hydrocarbons, are oxidised photochemically first to various peroxides, aldehydes, etc., then to CO (Andreae *et al.*, 1988 and Crutzen *et al.*, 1985). This CO is added to the amount directly emitted from fires and is finally oxidised to CO_2 by reaction with OH. In the presence of elevated levels of NO_x, as will be the case in smoke plumes, the oxidation of CO and hydrocarbons is accompanied by the formation of ozone (Crutzen *et al*, 1985).

In view of the large amounts of hydrocarbons and NO_x emitted from biomass fires, it is thus not surprising that very high concentrations of tropospheric ozone are produced in the plumes of biomass fires, often exceeding values typical of industrialised regions.

CHAPTER FOUR: THE ROLE OF ATMOSPHERIC CIRCULATION OVER SOUTHERN AFRICA

The atmospheric circulation over South Africa has been well documented in the literature (for example Preston-Whyte and Tyson, 1988). South Africa's location in the southern hemisphere sub-tropical latitudes between approximately 20°S and 35°S, results in its weather being influenced by circulation systems both in the tropics to the north and the temperate latitudes to the south. The objective of this study is not however, to outline the atmospheric circulation over southern Africa, but rather to concentrate on aspects of the circulation which are pertinent to the topic under investigation i.e. the role of atmospheric circulation in the relationship between biomass burning and ozone maxima off the east coast of South Africa. This task is accomplished by an examination of the circulation in terms of the scales of motion.

4.1 Macroscale Circulation

The mean atmospheric circulation over southern Africa, as has been documented by Jackson (1952) and Taljaard (1953), is anticyclonic (Figure 4.1). According to Tyson *et al.* (1988), this anticyclonic airflow is conducive to the subsidence of air (Figure 4.2) which produces adiabatic warming, drying of the atmosphere, increasing atmospheric stability, suppression of precipitation and the occurrence of dry spells. This is significant in dispersion terms, as it creates conditions favourable for the formation of surface radiation inversions of temperature, surface drainage wind inversions and elevated subsidence inversions, all of which inhibit the dispersion of atmospheric pollutants.

The adiabatic warming of subsiding air in high pressure systems is the primary cause of subsidence or elevated inversions over southern Africa (Preston-Whyte *et al.*, 1977). Subsidence inversions occur throughout the year, but most frequently from July to December.

The dry, stable winter period is of greatest significance for the accumulation of atmospheric pollution. Subsidence inversions have a summer base height of 2000m - 3000m over the plateau and in winter, with stronger subsidence, the base height decreases to 1500m or less over the plateau. In both seasons the strength of the subsidence inversion over the central interior of southern Africa is of the order of 1° to 2°C (Preston-Whyte *et al.*, 1977).

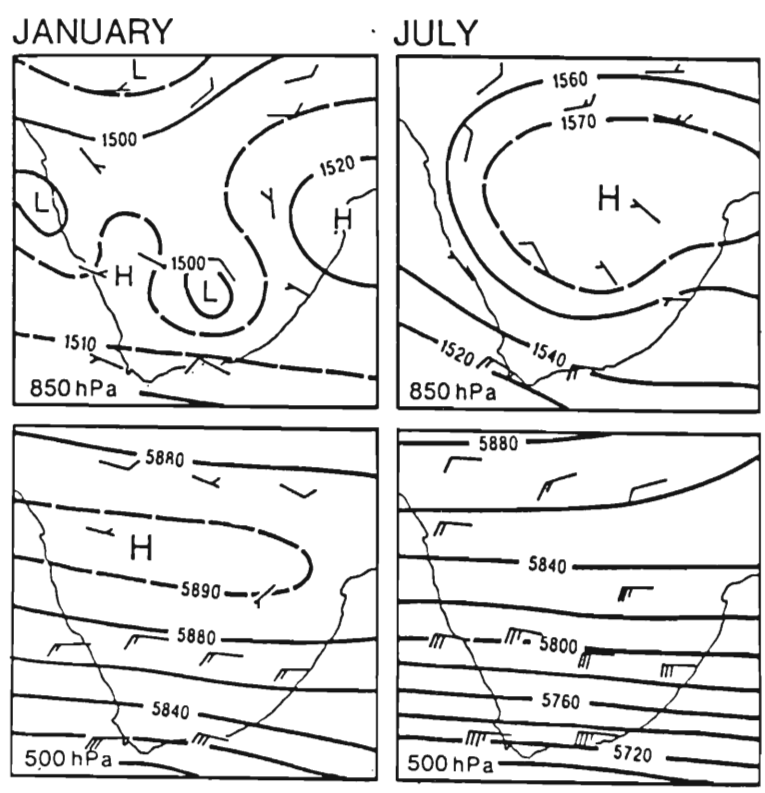


Fig. 4.1 Contours of the 850 and 500hPa surfaces (gpm) and associated wind vectors in January and July. (After Taljaard, 1981.)

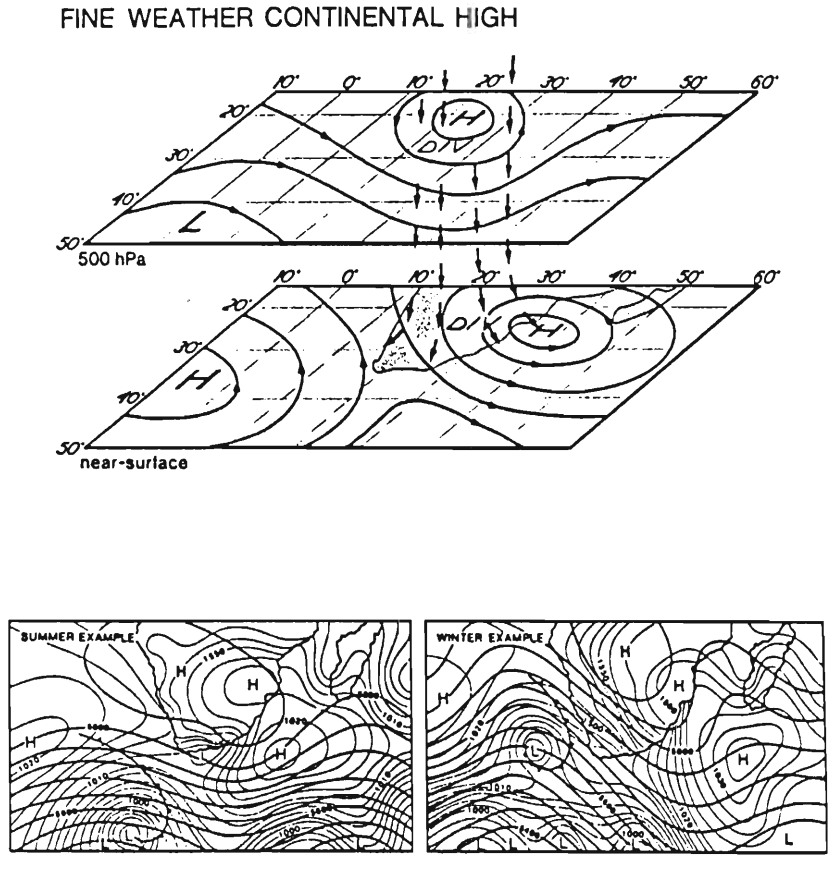


Fig. 4.2 *Upper*: a schematic representation of the near-surface and 500 hPa fine-weather circulation associated with high pressure systems over southern Africa. *Lower*: summer and winter examples of such systems. Light lines indicate isobars at mean sea level (hPa) over the oceans and contours of the 850 hPa surface (gpm) over the land; heavy lines show contours of the 500 hPa surface (gpm). (After Preston-Whyte and Tyson, 1988.)

Over Natal, the base of the subsidence inversion occurs at about 1500m but its height is influenced by the passage of weather producing systems which cause the subsidence inversion to be situated closer to the surface ahead of frontal disturbances (Preston-Whyte, 1975; Preston-Whyte and Diab, 1980). The inversion extends inland from the coast to transect the Drakensberg Escarpment, forming a bounded space which may be regarded as a vast coastal airshed open only to the sea (Preston-Whyte, 1990). Pollutants emitted into this airshed will be retained for as long as the inversion persists. Subsidence inversions occur with a frequency exceeding 70% from August to December over Durban (Preston-Whyte and Diab, 1980).

Inhabitants of Natal are familiar with the smoke haze often seen during veldfire burning. The smoke and particulate matter emitted, rises to the level of the subsidence inversion and is unable to rise further and as such is trapped within the airshed. As concentration occurs, a haze layer forms. The subsidence inversion displays little diurnal variation and almost always caps the midday mixing layer (Tyson *et al.*, 1976). Frequently the mixing layer does not reach the subsidence inversion since the average height of the midday winter mixing depth is about 1000m. Thus, it is likely that over time a trapping layer will develop beneath the subsidence inversion (Figure 4.3).

Surface inversions form at night through radiational cooling of the surface. They reach their maximum depth just before sunrise and normally break down after sunrise as a result of the convective heating and turbulent mixing of the near-surface air (Tyson *et al.*, 1976). With clear, undisturbed weather conditions this process is likely to be a daily occurrence throughout southern Africa, particularly during winter, when inversions of temperatures occur virtually every night at the surface.

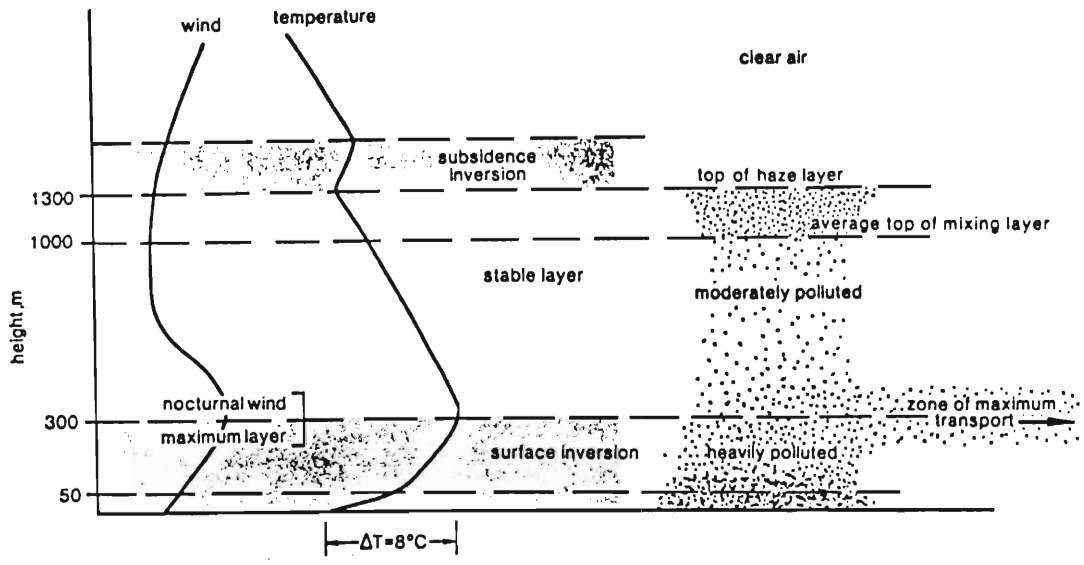


Fig. 4.3 Mean winter temperature and wind profiles for the Eastern Transvaal Highveld and major pollution accumulation layers. (After Tyson *et al.*, 1988.)

In winter, the depth of the surface inversion varies from less than 300m at the coast, to more than 500m over the plateau with an average strength of about 5-6°C (Tyson *et al.*, 1976). In summer, the depth of the surface inversion is about the same but has an average strength of less than 2°C. Surface inversions over Durban occur with a frequency exceeding 70% from May to August (Preston-Whyte and Diab, 1980).

Thus for much of the year in South Africa, the potential exists for high pollution concentration due to weak ventilation. In winter this is caused by frequent, strong and deep, surface inversions while in spring and summer it results from short periods of conditions of stagnation associated with an increased frequency of near-surface inversions (Preston-Whyte and Diab, 1980).

4.2 Synoptic Circulation

The continuous procession of eastward moving, high and low pressure systems is, according to Tyson *et al.* (1979), largely responsible for wind and other weather changes over the study area. These high and low pressure systems are influenced firstly by the climatic controls imposed by the Drakensberg Escarpment which separates the interior plateau from the narrow coastal margin and secondly by the contrasting temperatures of the ocean currents adjacent to the shores of the subcontinent. As a consequence, the weather over the coastal regions differs greatly from that experienced over the interior of the country.

It is at this point necessary, to outline the effect that synoptic weather systems have on the accumulation or dispersion of pollution along the east coast of South Africa. Air Pollution Potential (APP), according to Diab (1976), refers to the set of meteorological conditions which are favourable for the accumulation of pollution. The APP at any given time, is a function of the vertical and horizontal components of motion. Vertical motion depends on the stability structure of the atmosphere and horizontal motion is dependent upon wind speed.

The passage of mid-latitude frontal systems and accompanying coastal lows along the east coast of South Africa leads to a distinctive weather sequence. Associated with this weather sequence are well defined patterns of APP, which are summarised in Figure 4.4. Diab *et al.* (1991) discuss three synoptic regimes, each of which is characterised by a distinct APP. The first synoptic situation is that of the *established high pressure system* seen in Figure 4.5. It is characterised by light north-easterly winds and low mixing depths caused by the existence of an upper atmosphere subsidence inversion. The development of nocturnal surface inversions is common, thus the dispersal capacity of the atmosphere is poor and the APP high. The second synoptic regime is the *pre-frontal* regime seen in Figure 4.6. The approach of a low is accompanied by lowering of the subsidence inversion, which reaches its lowest level immediately before the wind reversal that is often associated with the passage of a low pressure system. Under these conditions the APP increases even further as the subsidence inversion dips towards the surface ahead of the low. The final synoptic regime

is the *post-frontal* condition seen in Figure 4.7. It is characterised by the presence of strong winds, the lifting of the subsidence inversion, and is often accompanied by rain. This gives rise to rapid dispersal and removal of pollutants and hence a low APP. With the passage of the low, the subsidence inversion either disappears or is displaced to higher levels.

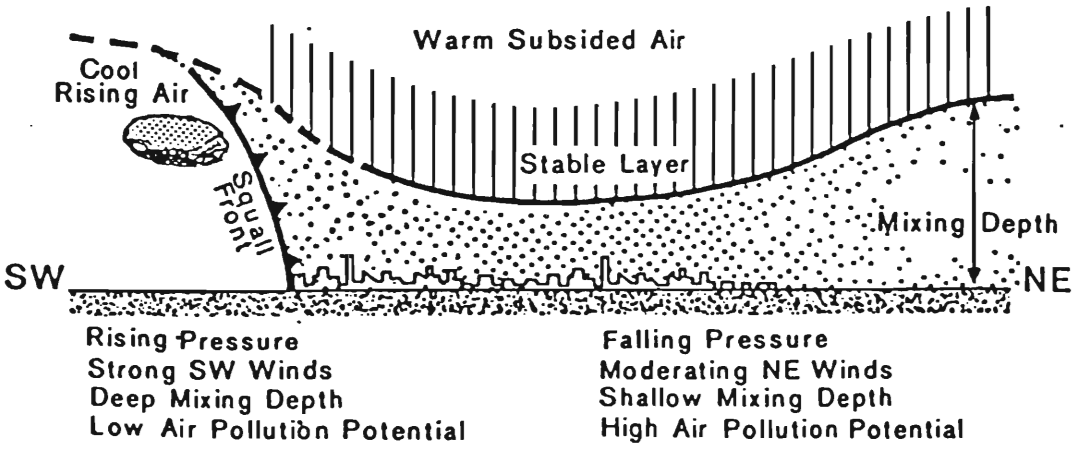


Fig. 4.4 Schematic diagram showing the fluctuations in air pollution potential with the passage of a frontal disturbance. (After Preston-Whyte and Diab, 1980.)

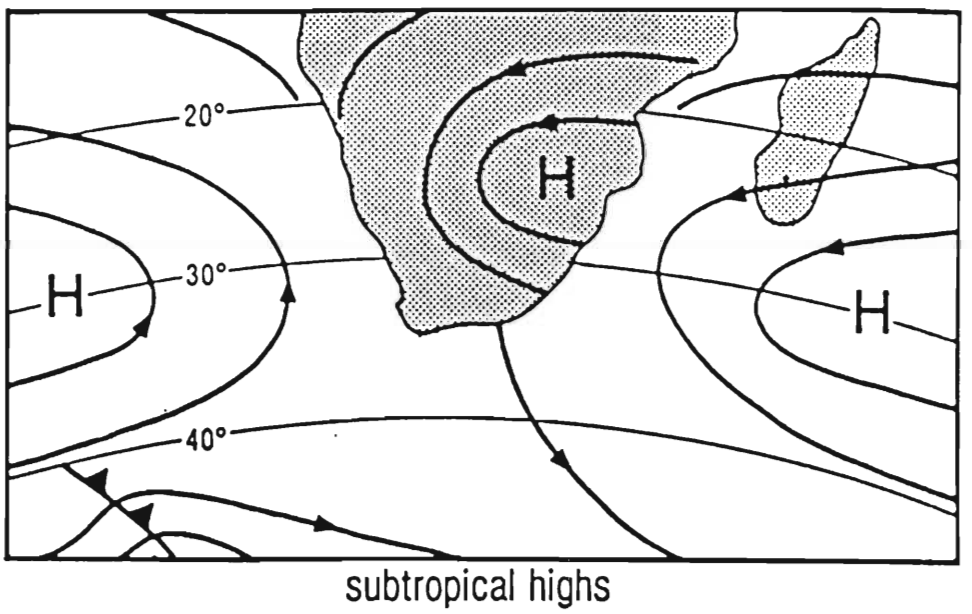


Fig. 4.5 Dominant high pressure system (After Preston-Whyte and Tyson, 1988.)

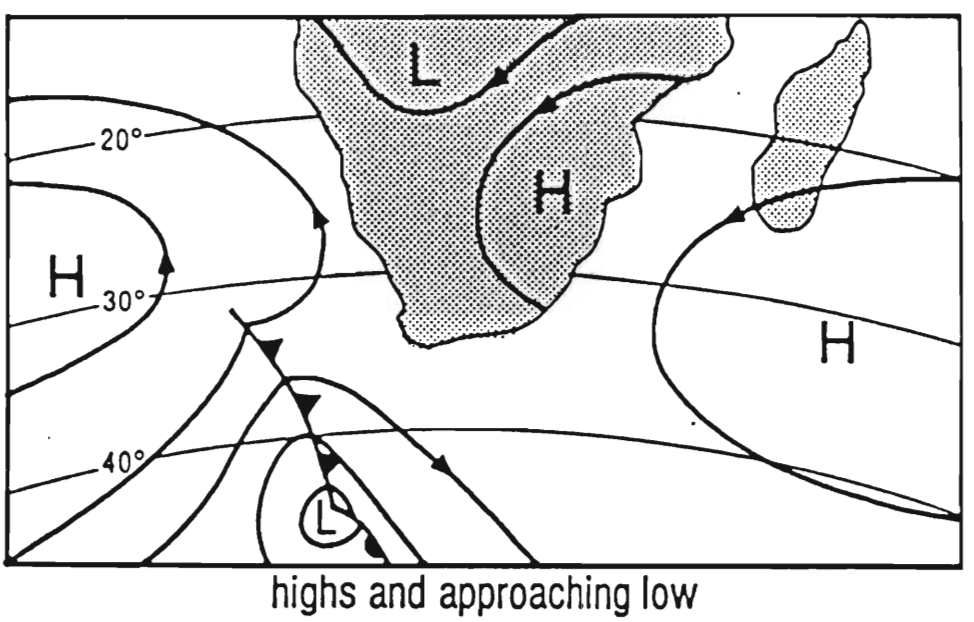


Fig. 4.6 Pre-frontal conditions (After Preston-Whyte and Tyson, 1988.)

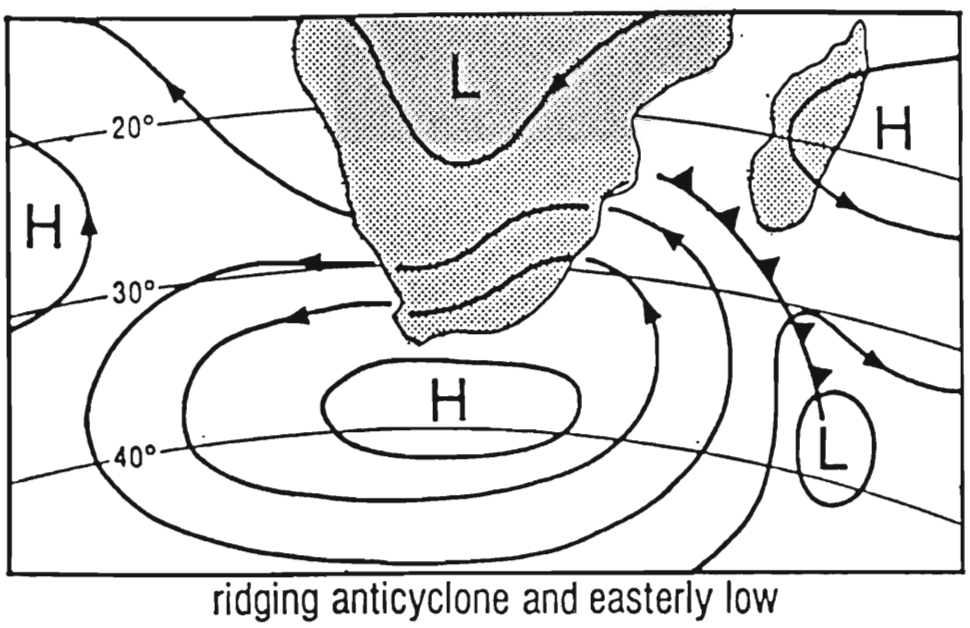


Fig. 4.7 Post-frontal conditions (After Preston-Whyte and Tyson, 1988.)

This sequence of changes in the inversion heights, mixing depths and winds is characteristic of the movement of low pressure systems along the Natal coast and has serious implications for air pollution concentrations and by implication biomass burn products, in this region (Diab *et al.*, 1991).

The study area also experiences Berg winds, which are important coastal climatic features causing the curious anomaly that the highest temperatures of the year frequently occur during

winter (Tyson, 1964). Berg winds are hot, dry winds blowing from the interior to the coast. They occur mainly from April to September (Tyson, 1964). According to Preston-Whyte and Tyson (1988), they are associated with large-scale, pre-frontal divergence and the dynamic warming of subsiding air moving offshore. This air is warm and dry owing to its origin in the semi-permanent high pressure cell over South Africa. The high temperatures are thus due in part, to the type and nature of the air mass. The extent of the warming is such, that even on the plateau inland of the Drakensberg Escarpment, positive temperature departures may be experienced. Additional adiabatic warming of the air occurs as it descends to the coast from the interior plateau and this enhances the warming effect. Thus the onset of a Berg wind is normally characterised by a large increase in temperature.

Owing to the subsidence, the air shows marked stability and extensive surface inversions exist. Apart from the large positive departures of temperature which occur, the humidity is low, lapse rates show marked stability and skies are clear (Tyson, 1964). The cessation of a Berg wind is associated with negative temperature departures and high relative humidities. The lapse rates reveal instability and the skies are covered with low cloud (Tyson, 1964).

In most instances in late winter and early spring, critical fire hazard warnings are issued when Berg winds occur as a result of the extra dry conditions and unusually high temperatures (Meikle, 1986). Berg winds are thus associated with poor atmospheric dispersal capacity and high APP.

4.3 Mesoscale Circulation

Mesoscale circulations in the form of land and sea breezes and topographically-induced winds cause diurnal fluctuations in circulation characteristics. Nocturnal, non-turbulent mountain winds and land breezes occur under stable near-surface conditions, while daytime plain winds and sea breezes prevail under conditions of instability (Tyson *et al.*, 1976). Land and sea

breezes and topographically induced circulations have a significant influence on stability and consequently on the dispersion efficiency of the atmosphere.

The generation of local winds may be attributed to the discontinuity in terms of heat, roughness and moisture which exists along the land-ocean boundary. During the day, sea breezes blow onshore, advancing inland as they strengthen (Preston-Whyte and Tyson, 1988). The sea breeze is most common in summer, when moist, relatively cool air over the sea is advected almost daily over the Natal coast. When deflected by the Coriolis force they become north-easterly winds (Preston-Whyte, 1969). By night, with the radiational cooling of the land, an offshore land breeze develops as a separate circulation. The growth of the land breeze circulation and the development of cold air drainage are closely linked to the macroscale weather patterns. Calm, clear weather is required to facilitate the strong nocturnal cooling of the land. Such weather is associated with anticyclones which are displaced to lower latitudes in winter thus increasing atmospheric stability over the Natal coast bringing warm dry weather (Preston-Whyte, 1968).

Due to atmospheric stability near the ground the ventilation is poor. At night, the radiational cooling produces a temperature inversion. The surface inversion persists for some time after sunrise. The land breeze is too weak thus the ventilation of the area is left to the sea breeze which is weak and of short duration during winter. Thus adequate ventilation only takes place with the arrival of a depression and unstable weather.

A significant aspect of the land breeze is its ability to transport atmospheric pollutants. Contaminated air would be moved seawards by the land breeze and then parallel to the coast by gradient winds. Pollutants could thus be carried a considerable distance from their source and may even be returned to land by the returning sea breeze (Preston-Whyte, 1990) (Figure 4.8).

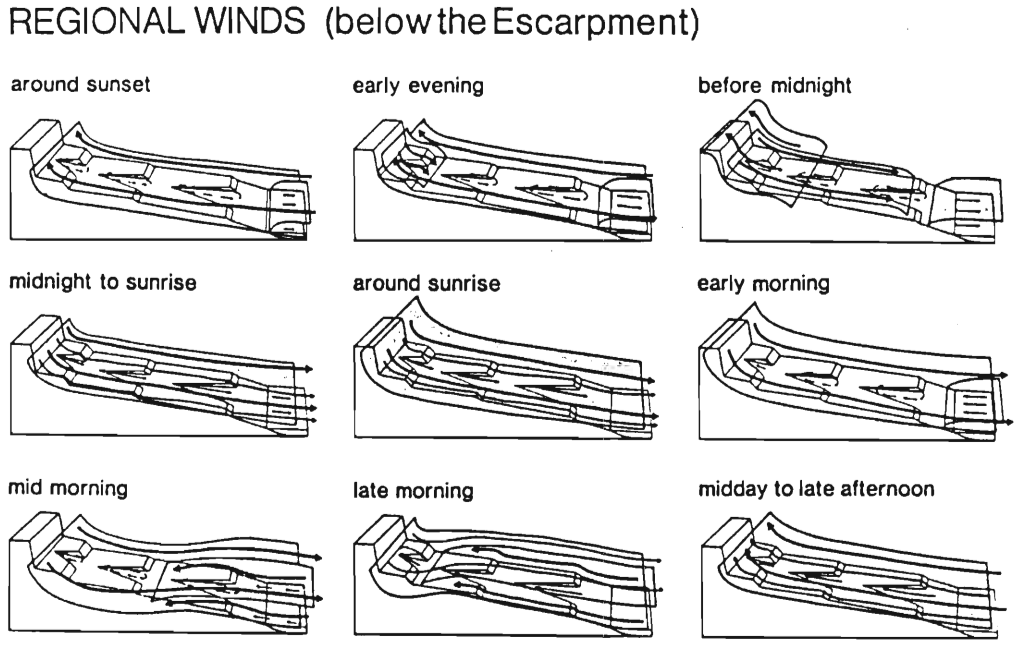


Fig. 4.8 The diurnal variation of local winds on a regional scale between mountains (or escarpments) and plains (or the sea). (After Preston-Whyte and Tyson, 1988.)

Regional topographically-induced circulations of a mountain to plain (or high ground to low ground) and plain to mountain variety occur on a large scale in southern Africa. Mountain-plain winds produce large-scale regional airflow between cooler mountains and warmer plains by night, whereas, plain-mountain winds produce an opposite flow between cooler plains and warmer mountains by day. In southern Africa the temperature gradient between the Drakensberg Escarpment and the coast, results in these winds being particularly well developed seaward of the escarpment over Natal (Figure 4.9). According to Preston-Whyte and Tyson, (1988), mountain winds dominate and are strongest in winter when the cooling effects are most pronounced.

In Natal the mountain-plain wind is over 1000m deep and is known to transport pollution in an undiluted, undispersed form for hundreds of kilometres (Preston-Whyte, 1990). Mountain-plain winds represent highly adverse pollution conditions, particularly as, with the early-morning decay of every nocturnal local wind, conditions are ideal for the occurrence of fumigations. Over the period of time covering the changeover from one regime to another, it is possible for recirculation to occur.

For instance, pollution being advected down the Tugela valley in a stable mountain or mountain-plain wind may be carried out to sea, be transported south along the coast in a north-easterly gradient wind of anticyclonic origin and then be re-transported back over land by a sea breeze.

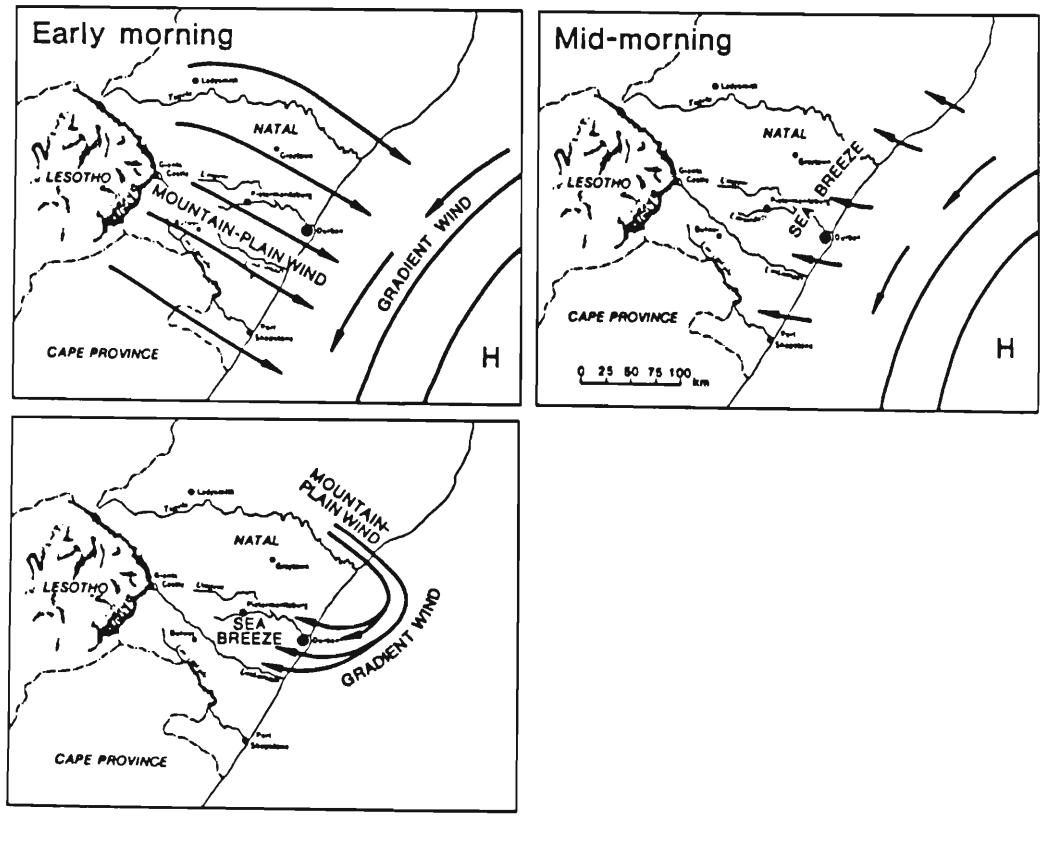


Fig. 4.9 Early morning surface and local gradient winds over Natal. Recirculation of pollution may occur as a consequence of such airflow patterns. (After Preston-Whyte and Tyson, 1988.)

CHAPTER FIVE : BIOMASS BURNING IN EASTERN SOUTH AFRICA

5.1 Introduction

Biomass burning occurs frequently in South Africa throughout the winter period of every year in the form of either prescribed burns or wild fires. The southern African landscape includes vast grasslands, wooded savanna, and forest-savanna mosaics which are prone to fire. Less extensive forest and desert regions are also present. The objective of this chapter is to establish the extent to which biomass burning occurs in South Africa. This will be accomplished by a review of the extent of biomass cover, both natural and anthropogenic (grassland, savanna, forest and commercial sugar cane) within the study area (Figure 2.1), and a recognition of the role of fire in each of these systems.

The study area in this analysis includes all areas of the provinces of Transvaal and Natal, which lie to the east of the Drakensberg Escarpment (Figure 2.1). Approximately 80% of this area was naturally composed of grasslands, while the remaining 20% comprised natural forest ecosystems and moist and arid savanna ecosystems (de V. Booysen *et al.*, 1984). However, as a result of agricultural development in South Africa, a large percentage of this area is currently under crop or commercial forest.

5.2 Grasslands and Savanna

Grasslands, according to de V. Booysen *et al.* (1984), are defined as those areas where the vegetation is dominated by grasses and occasionally by other plants of grassy appearance, in which woody plants are absent or rare. The grassland biome of South Africa occurs on flat to gently rolling upland plateaux at 1000m to 1800m above sea level to the west of the escarpment, and on the steeply sloping escarpment faces of the eastern seaboard, usually at altitudes exceeding 500m. Figure 5.1 illustrates the distribution of grassland vegetation throughout South Africa. According to Rutherford *et al.* (1986), the grassland biome of

South Africa occupies a total area of 31.40 million hectares, of which, on average 4.887 million hectares are burned both intentionally and accidentally each year.

Seiler and Crutzen (1980) define the term savanna as referring to a tropical or subtropical formation where the grass stratum is continuous and important but occasionally interrupted by trees and shrubs. Its overall structure is that of a wooded grassland where the woody vegetation comprises mature trees and shrubs. In southern Africa, the term savanna includes bushveld, thornveld, lowveld, woodland and scrub. The herbaceous vegetation is dominated by perennial grasses, some species of which occur in the open spaces between trees and shrubs and others occur underneath the trees.

Savanna constitutes one of the major biomes of South Africa. It occurs along the southeastern seaboard as a narrow strip of thornveld and includes the valley bushveld of the dry river valleys. Further north it broadens out into the lowveld and bushveld of Natal and the eastern and northern Transvaal and finally merges into the Kalahari thornveld of the southwestern Transvaal, western Orange Free State and northern Cape Province (Trollope, 1992b). Savanna in South Africa occupies, according to Rutherford *et al.* (1986), an area of 40.88 million hectares. They estimate that on average, 4.885 million hectares of savanna are burned annually. The distribution of savanna areas throughout South Africa is illustrated in Figure 5.2.

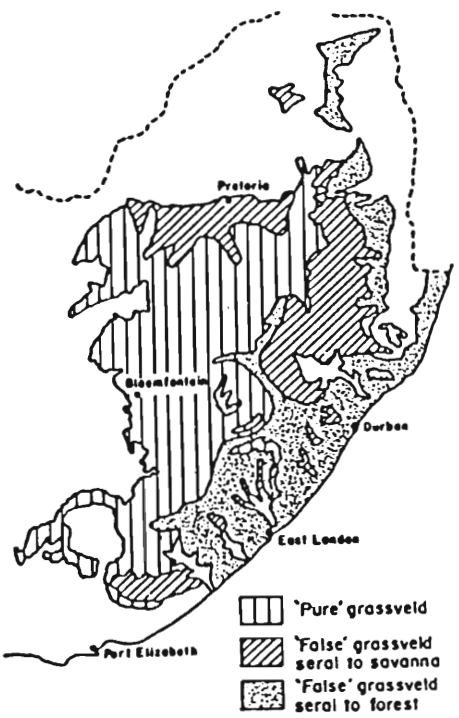


Fig. 5.1 Distribution of grassland vegetation in South Africa. (After Huntley, 1982).

Fig. 5.2 The savanna areas of South Africa. (After Trollope, 1992b).

Fire is regarded as being a natural factor of the environment in southern Africa and plays an important ecological role in the development and maintenance of numerous plant communities. In the absence of fire, grazing and other forms of defoliation, the inability of grasses to shed their leaves tends to result in the accumulation of self-smothering dead material (Trollope, 1992a). Accumulation is rapid in the productive moist and "sour" grasslands, but slow in the generally less productive dry and palatable "sweet" grasslands. Three years of protection from fires is usually enough in moist grasslands to cause a marked deterioration in structure and species composition. Thus fire is necessary under natural conditions to maintain the vitality of moist and sourveld grasslands.

Veld burning, according to Trollope (1992a), is also an important and often essential management practice in both agricultural and conservation areas. Planned burns of grassland and savanna areas are conducted regularly for the following reasons: for security of valuable assets (fire breaks); to remove unpalatable material; to control problem plants; to prevent grassland areas from becoming moribund; to even out selective grazing and to move animals in game systems.

The various types of natural savanna formations are potentially of edaphic, climatic, orographic, or fire (lightning fire) origin and are influenced by wildlife (grazing, browsing, trampling). Together with anthropogenic influences (eg. livestock grazing), fuelwood cutting and other non-wood product uses, most savanna areas are shaped at present mainly by regularly occurring man-made fires (Goldammer and Crutzen, 1993). In arid savannas, fire is an infrequent but significant phenomenon. In moist savannas, fire is a regular phenomenon, with annual winter burns being the normal pattern.

The intensity and duration of the dry winter season and the frost period determine the degree of inflammability during autumn, winter and spring. Most of the grasslands and savanna biomes do not normally receive measurable rainfall for 2 to 4 months during winter. However, due to the effect of the Drakensberg Escarpment in increasing the quota of winter

rainfall, the grasslands have a mean monthly rainfall of at least 10mm (de V. Booysen *et al.*, 1984). The winter rain together with the absence of frost along the coastal regions results in these grasslands being less inflammable than those further inland.

According to Seiler and Crutzen (1980), the burning efficiency of the above described biomass is dependent on the fire regime i.e. the type and intensity of each fire and the season and frequency of burning. There are three broad types of fires based on the layers in which vegetation burns viz., ground, surface and crown fires. A *ground* fire is a fire that burns below the surface of the ground in deep layers of organic material and plant debris. A *surface* fire is one that burns in the herbaceous surface vegetation. A *crown* fire burns in the canopies of trees and shrubs (Trollope, 1992c).

In southern Africa, ground fires are rare and are generally confined to old mature fynbos and forests that catch alight under extremely dry conditions. Surface fires are the most common type of fire according to Trollope (1992c). They can develop into crown fires in tree and shrub vegetation when foliage ignites and carries the fire above the ground. In savanna communities, crown fires only develop when tree foliage is very dry and atmospheric conditions are characterised by high winds, high air temperatures and relatively low humidities eg. berg wind conditions. The most common type of fire in dry savanna is however a surface fire which consumes only herbal vegetation. Surface fires produce a narrow belt of flames and pass very quickly because of low fuel load density and the general presence of strong winds. High temperatures are therefore generally uncommon so that damage to the rootstocks and basal portions of trees does not occur.

Trollope (1992c) recommends that when burning is undertaken to remove moribund and/or unacceptable grass material, burning should be applied after the first spring rains when the grass is still dormant and the fire hazard low. Conversely, when burning to control bush encroachment, plants should be burned before the first spring rains while the grass is very dry and dormant to ensure a high intensity fire. Sourveld areas are burnt every 2 to 4 years,

while the sweetveld areas are burned much less frequently as they are better grazed and accumulation occurs to a much lesser degree (Trollope, 1992c).

The burning of grassland and savanna areas in South Africa probably plays an important role in the production of tropospheric ozone. However, very limited records of grassland and savanna fires exist. Existing records are incomplete and kept by a large assortment of individuals and organisations. The limited and diffuse nature of the data set was the basis upon which it was decided that no case studies would be drawn from grassland and savanna fires, nor would statistics on the number and extent of fires be presented.

5.3 Forests

Indigenous forests cover only 300000 hectares of southern Africa to the south of the Limpopo River (Macdonald and Crawford, 1988). They grow on all geological formations within areas receiving mean annual rainfalls of between 600mm and 2000mm. The forests occur as scattered patches of varying size in the eastern zones of southern Africa. Forest plantations cover 1.3 million hectares of land and the forestry and forest products industry is one of the largest and fastest growing sectors of the South African economy (Forestry Council, 1992). The industry is based on man-made forests of pine, *Eucalyptus* species and black wattle (*Acacia mearnsii*). Over 80% of these commercial forests occur on the eastern seaboard of the country (Forestry Council, 1992). The forested areas of South Africa have been divided into 13 zones of which 9 are represented in the study area. They are:

Zone 1 Northern Transvaal
Zone 2 Eastern Transvaal
Zone 4 Southern and Eastern Transvaal
Zone 5 Maputaland
Zone 6 Zululand
Zone 7 Natal Midlands

Zone 8 Northern Natal

Zone 9 Southern Natal

The total area under forest is distributed among the different provinces as follows: 635098 hectares in the Transvaal, 360084 hectares in Natal, 165505 hectares in the Zululand and Maputaland area and 134844 hectares in the Cape Province, giving a total of 1295531 hectares under forest in South Africa (Forestry Council, 1992). Figure 5.3 shows the distribution of forests within the study area and includes both private and state owned forest plantations.

While changes in climate may have played a significant role in regulating the distribution of forests in South Africa, fire, especially in the last 300 to 400 years, has been a significant modifier of this vegetation (Granger in Macdonald and Crawford, 1988). Fires started by natural agencies (lightning and rockfall) have long been a feature of the forest biome. However, it seems unlikely that these were ever frequent or caused damage to forest on the same scale as fires started by man.

Prescribed burning is commonly used for forest management in many countries. It serves mainly to reduce the accumulation of dry, combustible plant debris in order to prevent destructive wildfires. In South Africa, however, there is very little prescribed or planned burning of forests. Only 4.6% of all forest fires which occurred in the study area between 1979 and 1992 were planned (see Table 5.1). It appears that the majority of forest fires are unplanned or accidental. Data on forest fires which occurred on both state owned and private forest plantations in parts of Natal and the southern and eastern Transvaal were extracted from the Department of Forestry records for the period March 1979 to March 1992. A total of 7228 fires occurred.

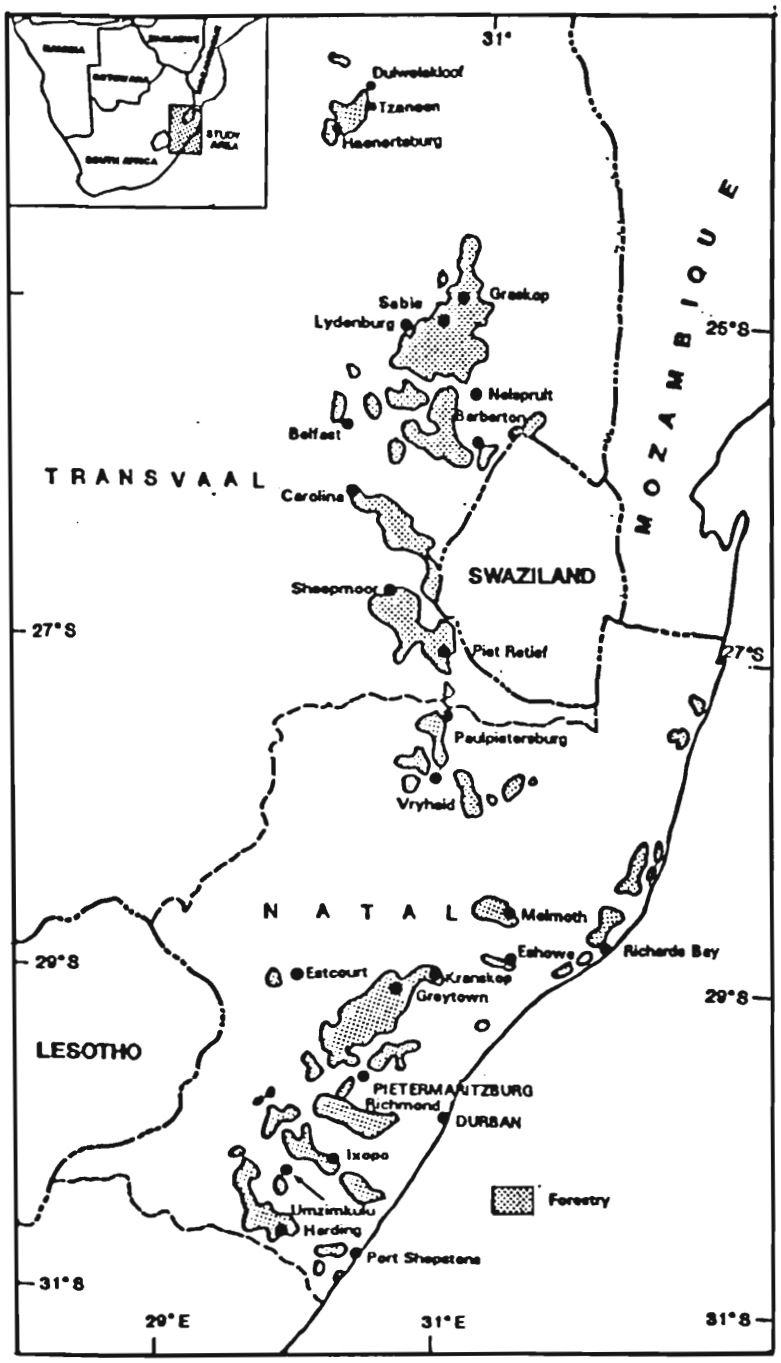


Fig. 5.3 The distribution of forests within the study region.
(Data from Department of Forestry, Pretoria)

Based on these data a summary of the causes of forest fires in plantations within the study area is presented in Table 5.1. It is clear that the four main causes of fires on both state owned and private plantations for the years 1979-1992 were: people (27.3%); honey hunters (21%); trains (13.8%) and lightning (11.2%). Incendiarism which was, according to Kromhout (1990), a primary cause of fires on private plantations throughout South Africa, did not feature prominently at all. Also it was found that the percentage of fires caused by unknown causes is remarkably low (2.2%) as compared to that of 30% found by Kromhout (1990) for private properties only. According to Kromhout (1990) the percentage of fires caused by runaway fires from adjacent private property is relatively small, as is the case in the data presented here.

Table 5.1 - Causes of plantation fires within the study area for the period 1979-1992. (Data from the Department of Forestry, Pretoria)

Cause	Private Plantations	State Plantations	Total
Unknown	138	22	160
Trains	475	514	989
Smokers	123	580	703
Lightning	421	384	805
Incendiarism	-	219	219
Honey Hunters	1464	21	1485
Fires From Private Property	470	45	515
Departmental	204	125	329
People	1944	79	2023

Tables 5.2 and 5.3, give a breakdown of the number of fires per month which occurred on state owned and private plantations respectively (during the study period). Figure 5.4 displays the average number of forest fires for the same period. Seventy percent of all fires, on both state owned and private plantations, occurred in the four months June to September, and clearly established this period as the fire season. July showed the highest number of fires with a total of 1282 fires and a monthly average of 128 fires.

A summary of the total area under forest burned per year during the years 1979 to 1992, on both state owned and commercial plantations within the study area, is presented in Table 5.4. This includes both planned and unplanned fires.

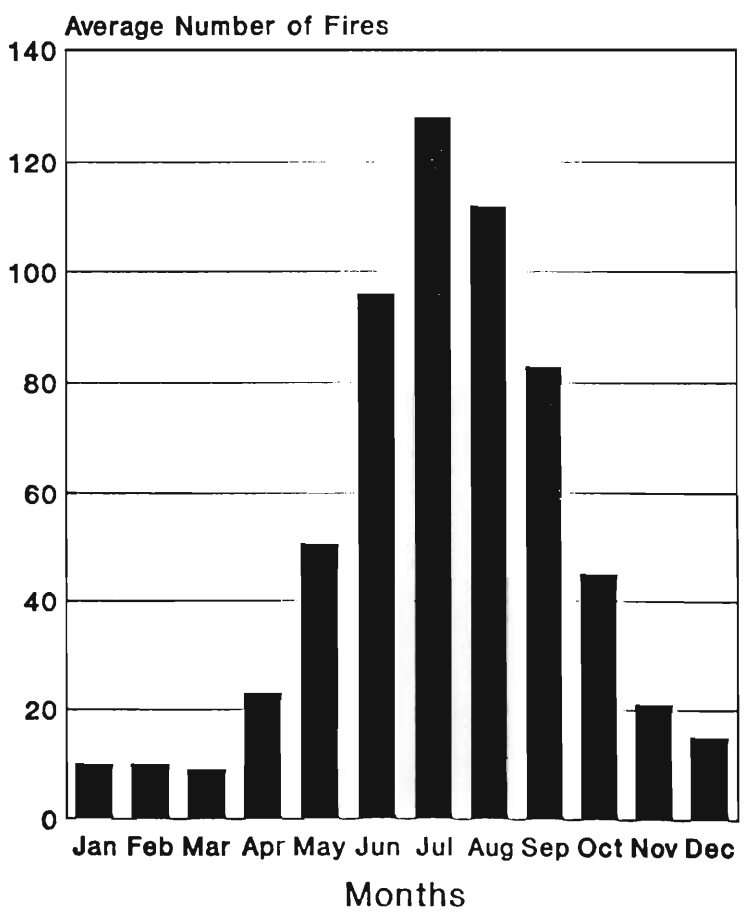


Fig. 5.4 The average number of forest fires per month, on both state owned and private plantations in the study area for the period 1979-1992. (Data from the Department of Forestry, Pretoria)

Table 5.2 - Reported forest fires on state plantations for the period 1979 to 1992

Monthly Totals (Data from the Department of Forestry, Pretoria)

Season	Total	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1979	-	-	-	-	-	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-	-	-	-	-	-
1981	168	-	-	-	10	2	28	26	17	33	15	23	14
1982	250	4	8	10	2	26	23	34	40	45	26	9	23
1983	206	6	12	6	26	27	23	31	17	28	19	4	7
1984	147	7	3	2	2	9	16	24	27	25	20	4	8
1985	220	10	2	4	18	20	18	34	33	19	30	22	10
1986	241	7	12	7	9	17	28	45	36	35	28	7	10
1987	90	2	5	3	1	22	12	15	16	3	3	7	1
1988	98	5	2	1	1	10	19	14	19	12	10	5	0
1989	150	4	3	8	12	15	13	11	40	27	13	2	2
1990	129	2	0	2	0	1	18	38	12	24	17	10	5
1991	121	6	4	0	11	18	17	14	16	20	6	3	6
1992	-	19	24	55	-	-	-	-	-	-	-	-	-
Average*	-	5	5	4	8	17	19	26	26	24	17	7	7
Total	1918	**72**	**75**	**98**	**92**	**167**	**215**	**286**	**273**	**271**	**187**	**96**	**86**

*The monthly averages were calculated for the period 1982 to 1991 only. This was done to eliminate years with missing data.

Table 5.3 - Reported Forest Fires On Private Plantations For The Period 1979 To 1992

Monthly Totals (Data from the Department of Forestry, Pretoria)

Season	Total	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1979	240	-	-	2	1	28	64	56	36	20	17	9	7
1980	287	7	4	4	18	30	75	60	31	27	24	5	2
1981	282	3	1	1	4	7	43	92	37	31	18	37	8
1982	406	5	6	8	5	29	61	79	88	54	25	15	31
1983	311	7	9	2	17	35	44	68	29	69	22	4	5
1984	183	2	7	3	7	13	29	26	32	36	24	0	4
1985	518	6	3	4	23	54	74	101	102	77	46	25	3
1986	448	4	4	5	14	31	93	104	76	79	12	17	9
1987	286	3	4	4	7	26	61	92	60	16	9	2	2
1988	391	8	3	0	15	54	102	67	80	25	22	11	4
1989	420	3	1	13	28	17	91	76	76	76	25	4	10
1990	783	5	2	2	16	26	150	210	142	106	74	42	8
1991	656	6	8	8	16	51	91	199	176	55	23	18	5
1992	-	11	34	53	-	-	-	-	-	-	-	-	-
Average**		5	5	5	15	34	80	102	86	59	28	14	8
Total	5309	**70**	**86**	**109**	**171**	**401**	**978**	**1230**	**965**	**671**	**341**	**189**	**98**

**The monthly averages were only calculated for the period 1982 to 1991. This was done to eliminate years with missing data.

Table 5.4 - The total area (ha) of forest in the study area burned annually during the period 1979 - 1992. (Data from the Department of Forestry, Pretoria)

Year	Private Plantations	State Plantations
1979	4474 ha	-
1980	5782 ha	-
1981	5587 ha	520 ha
1982	2877 ha	731 ha
1983	2734 ha	498 ha
1984	1004 ha	548 ha
1985	5550 ha	524 ha
1986	2694 ha	393 ha
1987	1853 ha	73 ha
1988	2115 ha	1249 ha
1989	2721 ha	9083 ha
1990	13 440 ha	568 ha
1991	2629 ha	949 ha

5.4 The Sugar Industry

A total of 471261 hectares of land along the east coast of South Africa is currently being used for sugar cane farming (J. Chadwick, *pers. comm.*). The distribution is as follows (Figure 5.5):

Midlands - 98399 hectares

North Coast - 115739 hectares

South Coast - 75225 hectares

Zululand - 142665 hectares

Northern Irrigated Areas:

Eastern Transvaal - 24706 hectares

Pongola - 14528 hectares

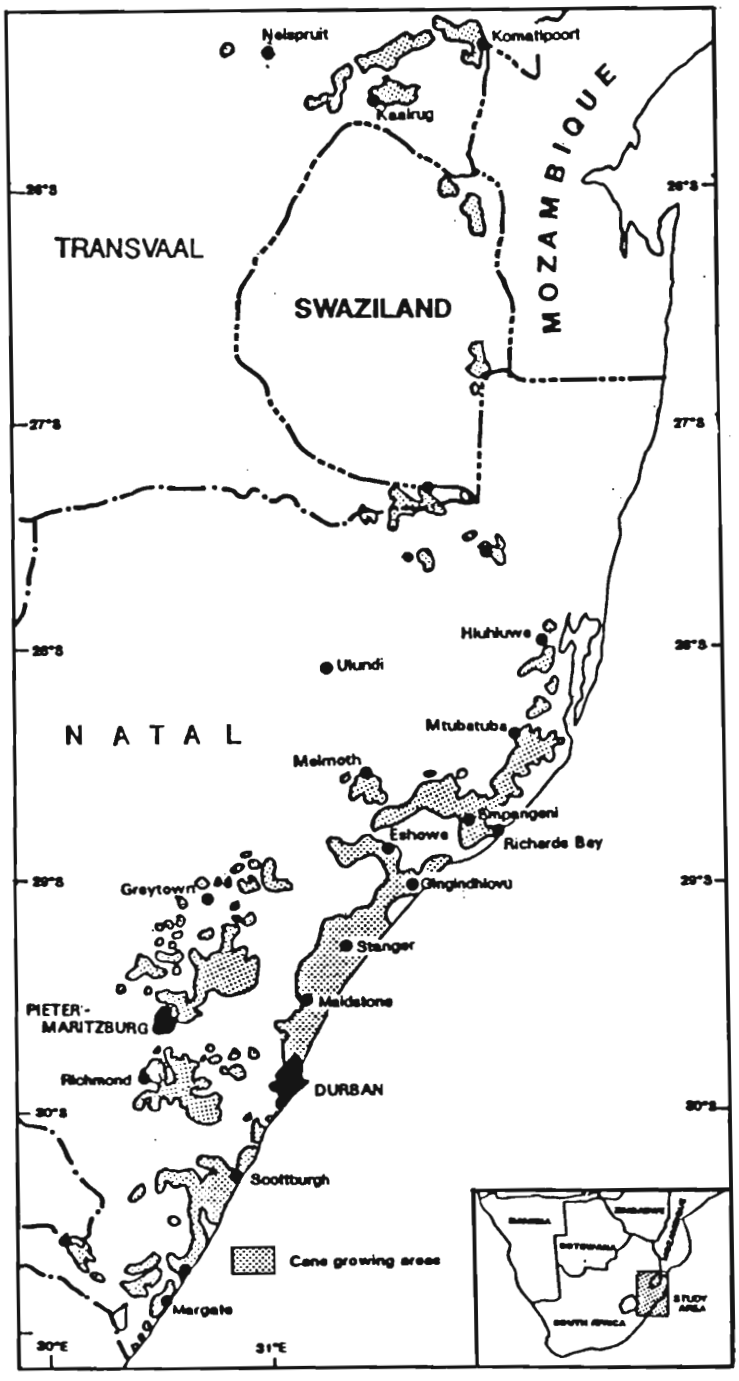


Fig. 5.5 Sugar cane areas of South Africa.
(After South African Sugar Journal, [1], 1993)

Sugar cane has a growing season of approximately 12 months, however harvesting of cane can occur when the cane is anywhere between 12 and 24 months old. In Natal, harvesting occurs between April and December. Mature cane has adhering to it dead leaves and these must be removed before it can be harvested. Removal can be carried out by preharvest burning or manual cutting off of excess foliage. The dead leaves together with the decapitated tops of the cane are collectively termed the "trash".

Cane burning is practised in sugar industries throughout the world and in South Africa as it is a cost-effective method of eliminating field trash. It also reduces labour and equipment requirements and costs, in addition to securing a larger, purer product of cane juice. The percentage of cane burnt differs widely by farmer and by region. It is estimated that the percentage burned annually per region is as follows: Midlands - 95%, North Coast - 40%, South Coast - 67%, Zululand - 90% and Northern Irrigated Areas - 99%. Thus approximately 78% of the total area under cane is burned annually, giving a total of 368526 hectares (B. Sugden, *pers. comm.*; J. Chadwick, *pers. comm.*; Scholes and Van der Merwe, 1993).

Much controversy surrounds the burning of cane as a result of public opposition to the intermittent smoke, odour, soot and poor visibility conditions. There has been considerable pressure exerted on the sugar farming community to seek alternatives to the burning of cane, one such alternative being a return to the practise of trashing.

In addition to preharvest burning, unplanned sugar cane fires occur frequently. Statistics on the number of unplanned sugar cane fires per month for the growing years 1982/3 to 1992/3 are presented in Table 5.5.

Table 5.5 - Reported Sugar Cane Fires Monthly Totals - 1982/3 To 1992/3

(Data obtained from GROCANE Fire Insurance Co.)

Season	Total	Apr.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Jan.	Feb.	March
1982/3	91	2	5	5	6	28	6	9	1	2	4	11	12
1983/4	87	16	11	8	17	8	10	4	0	1	3	5	3
1984/5	41	3	5	3	2	7	2	4	1	2	5	1	6
1985/6	138	18	14	6	19	29	10	11	4	2	7	11	6
1986/7	46	2	3	5	3	6	7	3	0	6	2	5	5
1987/8	30	2	1	5	2	7	2	1	2	0	0	6	2
1988/9	26	2	0	3	5	7	2	0	0	1	3	1	2
1989/90	63	4	0	4	9	14	10	5	0	4	1	5	7
1990/1	63	4	6	9	15	4	5	0	3	3	8	6	0
1991/2	141	9	6	9	3	20	13	0	3	7	10	32	29
1992/3	309	31	51	33	40	101	11	10	5	6	7	7	7
Total	1035	93	102	90	121	231	78	47	19	34	50	90	79
Monthly Averages		6.2	5.1	5.7	8.1	13	6.7	3.7	1.4	2.8	4.3	8.3	7.2

Monthly averages show that July and August exhibit the highest incidence of fire. The years 1985/6, 1991/2 and 1992/3 experienced particularly high occurrences of fires, as is confirmed by the statistics on the tonnage of cane lost in these years (Table 5.6).

According to Dewey (1992), by September 1992 it was evident that the 1992/3 sugar season would be one of the most severe on record. The extremely dry conditions brought about by the prolonged drought caused many runaway fires throughout the sugar belt. On 8 August 1992 for example, a fire destroyed large areas of cane lands in the Paddock district inland from Port Shepstone. Some 1465 hectares of cane lands were burnt out. Two weeks later on 22 August 1992 an even more destructive fire, which was centred in the north coast districts of Maidstone and Stanger occurred. It is estimated that 25000 tons of cane were lost in this case (Dewey, 1992).

Table 5.6: Tonnage loss due to sugar cane fires over the 11 year period 1982/3 - 1992/3, indicating the volume of fires. (Data obtained from GROCANE Fire Insurance Co.)

SEASON	TONNAGE LOSS
1982/3	3540
1983/4	7559
1984/5	2379
1985/6	15 932
1986/7	2623
1987/8	1410
1988/9	2569
1989/90	4866
1990/1	4437
1991/2	19 577
1992/3	40 598

5.5 Summary

Biomass burning is a common occurrence in South Africa especially during the winter months. Large numbers of both planned and unplanned biomass fires occur each year. The objective of this chapter has been to estimate the extent and nature of biomass cover in South Africa, and to examine the extent to which biomass fires occur.

Rutherford *et al.* (1986) put together some estimates of the extent of grassland and savanna coverage in South Africa. They estimate that the grassland areas of South Africa occupy a total area of 31.40 million hectares, of which, on average about 4.887 million hectares are burned both intentionally and accidentally each year. The savanna areas it is estimated, occupy an area of 40.88 million hectares, of which, on average 4.885 million hectares are lost to fire annually.

A total of 1.6 million hectares of land in South Africa is currently under forest. This area may be broken down into 300000 hectares of indigenous forest and 1.3 million hectares of commercial forest (Forestry Council, 1992). Prescribed burning is commonly used for forest management in many countries. It serves mainly to reduce the accumulation of dry, combustible plant debris in order to prevent destructive wildfires. However, in South Africa there is very little prescribed or planned burning of forests. Calculations show that only 4.6% of all forest fires which occurred in the study area between 1979 and 1992 were planned. Thus, no statistics on the average area lost to fire annually is available. Further analysis revealed that seventy percent of all forest fires between 1979 and 1992, occurred in the four months June to September. This indicates that a distinct fire season exists.

As at April 1992, it is calculated that an area of 471261 hectares is presently under sugar cane in South Africa. Of this area, some 78% i.e. an area of 368526 hectares, is burned annually (B. Sugden, *pers. comm.*; J. Chadwick, *pers. comm.*). However, this value represents only the planned burning of sugar cane at harvest. In addition to this preharvest

burning, unplanned sugar cane fires occur frequently, unfortunately, no average statistics are available.

The burning of grassland, 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 during a large biomass fire episode be examined. Because very limited records of grassland and savanna fires exist, it was decided that this data set would not be utilised. The availability of large, accurate data 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.

CHAPTER SIX: CASE STUDIES OF SEVERE FIRES

6.1 Introduction

The importance of biomass burning, as a significant source of atmospheric trace gases that are photochemically active in the troposphere, was first hypothesised by Crutzen *et al.* (1979). Since then, a number of studies have concluded that biomass burning contributes significantly to the global budgets of CO_2, CO (Logan *et al*, 1981; Connors *et al.*, 1991), CH_4, NO_x (Logan, 1983; Dignon and Penner, 1991), and NMHCs (Bonsang *et al.*, 1991), all of which lead to the photochemical production of tropospheric ozone. Recent measurements of ozone in the tropical troposphere by Logan and Kirchhoff (1986) and the analysis of satellite total ozone data by Fishman *et al.* (1986) and Fishman (1988), support the hypothesis that biomass burning contributes significantly to tropospheric ozone formation. The impact of seasonal burning, in the Amazon basin, on tropospheric ozone is to cause an increase in ozone throughout most of the tropical troposphere by 20-30ppbv (Delany *et al.*, 1985).

Fishman *et al.* (1990), propose that tropical biomass burning is the primary cause of the South Atlantic August-November tropospheric ozone maximum that has been observed by satellite (Figure 1.1). A significant portion of this ozone increase appears to be connected to biomass burning occurring in southern Africa. This is evidenced by ozonesonde profiles taken at Brazzaville, Congo and Ascension Island (Fishman *et al.*, 1991).

A number of studies have also made mention of the relatively high tropospheric ozone values found off the east coast of Africa. The "east coast ozone maximum" has, however never been examined in detail. Its character and occurrence in time and space will form the focus of the next section.

In South Africa, apart from the annual planned biomass burning, large areas of grassland, savanna and agricultural acreage are lost to wildfires annually. It is hypothesised that this biomass burning should influence ozone concentrations over southern Africa. An

examination of the characteristics of the east coast ozone maximum will contribute towards our understanding of the extent to which this is so.

6.2 The East Coast Ozone Maximum

The phenomenon of the "east coast ozone maximum" i.e. the region of relatively high ozone values found off the east coast of southern Africa has been referred to in studies examining the tropospheric ozone residual (Fishman and Larsen, 1987; Fishman, 1988; Fishman *et al.*, 1990; Fishman, 1991). Fishman and Larsen (1987) reported when examining total ozone, that the annual average of monthly total ozone values, shows the highest values near the west coast of Africa (10°W to 15°E), with the only exception being in April 1980 when slightly higher total ozone values (257 DU) were found near 55°E (near the east coast of Africa).

From the tropospheric ozone residual data set, derived from TOMS total ozone and SAGE stratospheric ozone profiles for October 1979 to September 1980, Fishman and Larsen (1987), show that tropospheric ozone maximises at a value of 40-50 DU along both coasts of Africa. Fishman (1988), examining the tropospheric ozone residual amounts using reprocessed TOMS data and SAGE data for October 1979 to September 1980, found that a distinct longitudinal gradient was evident. The highest tropospheric ozone value of 42 DU was found at 5°W, the second highest of 32 DU was found at 105°W and the third highest peak of 31 DU was found at 45°E, which coincides with the east coast of Africa. It should be noted that this longitudinal gradient of tropospheric ozone, is positively correlated with the MAPS flights in both 1981 and 1984. Both MAPS flights measured very high concentrations of CO off the east coast of Africa (Reichle *et al.*, 1990).

Although numerous references have been made to high tropospheric ozone concentrations off the east coast of Africa, no clear, concise description of the characteristics of the "east coast ozone maximum" exists in the literature. An examination of the ten years of tropospheric ozone residual data available, yields an indication of the magnitude, frequency

and spatial dimensions of the tropospheric ozone maximum situated off the east coast of South Africa.

The tropospheric residual data used in this study were derived from ten years (1979 to 1981 and 1984 to 1990) of TOMS, SAGE and SAGE II data. The spatial distribution of the tropospheric residual ozone measurements ranged from 0° to 50°E and from the equator to 50°S. The tropospheric residual data set utilised in this study was obtained from Jack Fishman of the Atmospheric Sciences Division at the NASA Langley Research Centre - Hampton, Virginia, USA. This data set was calculated from Version 5 TOMS data.

Maps of the tropospheric ozone residual data were produced for the area between 0°S to 50°S and 50°W to 50°E. Figure 6.1 depicts the spatial distribution of tropospheric ozone for each of the ten years of data available. Based on Fishman *et al.* (1990) an arbitrary value of 40 DU was chosen as a base and all areas of tropospheric ozone greater than this have been shaded (Figure 6.1) to highlight the spatial variation of areas of high tropospheric ozone over the last decade. According to Fishman (1988), the tropospheric ozone profile over the equatorial Pacific Ocean should have a tropospheric ozone column content of 10-15 DU, whereas a tropospheric ozone profile representative of one which has been influenced by biomass burning should have a tropospheric ozone column content of 40-50 DU. An examination of the tropospheric ozone concentrations over South Africa shows a consistent region of ozone values in excess of 40 DU off the east coast of South Africa (Figure 6.1).

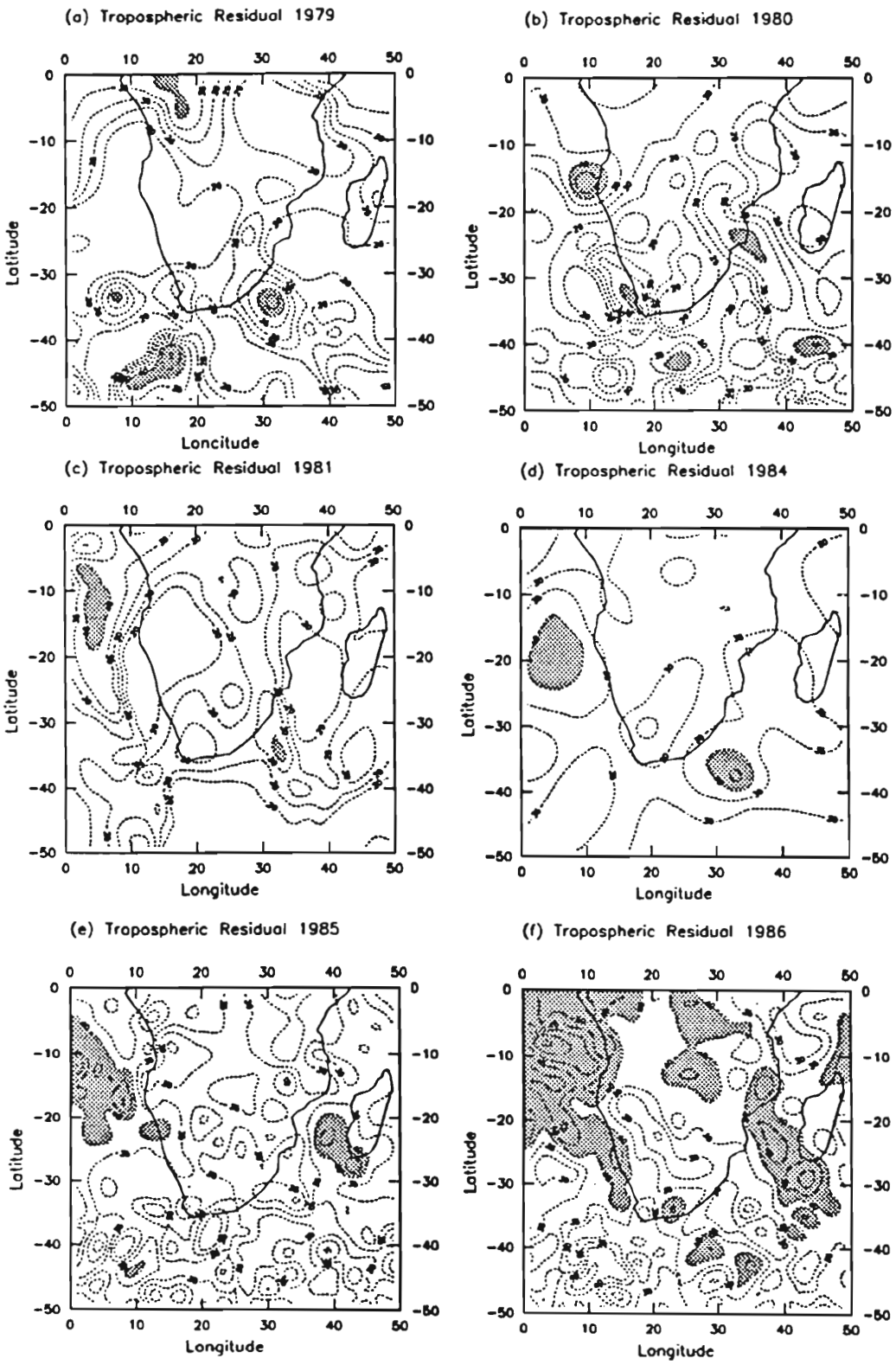


Fig. 6.1 The spatial distribution of the tropospheric residual for the years 1979 - 1981 and 1984 - 1986. The shaded regions represent areas of tropospheric ozone in excess of 40 DU.

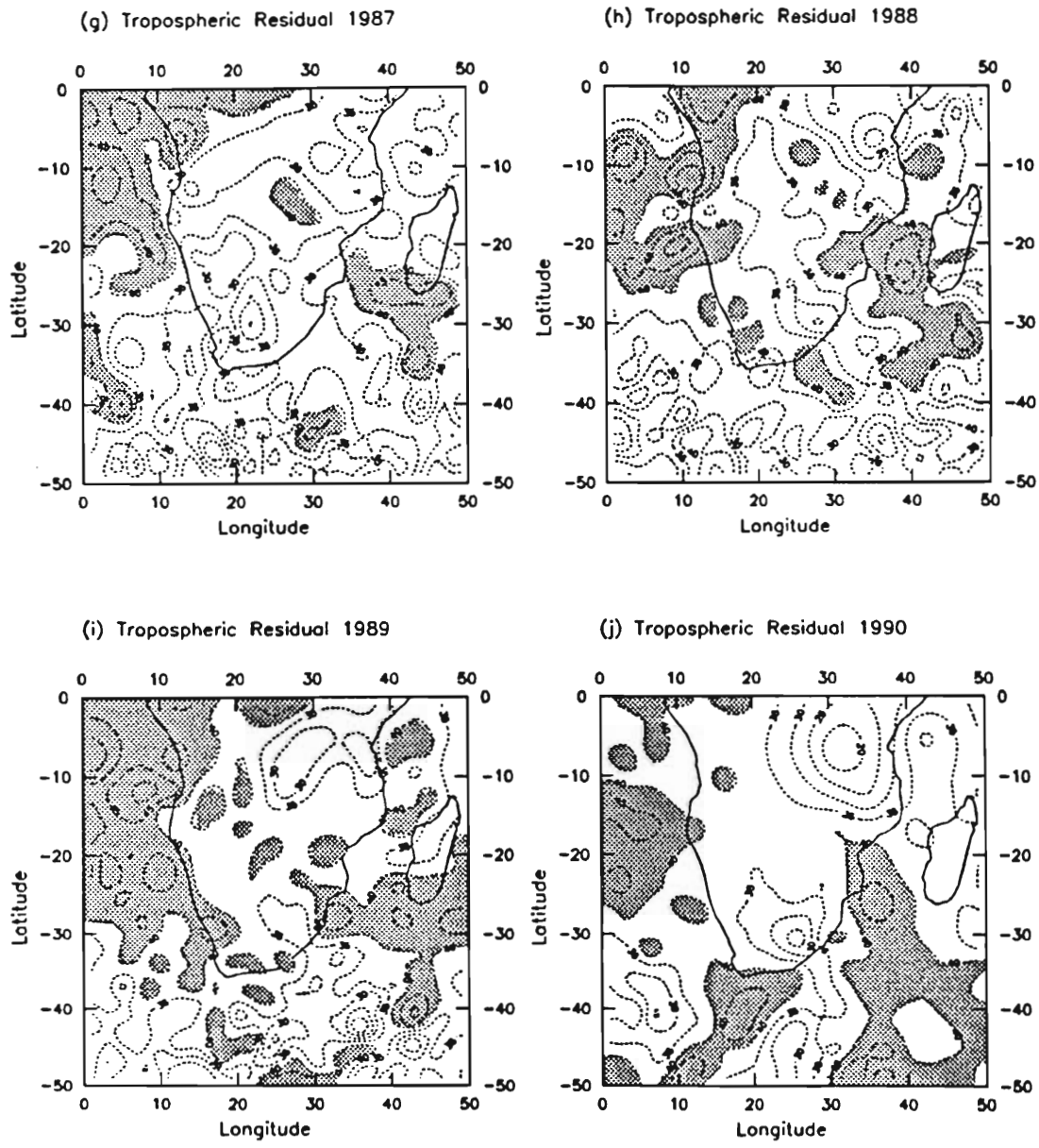


Fig. 6.1 contd. The spatial distribution of the tropospheric residual for the years 1987 - 1990. The shaded regions represent areas of tropospheric ozone in excess of 40 DU.

The position of the maximum varies from year to year, however it never goes beyond the latitudinal limits of 20°S - 40°S. It is present each year over the study period, with the exception of 1981. Diagrams (a) to (c) of Figure 6.1 illustrate the tropospheric residuals for the years 1979 to 1981. They show little variation, with few regions exhibiting values greater than 40 DU. However tropospheric ozone maxima are evident off the east coast of southern Africa for three years. The years succeeding 1984 reveal a rapid increase in the tropospheric residuals. Tropospheric ozone maxima are evident off the east coast of southern Africa for all years. The regions of high tropospheric ozone on both the west and east coasts of southern Africa can be seen to increase in size with time. The most dramatic feature of Figure 6.1 is the marked increase in tropospheric ozone which has been experienced over the past decade. The dimensions of the east coast ozone maximum have increased five-fold since 1979.

This descriptive analysis confirms the existence of an east coast ozone maximum and shows that it is a feature which has grown considerably in spatial extent, suggesting an anthropogenic origin. From the data presented it is not possible to conclude that the tropospheric ozone maximum situated off the east coast of South Africa is directly attributable to biomass burning. However it may be possible to establish such a link through the examination of data over shorter time periods.

6.3 Case Studies

From the examination of the tropospheric ozone residual amounts conducted above, it is evident that no direct link between biomass burning and tropospheric ozone increases may be established. To examine the role of biomass burning in the development of ozone maxima off the east coast of South Africa, it is appropriate to utilise a case study approach to investigate whether a large biomass fire has an effect on total column ozone amounts in the region. Case studies were selected from days on which particularly large or extensive fires occurred in the study region. The only criterion used was that the area burned by each fire should be in excess of 500 hectares. This minimum area burned criterion was chosen arbitrarily. It is highly unlikely that small fires, unless numerous and widespread, would

cause significant changes in tropospheric ozone. Thus only the largest and most widespread fires over 500 hectares were used in this study. Tables 6.1 and 6.2 show the case studies chosen.

Table 6.1: Forest Fire Case Studies

DATE OF FIRE	REGION	BURNED AREA (ha)
17-07-79	Eastern Transvaal Lowveld	600
05-08-79	Eastern Transvaal Lowveld and Natal Midlands	500
26-08-80	Southern Natal Interior	892
06-09-80	Eastern Transvaal Highveld	575
16-05-84	Eastern Transvaal Lowveld	500
12-09-85	Eastern and Southern Transvaal	12 000
05-08-86	Natal Midlands	406*
01-10-88	Southern Transvaal	602
03-10-89	Northern Transvaal	2534
05-10-89	Zululand	5571
05-10-89	Zululand	880
30-07-91	Zululand	411*
07-09-91	Southern Transvaal	570

* Apart from these individual fires, a large number of smaller fires occurred within the same region on this date.

Table 6.2: Sugar Cane Fire Case Studies

Date of Fire	Region/Area
31-08-82	North Coast/Midlands/Zululand
02 to 08-08-85	South Coast/North Coast /Midlands/Zululand
30t to 31-07-89	South Coast/North Coast
25-08-89 to 04-09-89	South Coast/ North Coast/ Midlands
01 to 03-08-91	South Coast/North Coast
16 to 17-03-92	South Coast/North Coast/Midlands
08-08-92	South Coast/North Coast/Midlands
22-08-92	South Coast/North Coast/Zululand

Note: Several 1992 fires were not included in this study as a result of missing ozone data as well as a calibration problem with the 1992 ozone data.

Of the 21 case studies chosen only 3 will be presented in this study. The motivation for the elimination of the remaining 18 case studies was as follows: The first criterion used to disqualify any particular case study, was the presence of a frontal system in the region ahead of an ozone maximum. In several instances, ozone maxima were observed within 24 hours of a large fire, however the presence of a frontal system in the region ahead of the ozone maximum, served to camouflage the role of the biomass fire. Barsby (1991) demonstrated that the passage of a low pressure system along the east coast of South Africa is accompanied by positive departures in ozone to the rear of the front. Thus, in the event of an ozone maximum occurring following a large biomass fire, but to the rear of a frontal system, there is some ambiguity as to whether the increase in ozone is attributable to the fire, the presence of the low pressure system, or a combination of both.

The second criterion used to disqualify any particular case study was the presence of clouds in the fire region. The presence of clouds are thought to mask any tropospheric increase in ozone as a result of a flaw in the TOMS algorithm for the calculation of tropospheric ozone under clouds (Thompson *et al.*, 1992). The TOMS instrument cannot sense ozone below cloud tops. Fishman and Larsen (1987) 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.

Having applied these criteria to each of the case studies, only three clear cases remained, and it is these three cases which will be presented in this chapter.

6.3.1 Case Study 1 (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 (Meikle, 1986). Forest plantations in the Eastern Transvaal cover approximately 260000 hectares, of which 4.6% were burnt on this occasion (Meikle, 1986).

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 with light north-westerly winds. These conditions persisted on 12 September 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 (Figure 6.2.a).

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 (Figure 6.2b). Typical post-frontal conditions were experienced throughout the region, with significant decreases in temperature and light south-easterly winds in the fire region, but no rainfall. The post-frontal conditions were accompanied by the elimination of the subsidence inversion.

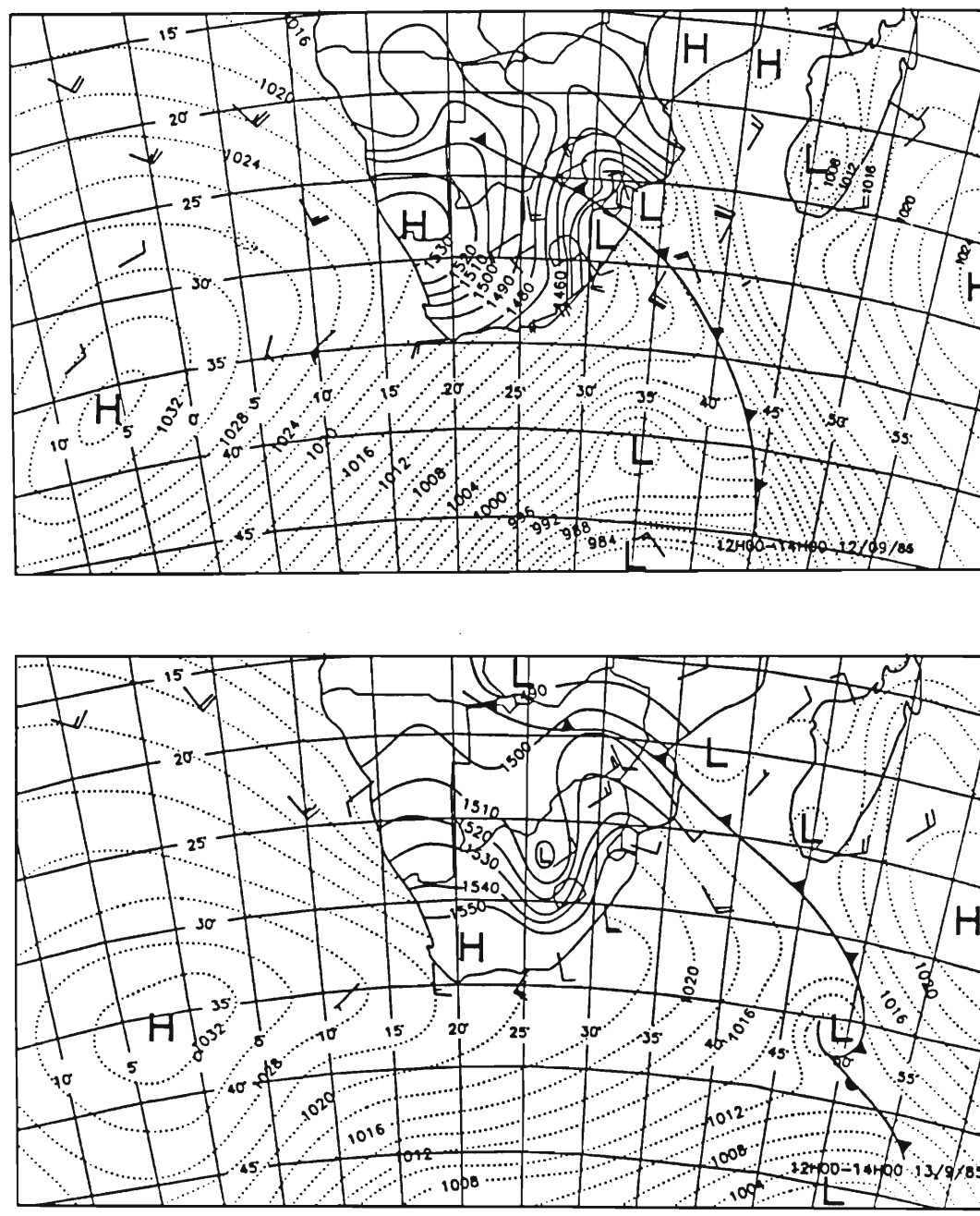


Fig. 6.2 (a) Surface synoptic chart, 12 September 1985. (b) Surface synoptic chart, 13 September 1985. Surface pressure expressed as isobars (hPa) over the sea and heights of the 850 hPa (gpm) over the land. Source: Daily Weather Bulletin, South African Weather Bureau (SAWB).

The intensity of the low pressure system is indicated in the streamline diagram of surface airflow for 12 September, which shows considerable convergence at the surface (Figure 6.3a). However, the system is shallow, for by the 850 hPa level, the streamlines indicate south-westerly flow (Figure 6.3b). 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 towards the north-east.

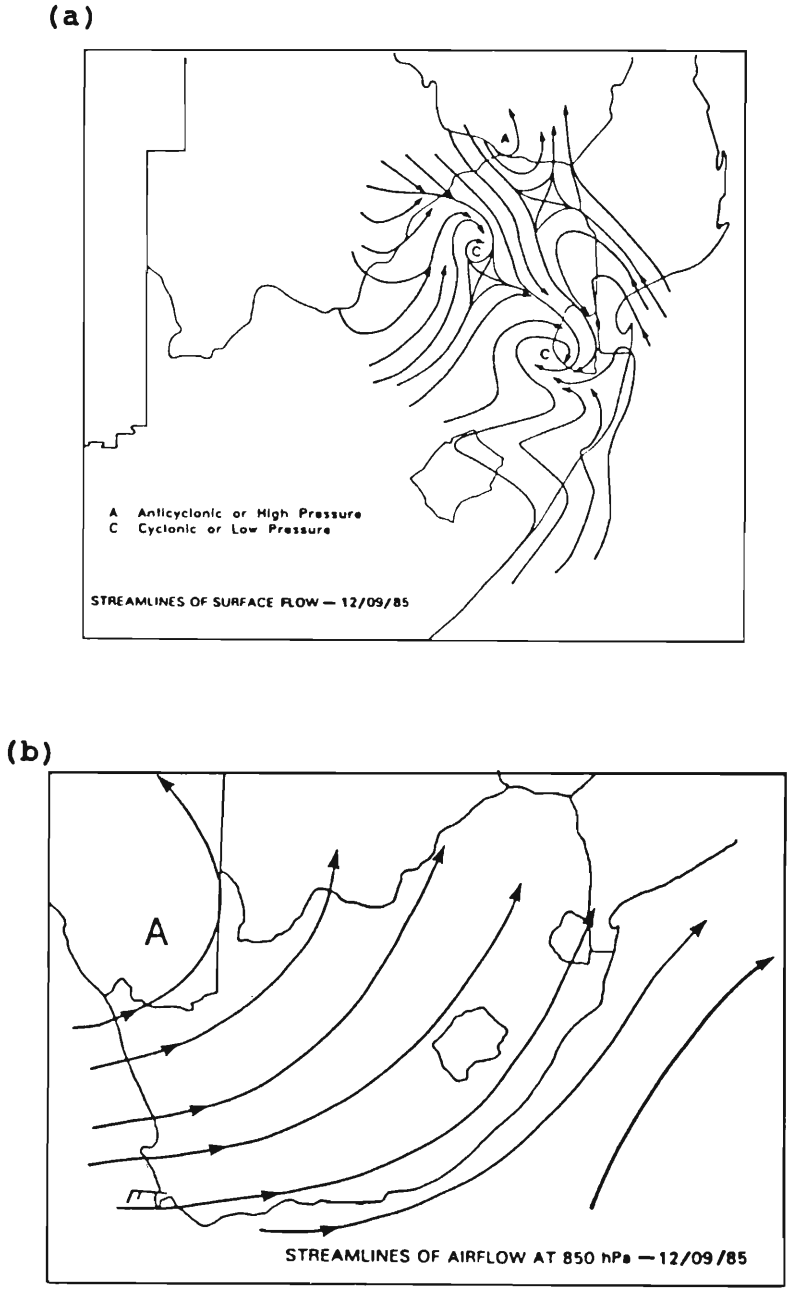


Fig. 6.3 (a) Streamlines of surface airflow for 12 September 1985. (b) Streamlines of airflow at the 850hPa surface, 12 September 1985. Source: SAWB

From the examination of the synoptic situation and circulation patterns on the day of the fire, it is clear that conditions were favourable for the production of tropospheric ozone. Because of the concentration of precursors as a result of the synoptic conditions, it is possible that the subsequent increase in tropospheric ozone may in fact be reflected in total column ozone concentrations. An examination of the TOMS total column ozone concentrations for the period 11-13 September 1985, shows that this does in fact occur (Figure 6.4).

The corresponding TOMS total column ozone concentrations for the period surrounding the fire on 12 September are shown in Figure 6.4 for the region 20° to 40° E and 20° to 40° S. 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 (Figure 6.4a). Barsby (1991) 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 6.4b depicts the TOMS total column ozone concentrations for 12 September 1985. An ozone maximum of 350 DU is seen in the region 30° to 35°S, reflecting the north-eastward movement of the front. By 13 September 1985 an anomalous equatorward extension of high total ozone has developed in the region 20°S to 25°S (Figure 6.4c). It represents an increase from 290 DU on 12 September to 320 DU on 13 September and appears unrelated to the frontal passage which is characterised by a linearly arranged gradient increasing towards the south-west.

Furthermore, 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 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 6.4c, is produced by an increase in tropospheric ozone generated by the forest fires of 12 September 1985.

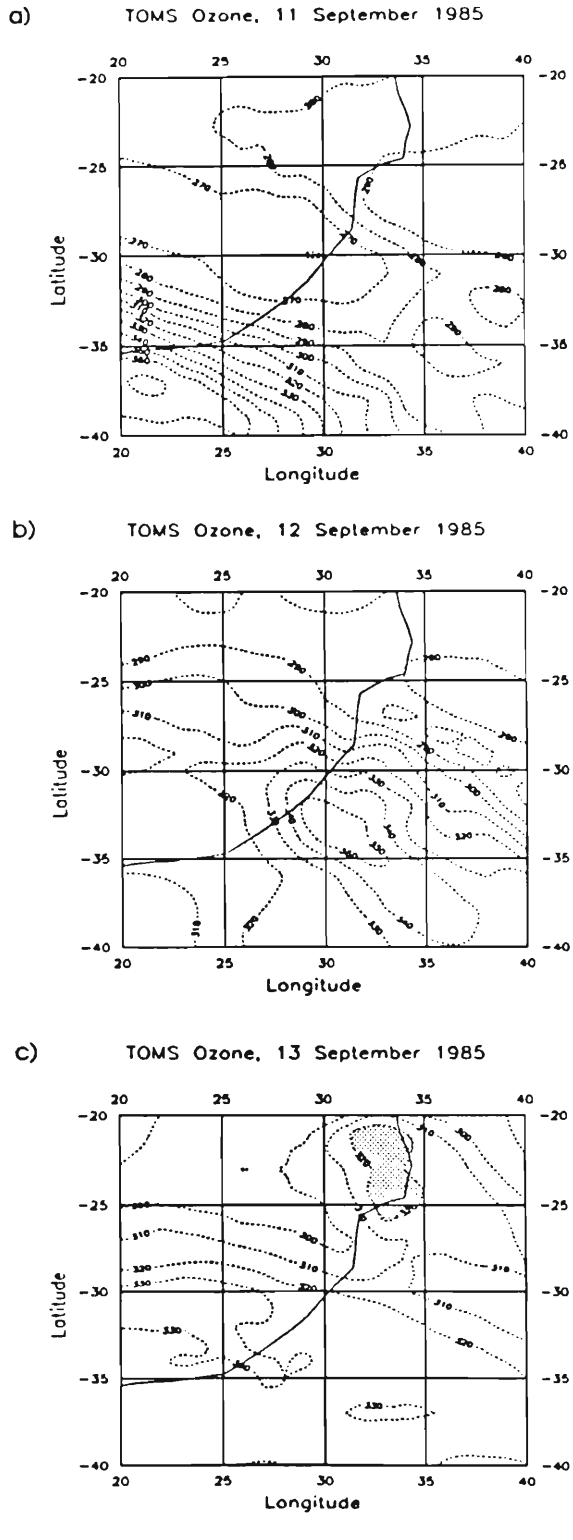


Fig. 6.4 TOMS total column ozone concentrations (DU) for the region 20° to 40°E and 20° to 40°S on (a) 11 September 1985 (b) 12 September 1985 (c) 13 September 1985

6.3.2 Case Study 2 (3, 5 October 1989)

On 3 October 1989 and 5 October 1989 approximately 10000 hectares of forest was destroyed by fire in the Zululand - Natal and the North Eastern Transvaal regions.

A synoptic sequence consisting of the passage of two frontal systems in rapid succession over a four day period characterised the synoptic conditions experienced in the study region during the period 3-6 October 1989. The first day of the fires i.e. 3 October 1989, was characterised by a frontal system situated north of Durban (Figure 6.5a). Berg wind conditions manifested by high surface temperatures were in evidence in the Northern Transvaal. There was subsidence ahead of the front, with the subsidence inversion at 14:00 on 3 October at Pietersburg, situated at 704m above the surface, with a depth of 293m. Wind speeds along the east coast and in the fire zone were high.

At 01:00 on 4 October, a strong surface inversion with a depth of 299m was situated at the surface, together with an upper air subsidence inversion situated approximately 2212m above the surface. During the day winds at the surface were light north-westerly, except along the coast where onshore flow prevailed (Figure 6.5b). Post-frontal conditions were experienced in the study region. A dominant high pressure with associated subsidence, clear skies and fine conditions prevailed. The midday subsidence inversion at Pietersburg on 4 October had lifted and was situated 1047m above the surface, with a depth of 370m.

At 01:00 on 5 October, two inversions, were in evidence, the first at ground level with a depth of 83m and the second at 434m with a depth of 321m. From the synoptic charts it is apparent that a cold front was situated south of Durban, with a coastal low hugging the coastline ahead of the front and a dominant high pressure system with strong subsidence in the interior.

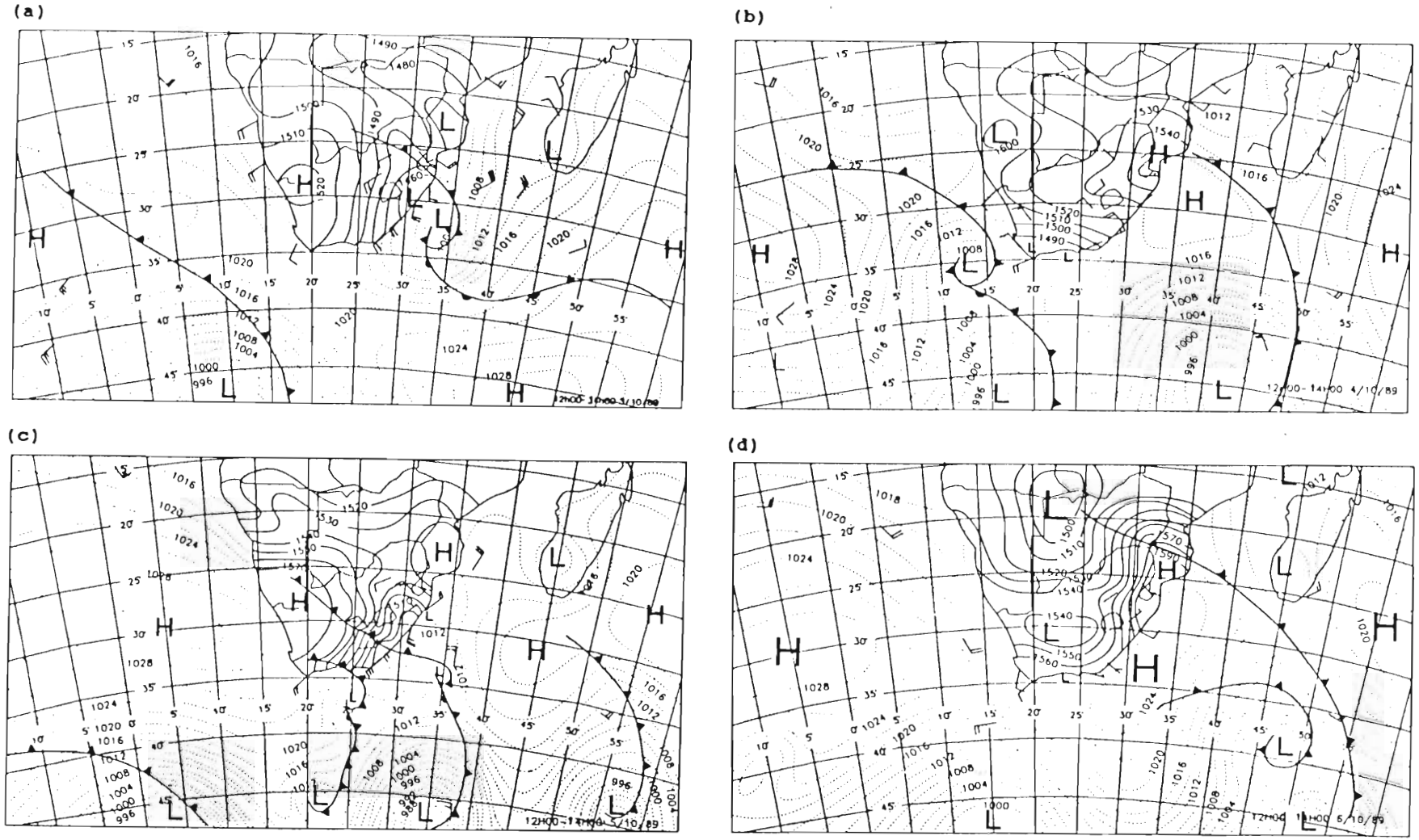
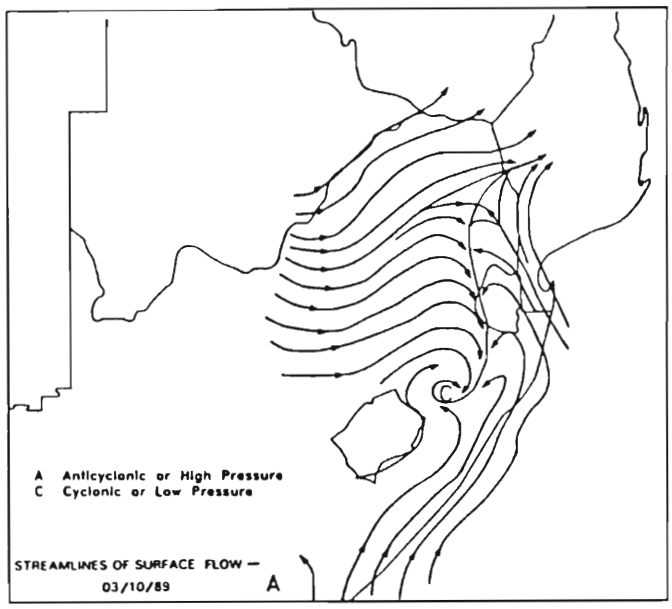


Fig. 6.5 (a) Surface synoptic chart, 3 October 1989. (b) Surface synoptic chart, 4 October 1989. (c) Surface synoptic chart, 5 October 1989. (d) Surface synoptic chart, 6 October 1989. Surface pressure expressed as isobars (hPa) over the sea and heights of the 850 hPa (gpm) over the land. Source: Daily Weather Bulletin, SAWB.

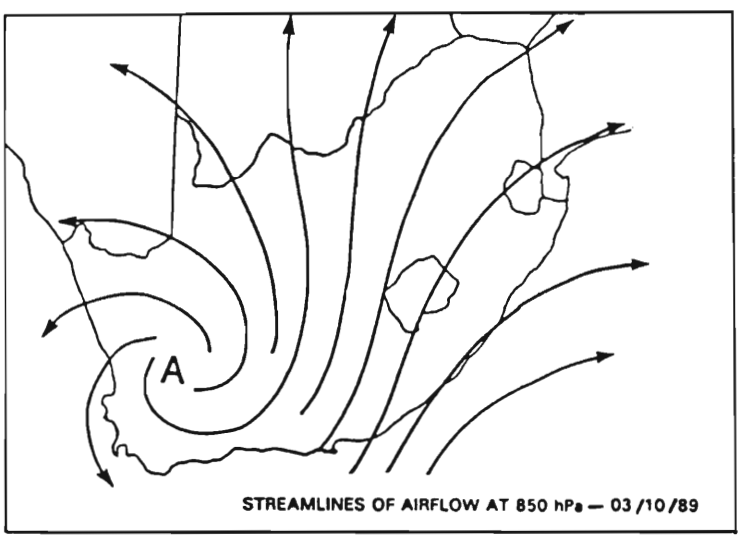
A subsequent strengthening of the along coast pressure gradient was noted and conditions were once again pre-frontal (Figure 6.5c). The surface winds along the coast were very strong. Abnormally high temperatures were noted in the fire region. Such conditions are typical of an intense pre-frontal Berg wind condition. By 6 October, the frontal system had proceeded north and post-frontal conditions were experienced in the study region. Light winds with onshore flow along the coast, converging upon the trough of low pressure in the central interior, were in evidence (Figure 6.5 d). Clear skies and fine conditions associated with a dominant high pressure were experienced.

The intensity of the low pressure system is indicated in the streamline diagram of surface airflow for 3 October, which shows considerable convergence and uplift at the surface along the convergence asymptote (Figure 6.6a). Intense concentration of pollution would have occurred along this zone. The ozone precursors would have been carried upward by smoke plumes along the convergence asymptote into the upper atmosphere and subsequently transported from west to east and out to sea by the north-easterly flow at the 850 hPa level (Figure 6.6b). The passage of the smoke plumes would have been influenced only by the 850 hPa flow as the inversion layer was situated at 700 hPa and any pollutants in the atmosphere would have been trapped beneath it. The subsequent ozone maximum should have occurred east of the region in which the fire occurred.

(a)



(b)



(c)

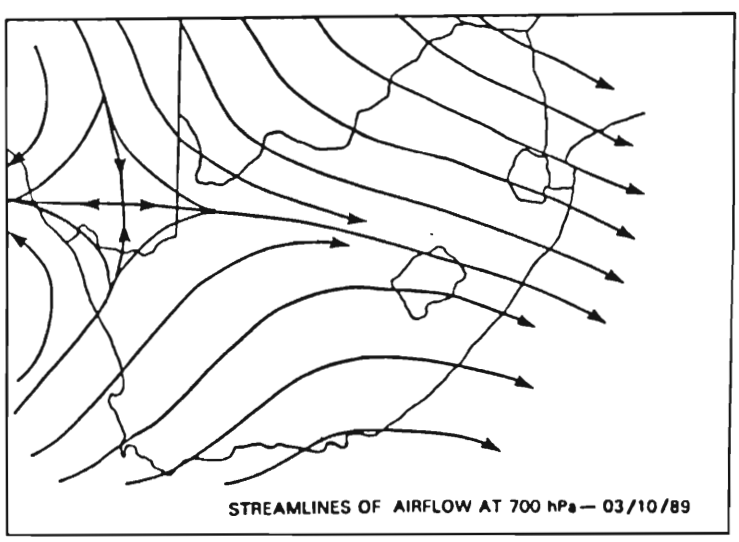


Fig. 6.6 (a) Streamlines of surface airflow, 3 October 1989. (b) Streamlines of airflow at the 850hPa surface, 3 October. (c) Streamlines of airflow at the 700hPa surface, 3 October.

Surface airflow on 5 October was similarly characterised by intense convergence along the convergence asymptote at the surface (Figure 6.7a). Poor visibility and hazy conditions were experienced in the fire region. Pollution concentration ahead of the front was intense. All the smoke and pollution coming off the fire would have converged along the convergence asymptote, been concentrated and uplifted into the upper atmosphere. Conditions favourable for tropospheric ozone generation existed. At the 850 hPa surface on 5 October, a north-westerly offshore flow was in evidence at 1.5km above the surface (Figure 6.7b). The flow at the 700 hPa level was roughly westerly. Thus the pollutants coming of the fires would have been transported approximately north-eastwards out to sea from the region of origin. The subsequent ozone maximum would have occurred north-east of the region in which the fire occurred.

From the examination of the synoptic situations and circulation patterns on the dates of the fires, it is clear that conditions were favourable for the production of tropospheric ozone. Because of the concentration of precursors as a result of the synoptic conditions, it is possible that the subsequent increase in tropospheric ozone may in fact be reflected in total column ozone concentrations. An examination of the TOMS total column ozone concentrations for the period 2-6 October 1989, shows that this does in fact occur (Figure 6.8).

The TOMS total column ozone concentrations for the period surrounding the fires is seen in Figure 6.8a for the region 20° to 40°E and 20° to 40°S. From the alignment of the contours it is evident that there is a frontal system situated at Durban on 2 October (Barsby, 1991). Figures 6.8b and 6.8c depict the TOMS total column ozone concentrations for the 3 October and 4 October 1989 respectively. On 4 October, an ozone maximum of 320 DU is centred at 35°E and 30°S. The maximum is situated east of the region in which the fire occurred. From the streamline analysis it is evident that this is also the region to which the pollutants transported from the fire would have been transported. However it is uncertain as to whether this maximum may be attributed to tropospheric ozone generation as a result of the forest fires, as it lies to the rear of the frontal system, and may conceivably be attributed to the positive departures in ozone accompanying the passage of a frontal system.

Figure 6.8d depicts the typical TOMS total column ozone concentrations for 5 October 1989. From the alignment of the contours and the sharp gradient, it is evident that there is another frontal system approaching from the south of the country (Barsby, 1991). Figure 6.8e depicts the TOMS total column ozone concentrations for 6 October 1989. Two ozone maxima of 330 DU are situated off the east coast of South Africa. This represents an increase from 310 DU on 5 October to 330 DU on 6 October. The first ozone maximum is situated between 30°- 35°E and 25°- 35°S, east of the region in which the fires occurred. From an examination of the circulation, it is apparent that the pollutants transported from the fire could have been transported into this region. But it is uncertain whether this maximum can be attributed to the forest fires as it lies directly to the rear of a frontal system and is characterised by a linearly arranged gradient increasing towards the south-west.

The second ozone maximum is situated between 30°- 40°E and 20°- 25°S, approximately north-east of the region in which the fires occurred. According to the circulation patterns highlighted earlier, the ozone precursors produced would have been carried to this region. This maximum cannot be attributed to the positive departures in ozone accompanying the passage of a frontal system, as it lies ahead of the frontal system. According to Fishman *et al.* (1991) the lifetime of ozone in the tropical boundary layer, where both water vapour and sunlight are abundant, is between 2 to 5 days. Thus the ozone produced from the fires of 3 October, would conceivably have formed a part of the enhancement seen on 6 October. It may thus be concluded that the northerly maximum in TOMS total ozone seen in Figure 6.8e, is produced by an increase in tropospheric ozone generated by the forest fires of both 3 and 5 October 1989.

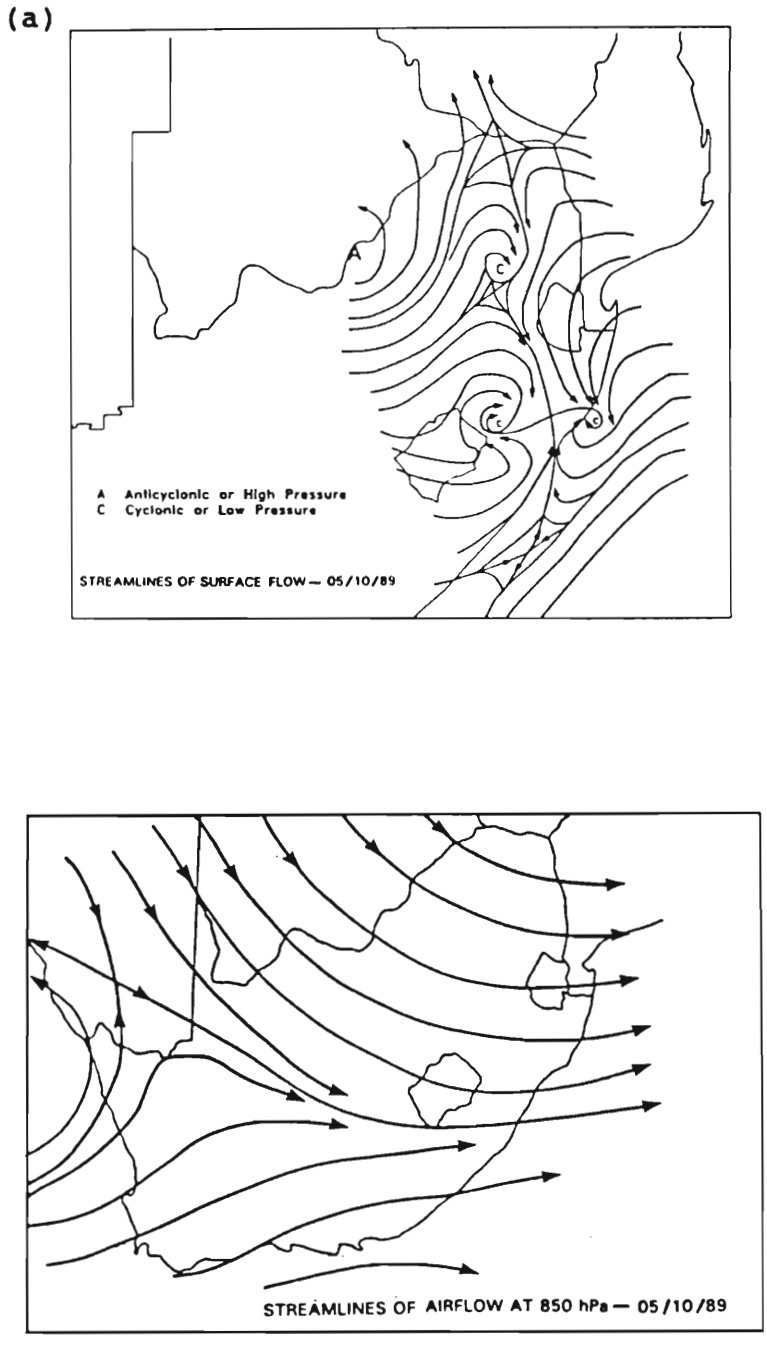


Fig. 6.7 (a) Streamlines of surface airflow, 5 October 1989. (b) Streamlines of airflow at the 850hPa surface, 5 October.

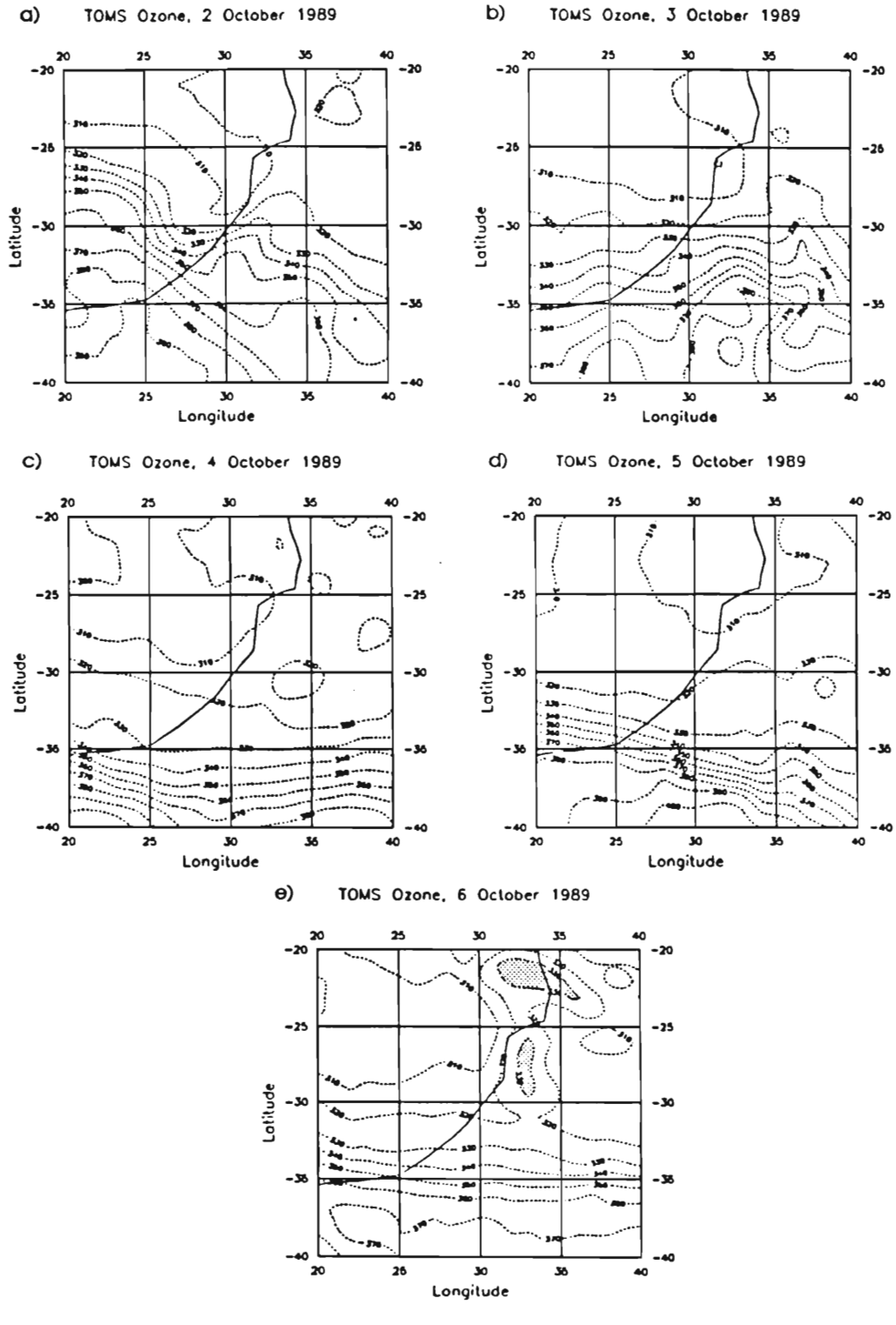


Fig. 6.8 TOMS total column ozone concentrations (DU) for the region 20° to 40°E and 20° to 40°S on (a) 2 October 1989 (b) 3 October 1989 (c) 4 October 1989 (d) 5 October 1989 (d) 6 October 1989

6.3.3 Case Study 3 (22 August 1992)

On 20 August 1992 approximately 145 sugar cane fires occurred in the north coast districts of Maidstone and Stanger. This was followed on 22 August 1992 by a larger more destructive fire centred in the same region. According to Dewey (1992) approximately 40000 tons of cane was lost. The burns occurred throughout the sugar cane growing areas of Zululand and Natal and were widespread.

On the day of the second fire episode i.e. 22 August, a strong cold front approached south of Port Elizabeth (Figure 6.9a). Conditions in the study region were fine and warm. The north-easterly wind blowing north of Durban would have augmented the spread of the fires. No inversion developed at noon on 22 August 1992.

At 01h00 on 23 August, a very strong subsidence inversion was situated approximately 1500m above the surface at Durban. During the course of that day, surface winds were light and onshore flow prevailed. The frontal system moved north-easterly (Figure 6.9b). Temperatures along the coast began to increase, and the wind direction changed to south-westerly. Conditions ahead of the front were fine and warm.

A shallow coastal low is present ahead of the front and this is indicated by convergence in the streamline diagram of surface airflow for 22 August (Figure 6.10a). Above the surface there is evidence of north-westerly flow indicative of Berg wind conditions which are typical under pre-frontal weather conditions (Figure 6.10b). The fires occurred in the Maidstone/Stanger areas just north of Durban. All the smoke and pollution coming off the fire would have converged along the convergence asymptote and been uplifted by the buoyant smoke plumes. Conditions suitable for the concentration of pollutants and for the subsequent photochemical generation of tropospheric ozone were in existence.

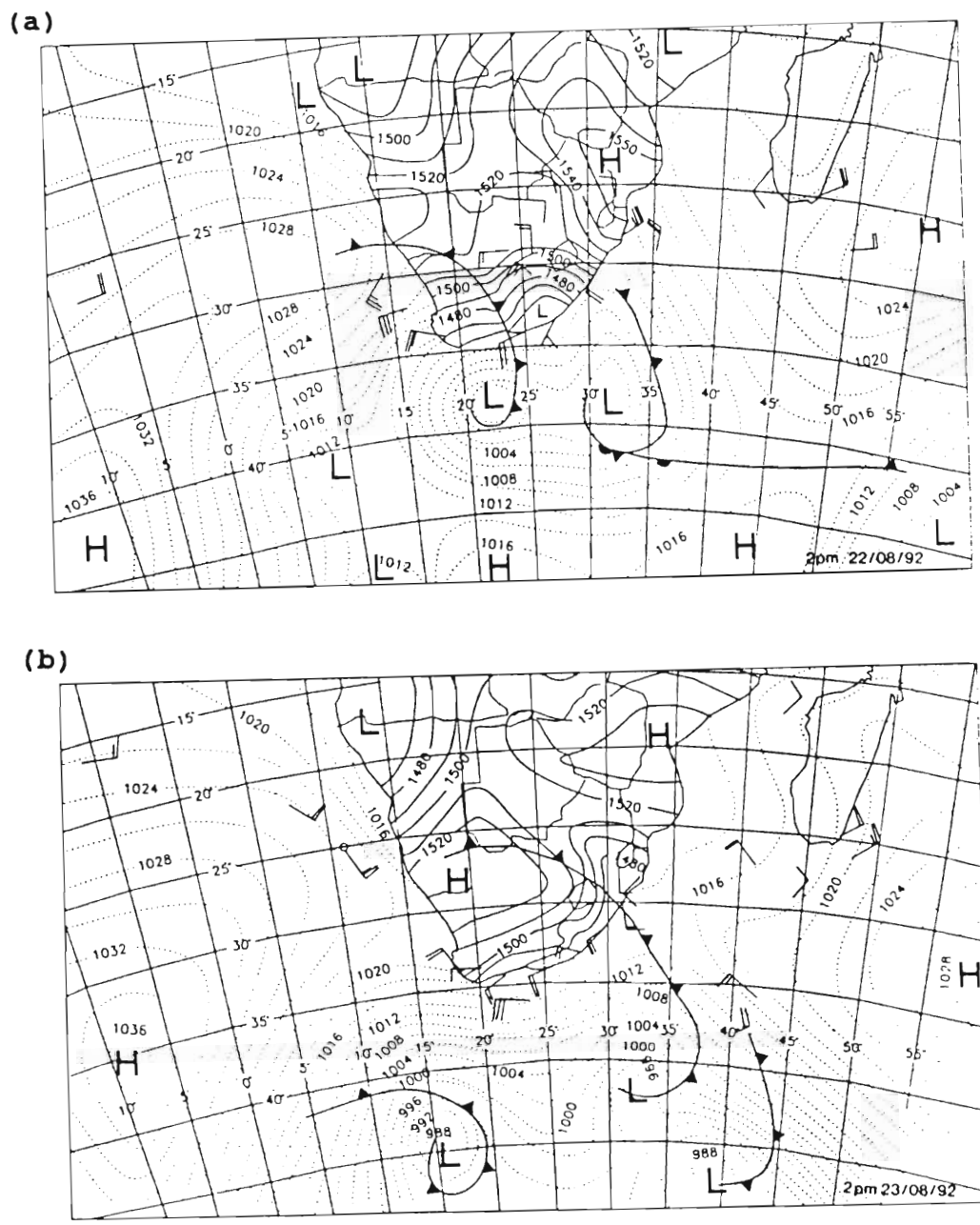


Fig. 6.9 (a) Surface synoptic chart, 22 August 1992. (b) Surface synoptic chart, 23 August 1992. Surface pressure expressed as isobars (hPa) over the sea and heights of the 850 hPa (gpm) over the land. Source: Daily Weather Bulletin, SAWB.

At the 700 hPa level the streamline flow was again north westerly (Figure 6.10c). Thus any pollutants in the atmosphere at this level would have been blown from west to east and out to sea. The passage of the smoke plumes would have been influenced by flow at both the 850 hPa and 700 hPa levels, depending on how high the plumes ascended in the atmosphere. Hence the subsequent ozone maximum should have occurred south-east of the region in which the fire occurred.

From the examination of the synoptic situation on the day of the fire, it is clear that conditions were favourable for the production of tropospheric ozone. Because of the concentration of precursors as a result of the synoptic conditions, it is possible that the subsequent increase in tropospheric ozone may in fact be reflected in total column ozone concentrations. An examination of the TOMS total column ozone concentrations for the period 21-23 August 1992, shows that this does in fact occur (Figure 6.11).

Figure 6.11a depicts the TOMS total column ozone concentrations for the period 21-23 August 1992 for the region 20° to 40°E and 20° to 40°S. On 22 August, from the linear arrangement of the contours, it is evident that there is a frontal system approaching from the south (Figure 6.11b). Localised enhancement ahead of the front in the form of an ozone maximum of 290 DU situated at 30°- 35°E and 30°S is present on 23 August (Figure 6.11c). The maximum is situated east of the region in which the fire occurred. The ozone maximum of 290 DU represents a departure of 10 DU from ambient concentrations. From the streamline analysis it is evident that this is the region to which the pollutants from the fire would have been transported.

This maximum cannot be attributed to the positive departures in ozone accompanying the passage of a frontal system, as it lies ahead of the frontal system. Thus the ozone produced from the fires of 20 August, would conceivably have formed a part of the enhancement seen on 23 August. From this we may conclude that the photochemically generated tropospheric ozone produced by the sugar cane fires of 20 and 22 August 1992 resulted in the maximum in TOMS total ozone seen in Figure 6.11c.

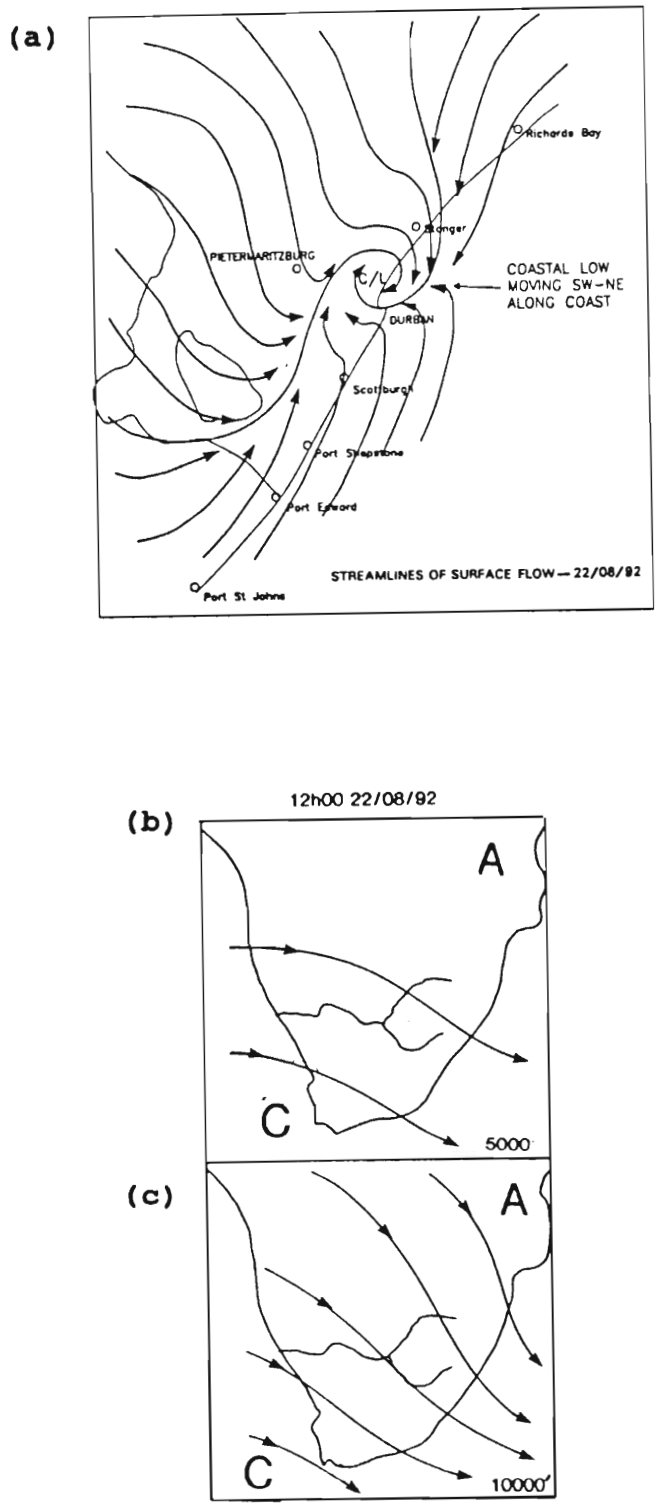


Fig. 6.10 (a) Streamlines of surface airflow, 22 August 1992. (b) Streamlines of airflow at the 850hPa surface, 22 August. (c) Streamlines of airflow at the 700hPa surface, 22 August. Source: SAWB

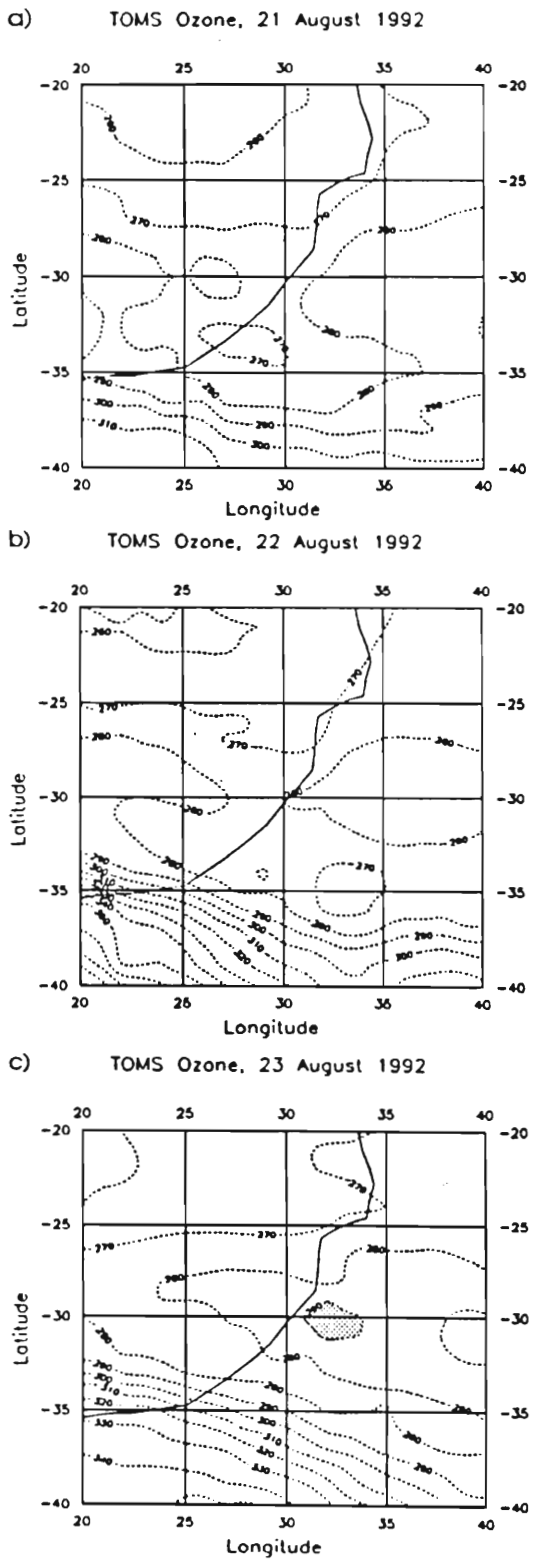


Fig. 6.11 TOMS total column ozone concentrations (DU) for the region 20° to 40°E and 20° to 40°S on (a) 21 August 1992 (b) 22 August 1992 (c) 23 August 1992

6.4 General Observations

From an examination of the case studies, a clear relationship between the occurrence of biomass fires, the prevailing atmospheric circulation and the formation of ozone maxima emerges.

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. In each of the three case studies a frontal system approached following a large biomass fire. As a result of the characteristics of the atmosphere at the time, a concentration of the ozone precursors released by the fires would have occurred. The pollutants being confined, react vigorously and large amounts of tropospheric ozone are formed.

Distinct ozone maxima ahead of the region of frontal influence were detected in the TOMS total ozone distributions in all three case studies discussed. Examination of the circulation patterns led to the conclusion that in each case the development of an ozone maximum was related to the occurrence of biomass fires.

CHAPTER SEVEN: SUMMARY AND CONCLUSIONS

Change is occurring on the earth at an ever-increasing rate. Many of these changes, such as the clearing of forest to provide more usable farmland or the increasing use of automobiles for transportation, are human-induced. These changes can have far-reaching and complex effects. Thus, the need to understand the dynamics of our environment and the effects on the earth's atmosphere has never been more important.

7.1 Summary of Results

The use of fire by humans as a tool to manipulate the environment has been instrumental in human conquest and domination of the earth. Biomass burning i.e. the intentional burning of forests, grasslands, agricultural stubble, agricultural waste and wood as fuel, etc. has been recognised as having a significant detrimental impact on the environment (Seiler and Crutzen, 1980; Crutzen and Andreae, 1990; Levine, 1990; Andreae, 1991).

The importance of biomass burning, as a significant source of atmospheric trace gases that are photochemically active in the troposphere, was first hypothesised by Crutzen *et al.* (1979). Since then, a number of studies have concluded that biomass burning contributes significantly to the global budgets of CO_2, CO (Logan *et al*, 1981; Connors *et al.*, 1991), CH_4, NO_x (Logan, 1983; Dignon and Penner, 1991), and NMHCs (Bonsang *et al.*, 1991), all of which lead to the photochemical production of tropospheric ozone.

Biomass burning is a common occurrence in South Africa especially during the winter months. Apart from the annual planned biomass burning which occurs, large areas of grassland, savanna and agricultural acreage are lost to wildfires annually. It is estimated that approximately 5 million hectares each of grassland and savanna are burned each year. Prescribed burning of forest areas is fairly uncommon in South Africa, with only 4.6% of all forest fires being planned. The majority of forest fires are unplanned. On average 78% of the 470 000 hectares of sugar cane grown on South Africa's east coast is burned each year (J. Chadwick, *pers. comm.*). In addition to this preharvest burning, unplanned sugar cane fires occur frequently. This burning of grassland, savanna, forest and sugar cane areas in South Africa probably plays an important role in the production of tropospheric ozone. To explore this role more thoroughly, the variations in ozone which occur during a large biomass fire episode were studied.

Because very limited records of grassland and savanna fires exist, these were excluded from the study. Forest and sugar cane fire records over the period 1979 to 1992 were used to identify case studies of severe fires using an arbitrarily selected value of 500 hectares as the minimum threshold of area burned. Twenty-one case studies were selected, of which 18 were eliminated because of potential ambiguities in the ozone signal due to the presence of cloud in the fire region or the presence of a frontal system ahead of the ozone maximum.

The TOMS instrument is unable to sense below clouds. Consequently, the algorithm for calculating ozone below clouds relies on a climatological tropospheric ozone amount estimated below a mean cloud base. This can lead to underestimates of total ozone in regions of cumulus clouds and overestimates in regions of low stratocumulus clouds (Hudson *et al.*, 1992).

The passage of synoptic weather systems is also known to influence total ozone. A number of workers have demonstrated that high total ozone values occur to the rear of surface fronts, which move across South Africa from south-west to north-east (Barsby, 1991; Diab *et al.*, 1992). The presence of a frontal system in the region ahead of an ozone maximum would therefore tend to obscure the potential role of biomass burning and for this reason these case studies were eliminated from the analysis.

The analysis of the 3 remaining case studies and the corresponding TOMS total column ozone concentrations, revealed a clear relationship between the occurrence of biomass fires, the prevailing atmospheric circulation and the formation of ozone maxima.

The pattern which has emerged from the analysis of the case studies is that severe fires are common in the period prior to the passage of a cold front. During this period Berg winds often prevail and owing to the hot, dry conditions, the fire hazard is great. The prefrontal conditions are also conducive to the accumulation of pollutants and by implication, biomass burn products, beneath a lowered subsidence inversion. The production of ozone is further favoured by the presence of high temperatures and high solar radiation input.

A clear distinction emerged between the pattern of the ozone maximum which is associated with a frontal passage and that which is assumed to be related to biomass burning. In the former, there was a sharp gradient in ozone increasing towards the south west, the isolines

were linearly arranged and the maximum was present to the rear of the surface front. The day-to-day progression of the "ozone front" across the country could also be traced as the weather systems advanced eastwards. In the latter situation, the maximum manifested itself abruptly as an anomalous equatorward extension of ozone enhancement ahead of the front. The enhancement was of the order of 10 to 20 DU and usually appeared the day after the occurrence of a fire episode. This is consistent with theories of photochemical production of ozone. The rapid disappearance of the ozone maximum may be attributed to the short life span of ozone in the lower troposphere.

7.2 Problems

Although it is well established that large quantities of ozone pollution can be generated by biomass burning, the importance of this source globally, relative to the amount of ozone that is transported out of the stratosphere into the troposphere by natural processes is still not clear. It poses a problem as there does not seem to be a way of ensuring that the ozone maximum is due to biomass burning and not S-T injection. One possible solution may be the examination of tracers.

The reliability of the TOMS data, given its tendency to under or overestimate total ozone in cloudy regions, is questionable. Although the percentage error which this problem gives rise to is small, when using TOMS data as a surrogate for changes in tropospheric ozone, the percentage error is significant. The development of a more refined algorithm, sensitive to cloud cover is needed.

7.3 Future Studies

1. The trace gas emissions from specific biomass fires need to be identified and accurately measured using *in situ* observations as well as remote sensing techniques. Actual quantification will enable future researchers to calculate the quantities of ozone precursors present in the atmosphere during and after a biomass fire and in so doing estimate the ensuing ozone enhancement. It will also allow researchers to distinguish between the emissions from different types of biomass fires.

2. The identification of chemical tracers in the specific vegetation being burned would enable researchers to track these in the atmosphere via forward and backward trajectory analyses, to obtain an accurate indication of transport processes in the local environment as well as to determine the origin or destination of particular emissions.

3. Chemical modelling to determine the potential production of ozone based on the nature and extent of the area burned is necessary.

4. The assessment of the impact of fires on the local and regional environment, and investigations of the interactions between biomass burn emissions, cloud formation, the radiation balance of the atmosphere and the hydrological cycle.

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