SYNOPTIC INFLUENCES ON AIR POLLUTION EVENTS IN THE DURBAN SOUTH BASIN, 2006 TO 2010

By

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As the candidate's supervisor I have/have not approved this thesis/dissertation for submission.

Signed: ________________ Name: ________________ Date: ________________

Preface

Research work described in this dissertation has been carried out in the School of Environmental Sciences, University of KwaZulu-Natal, Westville Campus Durban, from January 2011 to December 2013 under the supervision of Dr L.F. Ramsay

The study represents original work compiled by the author and has not been submitted to another tertiary institution. Where use has been made of others, it has been duly acknowledged in the text.

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I would like to extend my utmost appreciation to all those who have assisted me in the production of this dissertation. It feels unfair that it is only my name that goes on the cover page. Many thanks go to the following people for their assistance:

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Finally I would like to extend a huge thanks to my entire family and friends for providing me with the support to complete this milestone in my life.

Abstract

This study aimed to assess the relationships (if any) between air pollutant measurements in the Durban South Basin (DSB) and (i) local meteorology, (ii) community reports of pollution incidents in Durban, and (iii) air quality and meteorology in Cape Town on the days preceding the Durban South Basin events. With the use of daily synoptic charts and various meteorological variables at an hourly resolution, it was established that air pollution events were better associated with local meteorological events than a community complaint database. Visual analyses of graphed meteorological conditions during the course of air pollution events revealed three clear meteorological scenarios associated with these:

1. A pre-frontal scenario;
2. A scenario showing inversion conditions but no approaching front, and generally low wind speeds; and
3. A post-frontal scenario, likely to be associated with stack downwash under higher wind speeds with the passing of a front.

ANOVA revealed significant differences between peak PM_{10} and average PM_{10} across scenarios, with Scenario 3 showing highest average and peak PM_{10}. At the Wentworth monitoring station, 24.4% of pollution incidents fell under Scenario 1, 64.2% under Scenario 2, and 5.7% under Scenario 3 between 2006 and 2010. A further 5,7% of the air pollution incidents did not fall under these three scenarios. The latter were not associated with fronts, and did not show inversion conditions, and are likely to be associated with intermittent industrial pollution events.

Further statistical analysis assessed the relationships (if any) between various meteorological variables, traffic levels and air pollution concentrations at the Wentworth station between 2006 and 2010. Findings show that delta temperature (change in temperature with height) is the strongest explanatory variable with respect to $PM_{10,}$ wind speed the second strongest, and traffic levels the third strongest. On average, PM_{10} concentrations increased with increasing delta temperature, decreasing wind speed, and increasing traffic levels. The pressure minimum at Durban associated with an approaching front showed a negative relationship with PM_{10} during

pre-frontal events, but this variable was not significant at the 95% confidence level. This tentatively suggests that even when controlling for frontal influences on delta temperature, lower pressure minima (i.e. stronger frontal systems) are associated with higher pollution levels. Pollution maxima at various Cape Town stations and pressure minima in Cape Town prior to the incident in the DSB showed no relationships with incident PM_{10} levels at Wentworth. As such, pollution concentrations and meteorology in Cape Town as a front approaches do not appear to be effective predictors of pollution conditions in the DSB when the front approaches there.

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List of Acronyms

ADMS	Atmospheric Dispersion Modelling System
AEL	Atmospheric Emission License
AQG	Air Quality Guidelines
AQMP	Air Quality Management Plan
APP	air pollution potential
APPA	Air Pollution Prevention Act 45 of 1965
C_6H_6	Benzene
CMA	Cape Metropolitan Area
CSIR	Council for Scientific and Industrial research
DSB	Durban South Basin
DAEA	Department of Agriculture and Environmental Affairs
DANIDA	Danish International Development Agency
DEAT	Department of Environmental Affairs and Tourism
EHP	Environmental Health Practitioner
EIA	Environmental Impact Assessment
FCCU	Fluidised Catalytic Cracker Unit
GDP	Gross Domestic Product

H_2S	Hydrogen Sulphide
ICLEI	International Council for Local Environmental Initiatives
ISER	Institute for Social and Economic Research
IT	Interim Target
JHB	Johannesburg
KSIA	King Shaka International Airport
KZN	KwaZulu-Natal
LA21	Local Agenda 21
masl	Meters Above Sea Level
MET	meteorological
MPP	Multi-Point Plan
NAAQS	National Ambient Air Quality Standards
NEMA	National Environmental Management Act 107 of 1998
NE	north-easterly
NEM:AQA	National Environmental Management: Air Quality Act 39 of 2004
NILU	Norwegian Institute for Air Research
NO_2	nitrogen Dioxide
NO_x	nitrogen Oxide(s)

O_3	Ozone
ppb	parts per billion
PPMCC	Pearson Product Moment Correlation Co-efficient
PM_{10}	particulate matter with an aerodynamic diameter of less than 10 microns
SANRAL	South African National Road Agency Limited
SAPREF	South African Petroleum Refinery
SAPS	South African Police Services
SAWS	South African Weather Services
SDIB	South Durban Industrial Basin
SDSDMC	South Durban Sulphur Dioxide Management Committee
SDB-MPP	South Durban Basin Multi-Point Plan
SDCEA	South Durban Community Environmental Alliance
SE	south-easterly
SEA	Strategic Environmental Assessment
SO_2	sulphur dioxide
SPSS	Statistical Package for the Social Sciences
STANVAC	Standard Vacuum Oil Company
SW	south-westerly

TRS	total reduced sulphur
UKZN	University of KwaZulu-Natal
UNCED	United Nations Conference on Environment and Development
UN MDG	United Nations Millennium Development Goals
US EPA	United States Environmental Protection Agency
VIF	Variance Inflation Factor
WHO	World Health Organisation

Picture showing a portion of SAPREFs plant and stacks (SAPREF, 2010).

1 INTRODUCTION

1.1 BACKGROUND

Air pollution is regarded as a global environmental issue that affects both developed and developing countries. Key processes that influence the state of air quality include industrial, domestic and transport activities, which introduce a vast array of air pollutants into the atmosphere. Areas of concern with respect to poor air quality in South Africa include poor urban and rural households without electricity, and the impacts from the mining, energy, mineral and petro-chemical industries on ambient air quality (DEAT, 2007). Poor air quality impacts on human health, the functioning of ecosystems, and influences global climate with largely unpredictable and potentially severe consequences (Akimoto, 2003).

Four zones in South Africa (namely Mpumalanga, Vaal Triangle, Cape Town and the Durban South Basin) have particularly high concentrations of industrial activity, releasing pollutants associated with the burning of fossil fuels and chemical processing. High levels of air pollution, particularly sulphur dioxide (SO_2) and particulate matter (PM) have been found to occur over the Eastern Highveld of Mpumalanga where ten Eskom power stations operate, five of which are the largest in the world. The three main power stations alone produce 860 tons of SO_2 per square kilometre per year. This region is home to many coal mines, Sasol petrochemical plants and other industries. The largest industrial conglomeration in South Africa occurs in the Vaal Triangle, comprising a mixture of industrial, commercial, agricultural, mining, and residential land use activities that are in close proximity to one another. Past studies have proven the existence of high levels of PM, SO_2, nitrogen dioxide (NO_2), ozone (O_3), hydrogen sulphide (H_2S) and benzene (C_6H_6) in the region. This has led to significant health impacts, which have been well documented over the years (Scorgie *et al.*, 2007).

Cape Town is another air pollution hotspot in South Africa with pollutants emanating from industrial, urban and rural activities as well as vehicular traffic. Most industrial activity is found to the east of Cape Town in an industrial belt approximately 5 - 15 km wide. Heavy traffic, an oil refinery and a fertilizer complex contribute to air pollution within this industrial belt (Jury *et al.*, 1990). During days of heavy air pollution, residents eagerly await the south-easterly (SE) wind, commonly known as the ‘Cape Doctor’, which rids the city of its air pollution, transporting it seaward away from the city.

The Durban South Basin (DSB) is the second largest industrial centre in South Africa and the largest in the KwaZulu-Natal province, flanking one of the busiest ports in the Southern Hemisphere (Nriagu *et al.*, 1996). For the ease of transporting goods and other commodities to and from the harbour, major industries in the region developed around the port. To transport goods for import and/or export purposes, the South African National Roads Agency Limited (SANRAL) developed an advanced road network to service the inland cities of the country. As a result air pollution is not only emitted from industries in the DSB, but also from vehicles that transport goods to and from the port.

During South Africa’s period of isolation and international sanctions, the DSB’s oil refineries and other large industries were deemed of national strategic interest and were allowed to operate with little or no restriction on the release of pollutants into the environment (Nriagu *et al*., 1996). Apartheid land-use planning resulted in the juxtaposition of residential and industrial activities, which established a long-term conflict between local communities and industry due to odours, flaring, visible plumes and chemical leaks in the region (Diab and Scott, 1999). Air pollutant concentrations, particularly of SO_2, are elevated in the region due to an abundance of sources (Diab and Matooane, 2003). The DSB also has a basin-like topography that is conducive to air pollution accumulation, particularly with the onset of early morning winter radiative inversions (Preston-Whyte and Tyson, 1988).

Ongoing community resistance against poor environmental quality in the Durban South Basin received national attention post-1994. Air quality management in the DSB reached momentum after a visit by Nelson Mandela, then President, and Bantu Holomisa, then Deputy Minister of Environment, was intercepted by the community in 1994 (Guastella and Knudsen, 2007). The community highlighted their plight to these newly elected leaders and demanded action. After this visit, a Strategic Environmental Assessment (SEA) of the region was commissioned, culminating in a multi-faceted pollution management plan for the DSB. The Constitution of the Republic of South Africa (Act 108 of 1996) presents a right to an environment that is not harmful to human health or well-being (Section 24). Although often voiced by activists as a Constitutional guarantee, the last 15 years have revealed that this is a right of progressive realisation, and one that is often weighted against economic development and other socio-economic rights. This is very apparent in DSB where strategic industries are allowed to pollute with little minimal interference by the authorities despite clear laws and regulations now in place.

From an air quality management perspective, the year 2005 was significant since the then minister of Environmental Affairs and Tourism introduced the new National Environmental Management: Air Quality Act 39 of 2004 (NEM:AQA), which had been strongly influenced by the local municipality's experiences in managing air quality in the DSB (Ramsay, 2010). This Act replaced a weak and outdated piece of Apartheid era legislation, the Atmospheric Pollution Prevention Act 45 of 1965 (APPA). Since promulgation of the NEM:AQA, there has been an increase in the number of air pollution monitoring stations across the country, priority areas have been identified (such as Waterberg, Vaal Triangle and Highveld) and comprehensive action plans (e.g. Air Quality Management Plans, AQMPs) have been developed to improve poor air quality in air pollution hotspots.

A key requirement of NEM:AQA is that AQMPs are developed for air pollution hotspots, and that their implementation is effectively ensured by national, provincial and local government. An AQMP is an internationally recognised tool for management of air quality to protect human health and the environment. The overall objective of an AQMP is to ensure that air quality management planning and reporting is efficiently and effectively implemented by all the relevant spheres of government through support and leadership from the national department (Ramsay, 2010). In light of this, the South Durban Basin Multi-Point Plan (SDB-MPP) was established. This is a regionally specific strategy that forms part of the eThekwini Municipality's AQMP. The objective of this plan is to manage the air pollution 'carrying capacity' of the atmosphere in the DSB and to reduce air pollution to a level conducive to the health and wellbeing of people living in this area (Nurick and Johnson, 1998). Although the 2010 annual Air Quality Report by the eThekwini Municipality shows that air quality in the DSB has improved over the years for most priority pollutants, community complaints persist, particularly in light of decreasing faith in air quality management after the resignation of Siva Chetty (the former head of Pollution Control and Risk Management section) in 2011.

1.2 AIR QUALITY FORECASTING IN SOUTH AFRICA

During the 1970's, developed countries such as the United States began generating air pollution potential (APP) forecasting models to monitor regional air quality. Most of these early models were based on a combination of data on local mixing depth and vertically averaged wind speeds to produce an air pollution forecast. In the last decade, however, the United States and various European states have shifted away from the use of APP forecasting models towards more complex atmospheric dispersion models and the enforcement of standards (Scott and Diab, 2000).

In the case of the DSB, Diab and Scott (2000) conducted a comprehensive synoptic study for air pollution potential (APP) in the region for the period 1996 to 1998 and recommended a methodology for forecasting air pollution events. This study represented the first step in predicting air quality in the DSB but the authors highlighted the need to further refine their forecasting criteria to determine the endpoint of a pollution event. The forecast model was tested during winter and focused on SO_2 pollution peaks with the use of data from two air pollution monitoring stations, one located upwind and the other downwind of two major petrochemical refineries. The aim of this study was to develop an air pollution forecasting program that would notify industries about periods of poor atmospheric dispersion conditions. Local Industries could then temporarily reduce their emissions and lower pollution loading into the atmosphere.

Diab and Scott (2000) highlighted the difficulty in accurately predicting pollution events in the DSB with the use of a synoptic approach. Although an air pollution alert system was developed, it was not adopted by the Municipality for air quality management in the region. Furthermore, the difficulty (or perhaps impossibility) of large refineries adjusting production rates during poor dispersion conditions was not adequately considered. Subsequent to this study, the eThekwini Municipality made use of AirQUIS, an air pollution software tool created to facilitate the collection, management and reporting of air quality and meteorological data. AirQUIS was used to calculate ground-level air pollution concentrations at individually selected receptor points within the municipality, more specifically in the DSB. Unfortunately however, this management system has lapsed into non-use, after Nozipho Kathi, the Municipality's former meteorologist, resigned in 2009.

1.3 RATIONALE FOR THIS STUDY

This study serves to expand upon the work of Scott and Diab (2000) mentioned above by analysing PM_{10} and SO_2 data in the years subsequent to their study. This study also focusses more closely on the exact timings of changes in atmospheric pressure, wind speed and direction as well as delta temperature (change in temperature with height) relative to air pollution peaks to categorise frontal related pollution events and to highlight any deviations from the synoptic model originally presented by Diab and Preston-Whyte (1980). This study also aims to assess perceptions of air pollution events by comparing complaints databases with pollution events identified in the air quality monitoring datasets.

As originally shown in a study by Preston-Whyte and Diab (1980), and unpacked further in Scott and Diab (2000), meteorology strongly influences air pollution dispersion in the DSB. However, very often pollution peaks occur just before a synoptic event in the region, hindering prediction of pollution events based on meteorological data. This study intends to assess whether an assessment of meteorological events (specifically cold fronts) in Cape Town could assist with the prediction of air pollution events in the DSB. Cold fronts affect Cape Town before travelling along the coast in an easterly direction towards Durban and it is possible that their strength in Cape Town could correlate with their influence in Durban. This phenomenon will be assessed statistically in this study.

Effective prediction of pollution events in the DSB would allow for a community warning system. This study does not condone the impact of industries on the community, nor suggests that the community should be totally responsible for protecting themselves against the impacts of dangerous pollutant levels. However, 'to be forewarned is forearmed' and for as long as the existing pollution issues persist, predictions and warnings may help reduce the impacts on the most sensitive individuals. Findings from this study will also serve to assist a team of researchers from the University of KwaZulu-Natal and eThekwini municipality working on the EO2Heaven (Earth Observation and Environmental Modelling for the Mitigation of Health Risks) study, funded by the European Union. The aim of this EO2Heaven study is to develop a live air pollution index for the city, providing users (including community member's, researchers and environmental managers) with details of the present air pollution status of the DSB via an internet and cell phone application. The study team has developed a real-time pollution mapping system based on continuous iterations of a state of-the-art Atmospheric Dispersion Modelling System (ADMS) Version 5 inputted with local emissions (vehicular and point source), real-time meteorology and topography. With a better understanding of how present meteorology will influence pollution levels in the hours ahead, warnings can be issued with the live maps on the EO2Heaven system and SMSed to registered users (Dr L.F Ramsay, pers. Comm., 31 March 2013).

1.4 AIMS OF THIS STUDY

The aims of this study are as follows:

1. To assess how frequently ambient pollutant levels at local monitoring stations exceed legislated standards in the DSB;
2. To determine whether community complaints correlate with pollution peaks as indicated by the monitoring stations;
3. To statistically assess the possibility of accurately predicting these events based on available meteorological data for Durban and Cape Town.

1.5 OBJECTIVES OF THIS STUDY

The above aims will be met via the following objectives:

1. To define air pollution events and identify them in air quality monitoring datasets.

2. To compare ambient concentrations with National Ambient Air Quality Standards (NAAQS) as published under NEM:AQA.
3. To assess whether air pollution events correlate with the following:
   3.1. Emission events (as reported to the South Durban Community Environmental Alliance).
   3.2. Local synoptic events as identified through changes in:
      3.2.1. Air pressure
      3.2.2. Delta temperature
      3.2.3. Wind speed and direction;
4. To assess the following in Cape Town and Durban:
   4.1. Whether there is any relationship between air quality in Cape Town and subsequent air quality in Durban.
   4.2. To statistically assess whether there is any relationship between meteorology in Cape Town and subsequent air quality in Durban.
   4.3. If any such relationships exist, suggest possibilities for warning communities of pollution events using available data.

1.6 STRUCTURE OF DISSERTATION

A description of the study area, including the geographical location, climatology, environmental context, economic importance and environmental management of the DSB is outlined next in *Chapter 2*. *Chapter 3* has been split into two parts. The first part provides a theoretical framework for the study, specifically reviewing literature on the main meteorological controls of air pollution concentrations in the DSB and Cape Town. The second discusses how air pollution events are to be defined in this study, the health impacts of SO_2 and $PM_{10,}$ the relevance of the current South African NAAQS. *Chapter 4* outlines how air pollution and meteorological datasets were obtained from each monitoring network in Durban and Cape Town, as well as what methods of analysis that were applied in this study. This chapter thus provides background information necessary for interpreting the results presented in *Chapter 5*. *Chapter 5* comprises six sections namely, air quality monitoring results in the DSB, air quality monitoring results in Cape Town, a complete description of the top ten air pollution events that occurred between

2006 and 2010 in the DSB, a final discussion of the top ten events, an analysis of reported emission events and, finally, a statistical analysis of air pollution controls in the DSB. *Chapter 6* presents the final comments and conclusions of the study while the final chapter, *Chapter 7,* contains the references.

Engen Refinery located in the heart of a residential area in the Durban South Basin.

2 STUDY AREA

2.1 INTRODUCTION

The DSB is the main focus area of this study. Air quality data from Cape Town was also analysed to assess any relationship between pollutant concentrations in Cape Town preceding pollution events in Durban and the pollutant concentrations in Durban during these events. Figure 1 shows the locations of these cities. Both sites are situated along the coast of South Africa; Cape Town along the south-west coast and Durban along the east coast. Cape Town was selected as a comparison city because frontal systems that reach Durban are encountered by Cape Town in preceding days. There is thus a possibility that the impact of these fronts in Cape Town could indicate future impacts in Durban. Furthermore, Cape Town has a well-developed air pollution monitoring network that has been in operation for many years to provide the data necessary for this comparison. Port Elizabeth was another potential city for comparison, but the local authorities there were not forthcoming with their monitoring data despite numerous requests.

Figure 1: The location of Durban (study site) and Cape Town (comparison site) along the coast of South Africa.

2.2 GEOGRAPHICAL LOCATION

The DSB is located in the eThekwini Municipality, along the east coast of KwaZulu-Natal, South Africa. The basin is a narrow strip of land that is approximately 5 km wide, extending south-westwards from the harbour for approximately 12 km to the suburb of Umbogintwini (Ramasar and Banoo, 2003). It covers an area of approximately 60 km^2 and comprises a mixture of land zones including industrial, residential and commercial (Scott and Diab, 2000).

2.3 TOPOGRAPHY

The DSB is bound to the south-east by the 100 meter Bluff ridge and to the north-west by the 110 meter Berea ridge. This creates a flat, basin-like area with the harbour to the north (CSIR, 1999; Ramasar and Banoo, 2003). There are four main rivers that cut through the DSB from inland areas and drain towards the Indian Ocean, namely the Umbilo, uMhlathuzana, Umlaas, and Isipingo Rivers. These drainage features are responsible for forming broad valleys that indent the rising terrain on the western escarpment. Eventually these rivers either cut through the coastal dunes along the shore prior to entering the ocean. These drainage river basins were modified for industrial development over the course of the twentieth century (CSIR, 1999). The map below shows the topography of the DSB, the location of all air quality monitoring stations operated by the eThekwini municipality and the location of the South African Weather Services (SAWS) weather station at the old Durban International Airport.

Map displayed overleaf.

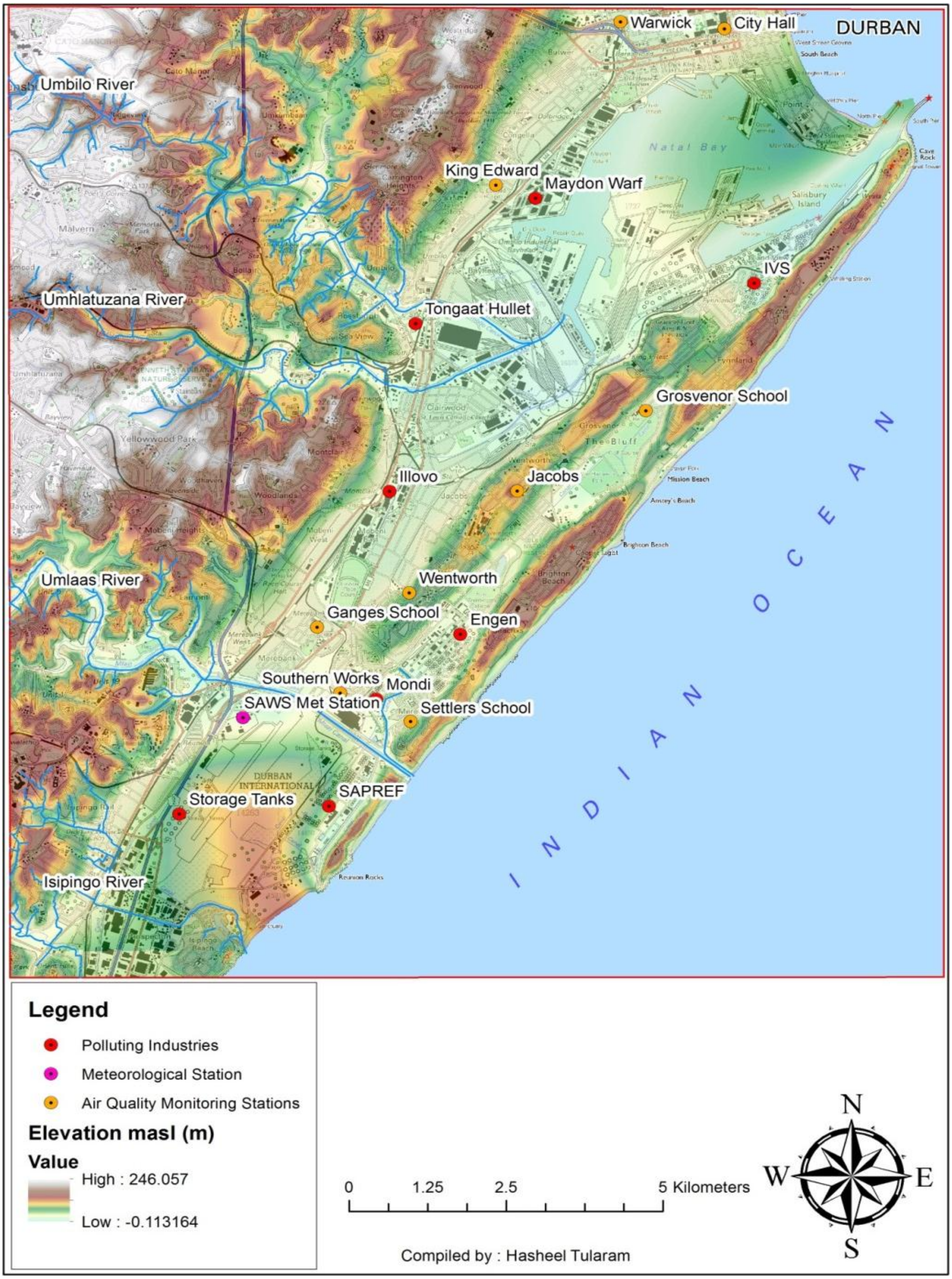

Figure 2: Map showing topography of the Durban South Basin, location of eThekwini Municipalities air quality monitoring stations as well as major rivers.

2.4 CLIMATE

The day to day climate of Durban is controlled by subtropical high pressure with temporary disruptions by low pressure cells or fronts. This high pressure zone is located at approximate latitude of 30ºS and is associated with strong divergence at the surface and convergence in the upper atmosphere. Figure 3 below shows the important atmospheric circulations over Southern Africa. The easterly waves and lows tend to be summer phenomenon, while the westerly wave and lows tend to be autumn to spring phenomena (Preston-Whyte and Tyson, 1988).

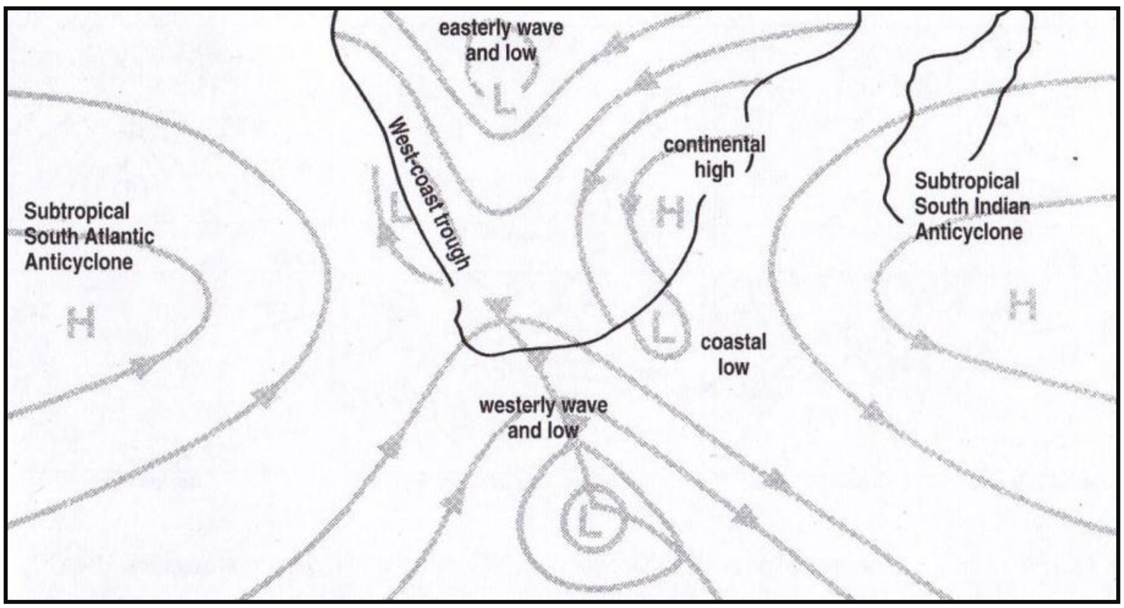

Figure 3: Map showing location of major pressure cells across South Africa (Preston-Whyte and Tyson, 2004).

The prevailing winds in this region are north-easterly and south-westerly (Preston-Whyte and Tyson, 2004). Figure 4 below shows a 2012 wind rose for the DSB generated using ADMS software and hourly wind field data as provided by the South African Weather Services (SAWS) from a station located at the old Durban International Airport. The north and north-easterly winds are associated with high atmospheric pressure and fine weather systems whilst the south and south-westerly winds are associated with the passage of coastal low pressure systems and cold fronts and therefore inclement weather (Guastella and Knudsen, 2007). Gentle North-westerly and westerly winds stem from inland and occur mainly during night time conditions.

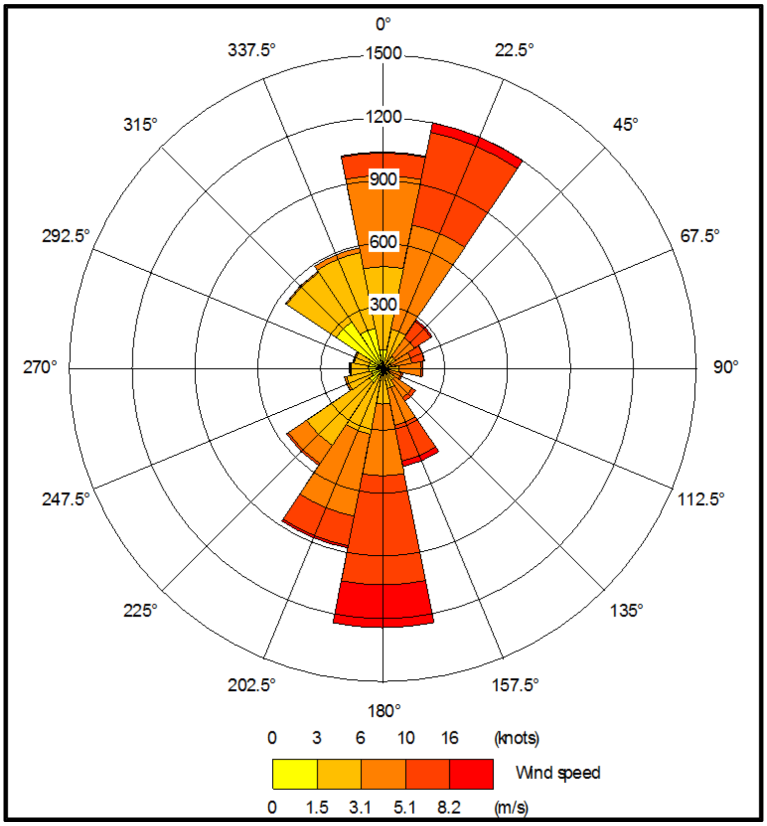

Figure 4: Annual wind rose for the DSB using 2012 wind field data.

As far as local winds are concerned, Preston-Whyte (1968) describes a system of drainage winds that flow down the Umbilo and the Umhlatuzana valleys at night, across the alluvial flats at the head of the bay to dam up against the Bluff ridge (Figure 5 below). From here the air is diverted between the Bluff and Berea ridges as a shallow south-westerly wind. The layer of cool air deepens at night to about 70 meters and travels in a south-westerly direction at a speed of 1 m/s, transferring ambient pollution with it. The Umgeni River valley to the north of the central business district (CBD) is also a source of cold air and pollutants emitted along the valley from the interior. The nocturnal air movement from this valley is unhindered in its movement by obstacles on land and the flow of this wind seaward depends on the strength of the drainage winds and may be diverted south westwards by the gradient wind towards the city (Preston-Whyte and Diab, 1980).

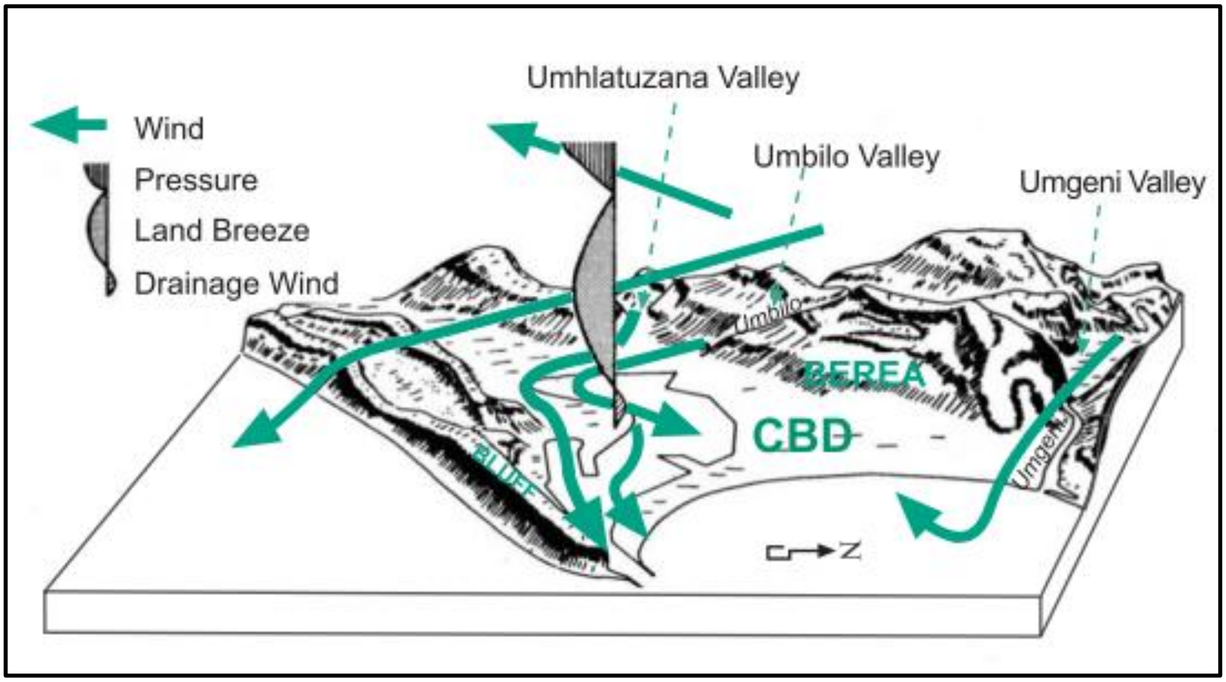

Figure 5: Diagram showing nocturnal air circulations in Durban (abstracted from Preston-Whyte and Diab, 1980).

Preston-Whyte and Diab (1980) further show how the nocturnal drainage winds are replaced above the crest line of individual valleys by the seaward movement of cool air. This seaward movement of air is termed a land breeze and integrates with the mountain plain circulation that is formed due to the pressure gradients between the mountain and coastal areas of KwaZulu-Natal. Mountain plain winds occur under conditions of stable equilibrium resulting in fanning plumes that are capable of travelling large distances beyond the Durban coastline.

2.5 HISTORICAL AND POLITICAL CONTEXT

Plans to develop the DSB as an industrial centre had begun prior to the 1920s (Scott, 1994). The DSB was classified as a zone of heavy industry by the Durban Town Council in 1938 and the council developed an apartheid system of racially zoned labour reservoirs (Scott, 2003).

Residential communities were located in close proximity to industry to allow for an abundant labour supply with little regard for community health. The communities most impacted by industrial activities were the Indian community of Merebank, and the former coloured community of Wentworth (Scott *et al.*, 2002). Ramasar and Banoo (2003) highlight the industrial impact on these communities located downwind and downstream of heavy industry. These communities continue to suffer from degraded living environments, high levels of unemployment, low average per capita incomes and associated social problems all of which are due to the product of apartheid urban design of the DSB (Diab *et al.*, 2002). Figure 6 below highlights the enduring juxtaposition of industrial and residential areas.

Figure 6: View of the Durban South Basin from Wentworth with Engen Refinery to the left, SAPREF in the centre and Mondi to the right (Guastella and Knudsen, 2007).

2.6 ENVIRONMENTAL CONTEXT

A paper by CSIR (1999) briefly describes the DSB as a flat coastal plain that is surrounded by higher land rising to the west, a steep ridgeline to the south and a coastal dune system to the east that extends from the harbour entrance southward along Isipingo beach and beyond. To the north, a coastal plain widens around the Durban Harbour before it narrows towards the Umgeni River. The DSB is mostly at or near sea-level and the ideal geomorphological setup for a swampy area. Most of the valuable flat land in the area has been reclaimed through drainage, river canalisation, mouth diversion and infilling to make space for industries, residences and transport systems that would be in close proximity to the Durban Harbour (Wiley *et al*, 1996).

The DSB is a rich coastal zone that contains a range of unique flora and fauna along the Indian Ocean. Coastal dune communities found in the remaining reserves extend from the harbour southwards along the Bluff, and through the Happy Valley Vlei. There is also a unique coastal grassland community preserved beyond the Umlazi Cuttings, extending to the Isipingo Estuary. Along Treasure Beach, a biologically diverse inter-tidal community exists and along the southern boundary, at the Isipingo River estuary, a mangrove community provides a habitat for numerous coastal birds including fish eagles (Wiley *et al*, 1996).

2.7 ECONOMIC IMPORTANCE

According to statistical analyses conducted by the CSIR (1999), the DSB comprises of approximately 600 industries. It is not expected that this number has changed significantly since then, although industries may have changed ownership or name. An excess of 70% of Durban's industries are located in this topographically confined basin. The basin is of great importance to the entire South African economy as it contributed to 10% of the country's GDP and 90% of its chemical requirements in 1999 (updated data is not readily available but it is surmised that these values have not changed drastically). The main industries in the DSB include two of South Africa's major oil refineries, as well as chemical, metal, paper, food and beverage, motor vehicle, textile and clothing industries (Ramasar and Banoo, 2003).

The two oil refineries refine approximately 60% of South Africa's petroleum (Groundwork, 2001). These refineries, together with the paper mill owned by Mondi, produce more than two thirds of the SO_2 emissions in the DSB (Bisset *et al.,* 1999). With sustained pollutant emissions, regular chemical leaks, spills, fires and explosions and other industrial accidents that occur in the area, the DSB is arguably South Africa's most polluted zone (SDCEA, 2009a). The massive island view storage and loading facility is found along the harbour and is used to store numerous chemicals, liquid fuels including jet fuel, petrol, diesel and paraffin and poses a major risk as far as fire and explosions are concerned (SDCEA, 2009a). A brief description of the three major industrial enterprises follows.

2.8 ENGEN

After three years (1948 to 1951) of negotiations between the Standard Vacuum Oil Company (STANVAC) of South Africa and South African government of the time, a new refinery was established in the Wentworth Valley in the DSB in 1952 (Engen, 2004). STANVAC started operating in 1954 with an initial crude capacity of 15 000 barrels per day (Engen, 2004). Up until 1990, the refinery was wholly a South African company with no foreign interest. It initially operated as STANVAC, then changed its name to Mobil Oil SA (Pty) LTD in 1962, became Trek Beleggings Berperk in 1989, and Engen in 1990 and is currently a subsidiary of Petronas, a Malaysian-owned oil and gas company (Engen, 2004). The Engen refinery tends to be the focus of environmental concern for local communities since it is located within the Wentworth community, while the second refinery (SAPREF, see below) is located a greater distance from residences in Prospecton, a predominantly industrial zone. Due to a number of advances in the production process, Engen has shown a progressive improvement in SO_2 emissions over the last ten years.

2.9 SAPREF

SAPREF is essentially a 50/50 joint venture between energy multinationals, Shell and BP. SAPREF is Southern Africa's largest crude oil refinery, with 35% of the country's refining capacity, which equates to 185 000 barrels of oil per day or 8.5 million tons per year (Groundwork, 2005). The refinery started operating in 1963 and is located in Prospecton, about 16 kilometres south of the Durban city centre. SAPREF's facilities comprise a single buoy mooring, the refinery itself, a storage facility at the Durban harbour and joint bunkering services. There are seven underground fuel transfer lines that run for about 12 kilometres between the refinery and the Island View Storage facility. The refinery's products include petrol, diesel, jet fuel, lubricating oil, liquid petroleum gas, paraffin, solvents, bitumen, marine fuel oil and chemical feed stocks (SAPREF, 2010). The company has recently embarked on its Cleaner Fuels

Phase 2 project which requires upgrading of the refineries processing facility to further refine its fuel product. While this will result in an increase in SO_2 emissions from the refinery, there will be a significant reduction in SO_2 and benzene emissions from vehicles across the country (WSP Environmental, 2013).

2.10 MONDI

The construction of the Mondi Merebank Mill commenced in 1969 and it was commissioned with one newsprint machine in 1970. By the year 1980 there were five paper machines on site, which produced mechanical and fine papers and there were two coal boilers that generated steam to dry the paper. As part of the mill's plans to reduce its environmental impact, the coal boilers were converted to gas boilers in 2000 and SO_2 emissions showed a major improvement. The mill has grown over the years with a capacity of 540 000 tons of paper per year in 2004. Products include newsprint and magazine papers for the publishing industry and cut paper grades for the office papers market (Motha, 2004). Recently, the mill commissioned a state of the art paper machine (PM31) to generate an additional 265 000 tons per a year of mostly A4 office paper for export (Mondi, 2013).

2.11 ENVIRONMENTAL MANAGEMENT IN THE DURBAN SOUTH BASIN

Environmental management in the DSB was poor during the apartheid era. It was only after 1994 that the critical environmental issues of the DSB were seriously addressed. Durban was the first city in South Africa to adopt the UNCED LA21 (United Nations Conference on Environment and Development Local Agenda 21) principles. In 1994, the City Council recommended that Durban apply for full membership to the International Council for Local Environmental Initiatives (ICLEI) and become part of its LA21 Model Communities Programme (Patel, 2002). In a report to ICLEI (City of Durban, 1995), the City committed to "*develop a municipal environmental strategy and an action plan which incorporates the principles of sustainable development, and an integration of all management and community participation*." A 'State of the Environment' study was conducted for the city by the Council for Scientific and Industrial

Research (CSIR) and the Institute for Social and Economic Research (ISER) during the first phase of the programme (Ramsay, 2010). The DSB was one of the three important case studies that had been outlined in this study and eventually emerged as Durban's most impacted environment.

As highlighted in Patel's (2002) doctoral dissertation, a Strategic Environmental Assessment (SEA) of the area formed part of the implementation phase of the LA21 Programme. An extensive consultation process occurred as part of the SEA, which comprised capacity-building and engagement with commercial and industrial sectors and local communities. This SEA was aimed at identifying and potentially resolving the local tensions around current industrial activity (CSIR, 1999; Wiley *et al*, 1996). The SEA had set out a range of development strategies for the Durban South Basin and the final integrated report was submitted to the City Council in March 1999.

Upon completion of this SEA, the South Durban Basin Multi-Point Plan (SDB-MPP) was launched in 2000. This strongly influenced the National Environmental Management: Air Quality Act 39 of 2004 (NEM:AQA), which was promulgated under the National Environmental Management Act 108 of 1996 (NEMA). The SDB-MPP is part of Durban's Air Quality Management Plan (AQMP), and was developed using a multi-stakeholder approach that was jointly funded by the government, the industrial sector and international agencies (Roemer-Mahler, 2006). This stimulated the development of an air quality monitoring network that was intended to resolve tensions over the lack of independent pollution monitoring data in the region, since previously, data collected by either industry or civil society organisations were considered unrepresentative or unreliable by the other party (Roemer-Mahler, 2006). Thus far, the monitoring network has revealed that there has been a decrease in SO_2 levels since 1997 (Fourie, 2008).

The Air Pollution Prevention Act 45 of 1965 (APPA) had revealed its deficiencies over the years by lacking clear national air quality standards and enforcement strategies. APPA was replaced by the NEM:AQA in 2004. The new Act focuses on ambient air quality management strategies for particulate matter (specifically PM_{10}, with a diameter less than ten microns), SO_2, ozone (O_3), nitrogen dioxide (NO_2), lead (Pb) and carbon monoxide (CO). It also outlines the activities requiring Atmospheric Emission Licenses (AEL) and provisions for the declaration of priority areas for special focus.

2.12 SDCEA - COMMUNITY RESISTANCE TO INDUSTRIAL POLLUTION

The South Durban Community Environmental Alliance (SDCEA) is a community based organisation campaigning for environmental justice in the DSB. The organisation was established in November 1996 and currently consists of 16 affiliate organisations. Being a community alliance, their primary concern entails protecting the health and wellbeing of the community living in the DSB. SDCEA primarily supports their campaign with the assurance provided by the South African Constitution (Section 24) that *"South Africans have a right not to be harmed by their environment*" and they challenge industries and government authorities to make DSB a cleaner and healthier place to live. Their primary aim is to improve the environmental performance of polluting industries by monitoring them on a continuous basis. The organisation has received funding from the Danish International Development Agency (DANIDA) and Oxfam International. DANIDA also assisted in the development of a GIS system that captures all the air pollution complaints in the DSB. This creates important air pollution maps that are used for research and educational purposes (SDCEA, 2009a). These data were used in this study.The organisation is currently co-ordinated by Desmond D'Sa, a former industrial worker, a passionate community activist and a resident of Wentworth (Ramsay, 2010). He and his team partake in several activities to combat air pollution in the DSB. For example, they are involved in government lobbying, creating community awareness programmes, linking themselves to media, and collecting their own air quality data around the refineries (SDCEA, 2008).

As stipulated by SDCEA (2008), SDCEA's main objectives are as follows:

- To protect and ensure an environment conducive to positive well-being of the citizenry
- To promote "clean" development that aids local job creation

- To protect resources for present and future generations

One of the main strengths of SDCEA is that its members are made up of people from various race groups. It appears that SDCEA brings the community together and allows them to speak out for environmental justice. This melding together of the different race groups and communities within the DSB helps SDCEA to overcome and tackle issues which in the past seemed disparate because of a lack of knowledge or information (SDCEA, 2009a). However, complaints from the Municipality have been that SDCEA assumes it represents the entire community of the DSB and 'hijacks' consultation processes when the organisation (and its co-ordinator particularly) do not automatically represent a multiplicity of local viewpoints on environmental management in the region (Patel, 2002).

SDCEA has over the years developed strong links with numerous environmental organisations, both nationally and internationally. These organisations thus assist SDCEA by providing technical support and guidance. One such organisation is groundWork, directed by Bobby Peek who was also a Wentworth resident. SDCEA benefits from groundWork's links with international civil society organisations such as Friends of the Earth and the California-based Communities for a Better Environment (Roemer-Mahler, 2006).

SDCEA has a 'bucket brigade' to collect air samples frequently within the DSB. This method is based on a simple "grab sample" technique developed in the 1990s by civil society organisations in the United States. Once the instantaneous sample is collected, the bag is couriered to the United States where a laboratory identifies the gases and their respective concentration levels for which they were collected at. In the past, these results showed particularly high levels of benzene and toluene around the major refineries (SDCEA, 2003).

One of the downfalls with this method is that samples are only taken when there is a public complaint, incident or accident in the DSB (SDCEA, 2008). However, as this study will show, public concern is not always the best indicator of ambient pollutant concentrations, particularly when pollution is invisible. The bucket technique also attains values that are instantaneous (averaged over less than a minute) and almost all international guidelines and standards have averaging times of 10 minutes, an hour or a year. Industries can therefore automatically respond to the data collected by SDCEA via the bucket method as being inadequate since they cannot be compared to the National Ambient Air Quality Standards (NAAQS) under NEM:AQA (Ramsay, 2010).

The ultimate success of this organisation lies in its persistence in the struggle against polluting industries. Air quality in the DSB has shown a continual improvement over the last ten years as revealed in the eThekwini annual air pollution monitoring reports. It is fair to say that without this persistent watchdog such improvements were unlikely. After the resignation of Siva Chetty, it is uncertain whether recent lapses in effective air quality management in the region will continue

2.13 CHAPTER SUMMARY

The Durban South Basin developed into an industrial hub over the course of the 20th century. Industries and communities were located together due to apartheid land use planning that did not take community health into consideration. At present, the three main air polluters in the DSB are Engen, SAPREF and Mondi. These industries are of vital economic importance to the South African economy therefore the eThekwini Municipality faces a major dilemma of either protecting community health or jeopardising economic growth. The eThekwini Air Quality Management Plan and the area specific Durban South Basin Multi-Point Plan was specifically developed to monitor and mitigate pollution in the region. There have been clear successes as evident in decreasing pollutant concentrations in the region, but health impacts persist.

Residential area in close proximity to air polluting industries in the Durban South Basin

3 THEORETICAL FRAMEWORK - DISPERSION CLIMATE AND AIR POLLUTION EVENTS

3.1 AIR POLLUTION DISPERSION CLIMATOLOGY

Research has shown that air pollution dispersion is strongly related to meteorological conditions. The day-to-day ventilation of the atmosphere via vertical mixing as well as the nature of horizontally induced wind circulations have been found to influence air pollution dispersion characteristics. Preston-Whyte and Diab (1980) have described how air pollution dispersion is primarily dependent on the following two aspects of meteorology:

i. The ventilation of the atmosphere by vertical mixing of air, and;
ii. The horizontal transport of pollutants by wind.

These meteorological aspects are depicted further in Figure 7 below and are then discussed further in the sections that follow.

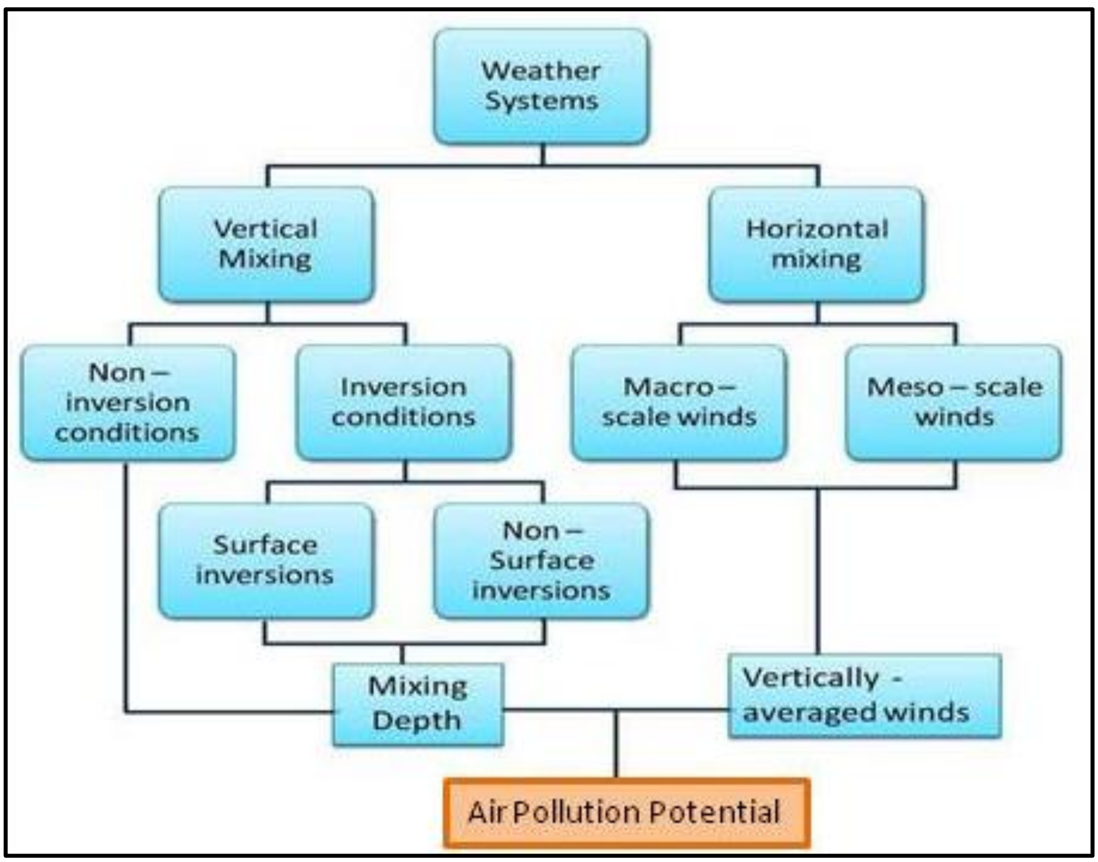

Figure 7: Components of air pollution potential as presented by Preston-Whyte and Diab, 1980.

3.1.1 VERTICAL DISPERSION OF AIR POLLUTION

The nature and characteristics of vertical mixing over Durban is known to fluctuate during the year with the change of the seasons (Preston-Whyte and Tyson, 2004). During winter, the slow moving South Indian High is responsible for clear skies, low levels of precipitation and weak north-easterly winds. The frequency and strength of inversions are known to be greatest during winter months of June and July. Surface inversions trap air pollution by inhibiting vertical mixing (Preston-Whyte and Tyson, 2004).

3.1.1.1 STABILITY CHARACTERISTICS

In a greater volume of atmosphere, the ability for air pollutants to disperse increases and there is a greater chance for its concentration to be reduced. During summer, mainly unstable conditions are found to develop and the depth of the mixing layer is increased thereby enabling free convection of air into the upper boundary layer. This phenomenon assists air pollutants to disperse into the upper atmosphere. Conversely, during winter, particularly in the early mornings, stable conditions arise and the vertical diffusion of air pollutants is limited. A surface inversion may exist nearer to the ground, or pollutants may be diffused upward only to be halted by an elevated inversion layer. Both of these surface and elevated inversions need to be considered in the DSB when analysing their relationship with air pollution dispersion (Preston-Whyte and Tyson, 2004).

3.1.1.2 SURFACE INVERSIONS

Surface inversions occur when clear, calm, cloudless, undisturbed weather conditions prevail. They form at night due to radiational cooling that occurs at the surface of the earth. They start forming shortly before sunset and by 21h00 are usually fully developed into several hundred meters deep. During the morning, surface heating from the sun erodes the inversion layer from the earth’s surface upwards (R.A Preston-Whyte, 1991). Surface inversions commonly occur in hilly mountainous regions, particularly on cold, clear and still nights. In these areas, cold, dense air drains to the bottom of the valley after sunset, displacing warmer air. As such, the layer of warmer air forms over the cooler air resulting in the formation of the inversion. Figure 8 below shows a surface inversion over Pretoria. Similarly, surface inversions are common in the DSB due to the basin-like structure of the region itself, and the flow of cold air down the local river valleys at night (Preston-Whyte and Tyson, 2004).

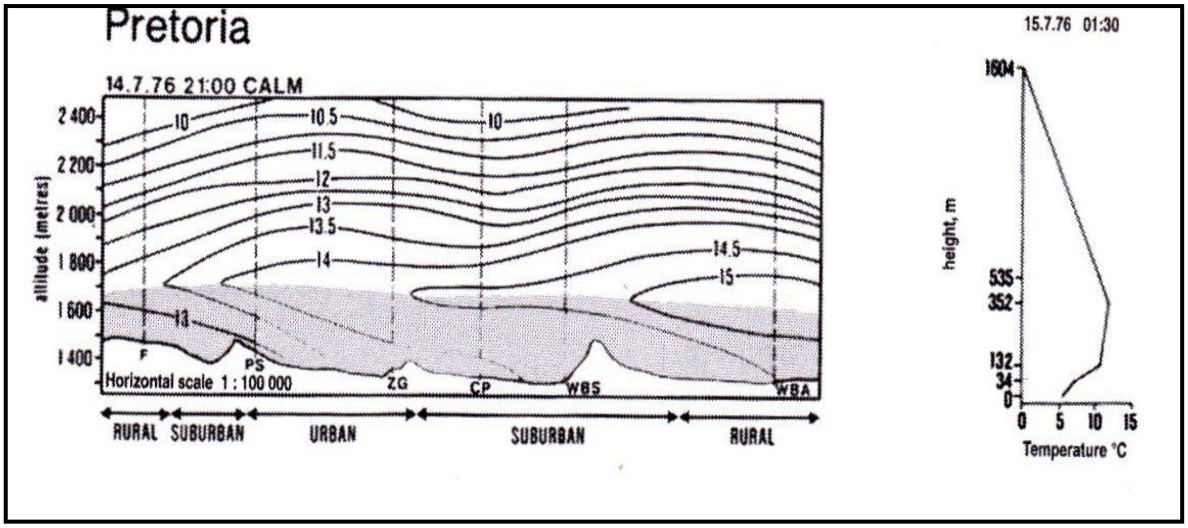

Figure 8: Example of a surface inversion over Pretoria (Preston-Whyte and Tyson, 1988).

Surface inversions tend to be eroded from the 'bottom up' when the sun rises and the surface is heat. The contents of an initial fanning plume are carried to the surface once lapse conditions deepen to reach the plume, potentially resulting in thermal fumigation. High ground-level concentrations then result until such time the elevated inversion dissipates or is lifted. Colloquially, this is referred to as 'popping of the inversion layer'. This phenomenon has been described for Pietermaritzburg by Simpson and McGee, (1996) and the DSB by Diab *et al.* (2002).

3.1.1.3 ELEVATED INVERSIONS

Elevated inversions commonly occur in areas of high pressure where sinking air warms adiabatically to temperatures in excess of that in the boundary layer (R.A Preston-Whyte, 1991). There exists an interface or a region known as the elevated inversion layer that separates the gently subsiding air and the mixed boundary layer air and shown further in Figure 9 below. This type of elevated inversion is common in Southern Africa were they may extend over considerable distances. The important features of these stable layers of air are depth, temperature intensity and height above the ground which all influence air pollution dispersion (Preston-Whyte and Tyson, 2004).

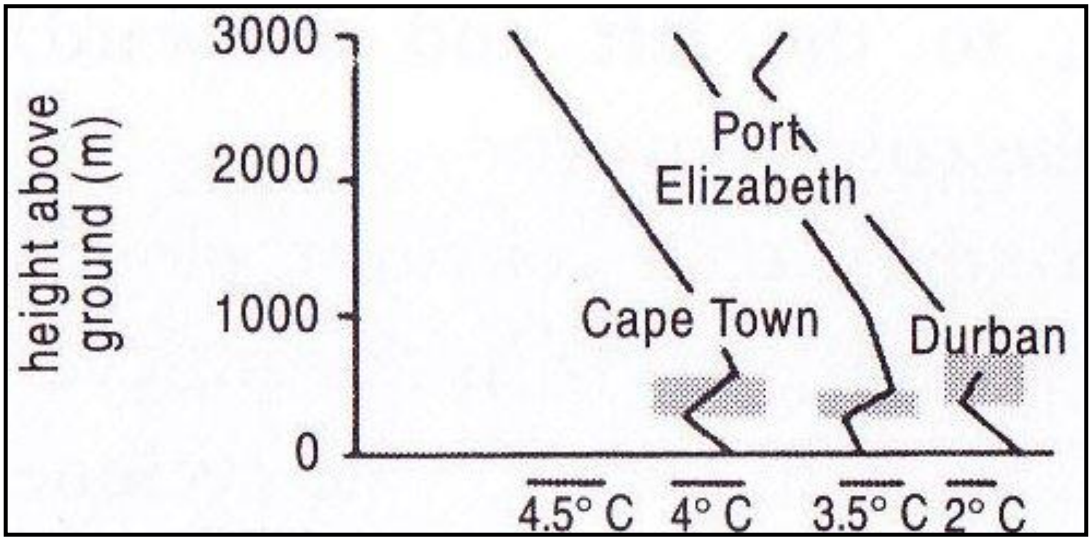

Figure 9: Example of inversion layers heights over Cape Town, Port Elizabeth and Durban (Preston-Whyte and Tyson, 2004).

3.1.1.4 SUBTROPICAL HIGH PRESSURE AND SUBSIDENCE INVERSIONS

High pressure cells are large systems with centres characterised by weak pressure gradients. They are associated with subsidence, compression and adiabatic warming of the local atmosphere. They are thus responsible for generally fine weather conditions. In Southern Africa there are three dominant high pressure cells at approximately 30ºS, namely the South Indian High, Continental High and South Atlantic High. The South Indian High is located along the east coast of South Africa over the Indian Ocean, the Continental High is positioned over the subcontinent and the South Atlantic High is situated along the west coast of South Africa over the Atlantic Ocean. These pressure cells migrate with the change in the relative position of the sun and the strength of convection over the land surfaces. The South Indian High generally is found closer to the coast of Durban during winter and further east away from the coastline during summer. It also migrates north and south, lying most southerly from February to May, and most northerly from May to July and again in October. This was phenomenon was highlighted by Preston-Whyte and Tyson (2004) and is presented in Figure 10 below.

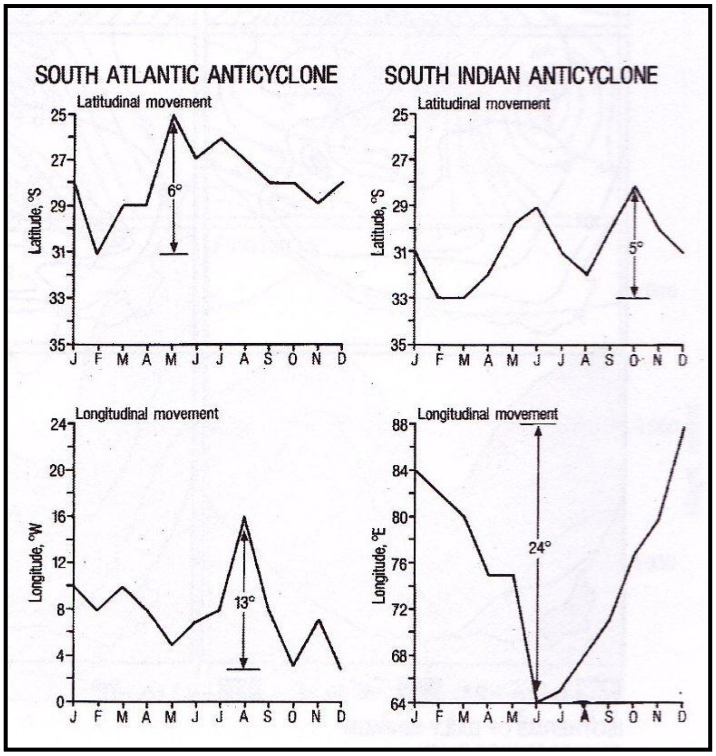

Figure 10: The latitudinal and longitudinal migration of South Indian and South Atlantic Highs (Preston-Whyte and Tyson, 2004).

The South Atlantic High generates inversion layers over Cape Town, where the mixing characteristics over the coastal zone periodically deteriorate when a cold front approaches and the elevated inversion shifts downwards from a mean height of 1200 m to 600 m. This decreases the mixing height, thus increasing pollutant concentrations. Rain and fresh south-westerly winds help cleanse the atmospheric boundary layer of pollution after the passing of the front and the lifting of the elevated inversion as highlighted further below. Following the rainy spells, cold anticyclones may ridge eastward over the south-western tip of Africa and set up conditions favouring the re-accumulation of atmospheric pollutants (Jury *et al.*, 1990).

3.1.1.5 LIFTING OF SUBSIDENCE INVERSIONS

A subsidence inversion layer can be lifted or temporarily elevated as a cold front passes over. Preston-Whyte and Diab (1980) explain that the inversion layer reaches its lowest level above the ground just before the cold front passes over. The inversion layer is then temporarily eliminated or uplifted when the cold front passes over. This is schematically represented in Figure 11 below. The narrower mixing depth and light north-easterly winds as the front approaches increases the potential for air pollution events (Preston-Whyte and Diab, 1980). As the cold front passes over, the wind direction generally shifts towards the south-westerly direction and wind speed increases. The inversion layer is lifted and the mixing depth increases. This combined with the increased wind speeds decrease air pollution potential. Rainfall often follows the passage of a cold front, which helps to "wash out" air pollutants.

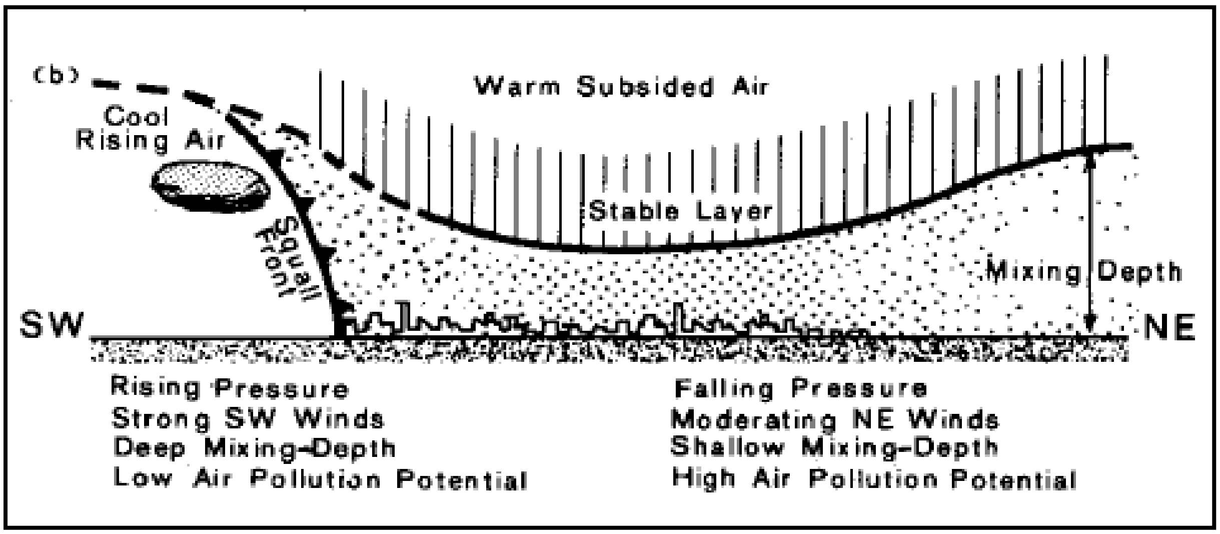

Figure 11: Diagram showing how the passage of a cold front effects an inversion layer and its ability to trap air pollution over Durban (Preston-Whyte and Diab, 1980).

3.1.2 HORIZONTAL DISPERSION OF AIR POLLUTION

The horizontal component of air pollution dispersion is directly related to wind speed. The greater the wind speed, the greater the level of dispersion away from the source. Preston-Whyte and Tyson (1988) describe the relationship between pollution concentration (x), and average wind speed (U) by the following simple equation:

$$x = k/U^{\alpha} \qquad (0 < \alpha < 1)$$

Here "k" refers to a proportionality constant that is dependent on wind direction, wind location and "α" is a constant. The equation above explains the inverse relationship between wind speed and air pollution concentrations. This implies that under high wind speeds, the transport of air pollutants away from the source is most efficient.

3.1.2.1 MACRO-SCALE WINDS

The prevailing winds that occur along the KwaZulu-Natal coast are north-easterly and south-westerly. During summer the South Indian High is located offshore of the east coast of South Africa and is responsible for creating the north-easterly onshore wind along Durban due to its anticlockwise circulation. These winds advect warm, moist air over the coastal area of KwaZulu-Natal. This causes high rainfall in summer to be experienced over the eastern parts of South Africa. Rain, generally a phenomenon that helps to clean the air of all its air pollutants, is welcomed in the DSB.

In Cape Town, the dominant winds are from the south-westerly direction as a result of anticyclonic circulation of the South Atlantic High in this region. The cool Benguela current that flows along the Namibian coastline causes this wind to be dry and icy. Strong subsidence within the South Atlantic High prevents surface air from rising; hence in summer very little rainfall is experienced over this area.

The South Atlantic High can extend across the southern and south eastern parts of the country. This phenomenon is known as 'ridging' of the anticyclone and enables cool, moist air to be advected onto the south and east coast of South Africa with resultant rainfall.

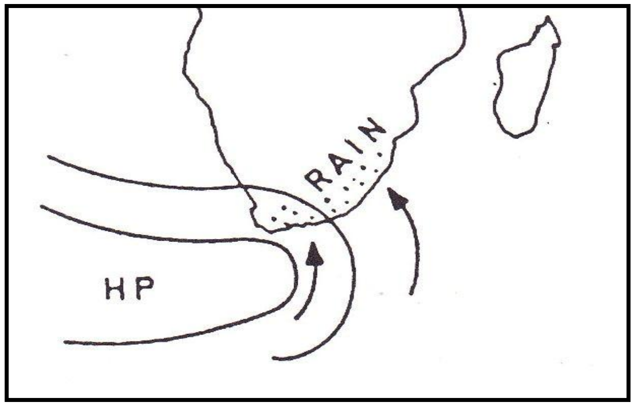

Figure 12: Simple synoptic representation of a ridging South Atlantic High over South Africa (Preston-Whyte and Tyson, 1988).

In winter, the Continental High dominates circulation over the interior of the country and is generally responsible for causing fine weather conditions. Periodically low pressure cells, such as coastal lows or cut-off lows, and cold fronts travel along the coastline of South African towards Durban. The interaction with the Continental High and these lows results in the formation of a berg wind (Figure 13). Air descends down the plateau towards the coastal low and is warmed adiabatically resulting in a warm, dry wind. As the low passes over Durban, the wind direction generally backs from a north-easterly to a south-westerly direction and rainfall usually occurs (Naidoo and Batterman, 2007).

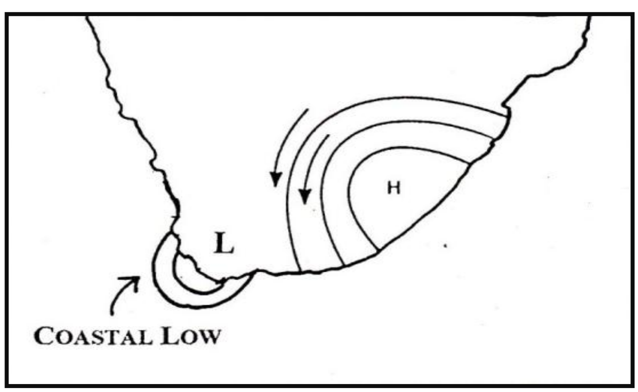

Figure 13: Simple representation of air movement around a Coastal Low and the Continental High (Preston-Whyte and Tyson, 1988).

3.1.2.2 TOPOGRAPHICALLY INDUCED WINDS

The temperature gradients between mountains and coastal plains are responsible for producing large scale air flow systems. There are two macro-scale topographical winds namely, mountain-plain winds and plain–mountain winds. Mountain-plain winds blow from cooler mountains to warmer plains by night, whereas plain–mountain winds are the opposite flow from cooler plains to warmer mountains during the day. These winds are particularly well developed seaward of the escarpment over KwaZulu-Natal as shown in Figure 14 below (Preston-Whyte and Tyson, 1988).

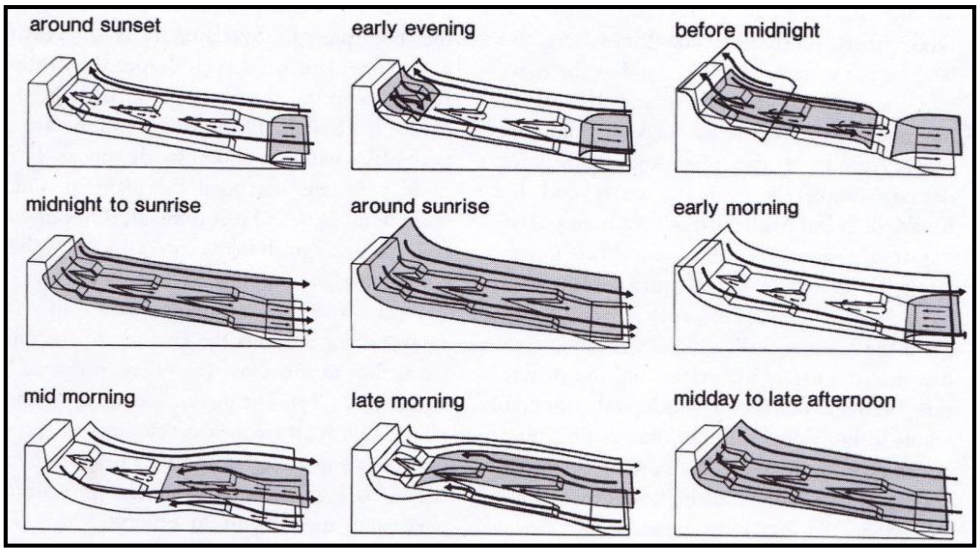

Figure 14: Diagram showing how mountain plain winds traverse across an escarpment (Preston-Whyte and Tyson, 2004).

Figure 14 shows that in the early evening, land breezes (see section 3.1.2.3.2 below) flow in individual valleys. Overlying these local winds, a deep mountain-plain wind prevails within the boundary layer to a depth of about 1000 meters. By late morning, the escarpment has warmed up and the wind flow has reversed with a plain-mountain wind dominating. At the coastline, a sea breeze is set up (see section 3.1.2.3.1 below). These mountain-plain and plain-mountain winds integrate and strengthen the land and sea breezes respectively over the DSB region. These winds influence air pollution dispersion at the regional scale.

3.1.2.3 LOCAL-SCALE WINDS

Local-scale winds occur on a smaller scale than macro-scale air circulations and are generally referred to as local winds. Local winds arise due to temperature discontinuities that occur across shorelines of lakes, seas or dams, between sloping surfaces and the air beyond, or between mountains and valleys (Preston-Whyte and Tyson, 2004). This may occur as a result of nocturnal cooling, which establishes cooler conditions in one area with respect to another (Preston-Whyte, 1968). These winds are most enhanced during clear, calm conditions such as conditions associated with anticyclones, which intensify during winter. These stable conditions are periodically interrupted by mid-latitude cyclones and strong gradient winds (Fouche, 1990).

3.1.2.3.1 LAND AND SEA BREEZES

Land and sea breezes arise due to differences in temperature between land and ocean (Preston-Whyte and Tyson, 2004) These land and sea breezes, presented graphically in Figure 15 below, are known to be best developed along the west coast of South Africa. This is due to the large horizontal temperature gradient between the cold Benguela Current and the hot, bare semi-arid surfaces (Preston-Whyte and Tyson, 1988). The temperature gradient along the east coast of Southern Africa is smaller than that of the west coast, but still significant. This results in relatively weaker local wind systems. With the effect of Coriolis force, the sea breeze is deflected to the left to become a north-easterly winds along the east coast of South Africa (KwaZulu-Natal) while on the west coast (along the Namib) the winds are deflected to left resulting in a south-easterly direction (Preston-Whyte and Tyson, 1988).

Offshore land breezes develop during the evening due to the difference in radiational cooling rates over the land and ocean surface. The land generally heats and cools faster than the sea due to a lower heat capacity. Land breezes best develop under stable anticyclonic conditions, when clear, calm conditions prevail. This breeze has the ability to transport atmospheric pollutants towards the ocean after which they are transported parallel to the coast by gradient winds. As a result, pollutants could potentially travel great distances away from their source but can return to land in a sea breeze the next morning (Preston-Whyte, 1968).

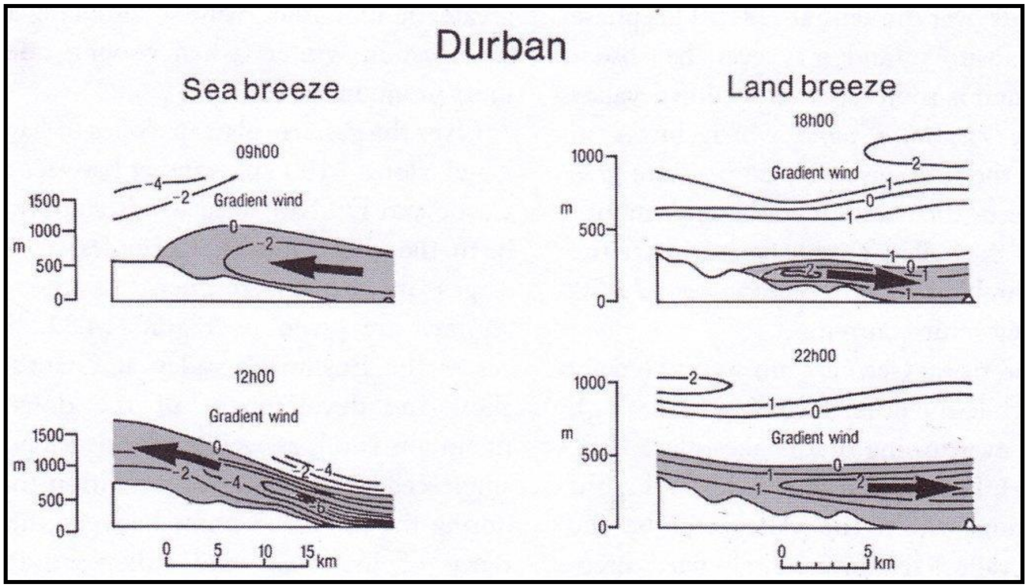

Figure 15: Diagram showing how land and sea breezes develop over Durban (Preston-Whyte and Tyson, 2004).

3.1.2.3.2 KATABATIC AND ANABATIC WINDS

Katabatic winds refer to air flow down the slope of a valley under the influence of gravity. They are also known as downslope winds, gravity winds and drainage winds and are shown in Figure 16 below. This type of air flow generally occurs during clear, calm winter nights. After sunset, land surfaces are cooled via the process of terrestrial radiation. Air that is resting on the cold valley cools and becomes denser thus draining down the valley sides under the influence of gravity. This cold air accumulates at the bottom of the valley causing the warm air to be displaced and as a result, this rests over the cold air. This implies that temperatures in the valley are lower than temperatures upslope (i.e. temperature increases with height in the valley). This atmospheric condition is known as a temperature inversion and it inhibits upward dispersion of air pollution. Figure 16 below presents the phenomenon. Pollutants emitted by heavy industries can potentially be trapped in the valley below the inversion, particularly in the early morning when the inversion strength peaks (Preston-Whyte and Tyson, 2004). Valley inversions commonly occur in the DSB, particularly on winter mornings. Surface inversions tend to be eroded from the surface upwards when the sun rises, which may result in fumigation of pollution as described for Pietermaritzburg (Simpson and McGee, 1996) and the DSB (Diab *et al.*, 2002).

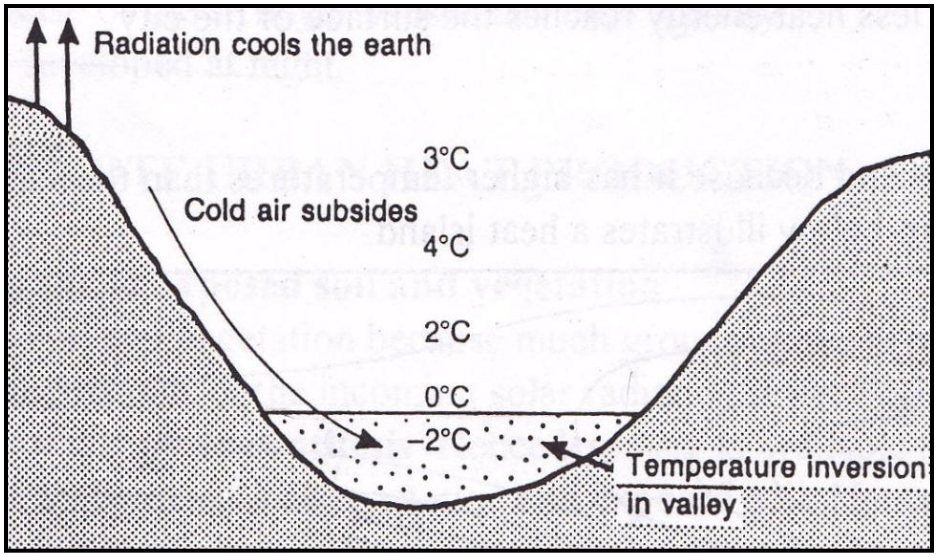

Figure 16: Diagram showing how katabatic winds occur downslope and how temperature inversion develops (Reddy, 1999).

Anabatic winds are upslope flows of warm air. Anabatic winds generally occur during the day when the valley sides are warmed by solar radiation. Air resting on each of the valley sides is also warmed causing the air to become less dense and lighter and rises up the valley. Anabatic air flow is important since it helps in dispersing pollutants from the valley floor during the day (Preston-Whyte and Diab, 1980).

3.1.3 INTEGRATION OF HORIZONTAL AND VERTICAL DISPERSION OF AIR POLLUTION

It is very important that the above meteorological factors affecting the horizontal and vertical dispersion of air pollutants are not viewed in isolation. They both work 'hand in hand' in the dispersion of air pollutants, which are transported vertically into the upper atmosphere and horizontally away from their source, generally decreasing in concentration with time and distance. Meteorological conditions such as atmospheric stability, inversion layers, wind speed, and wind direction all influence the dispersion of air pollutants. This integration of meteorological factors is discussed in the subsequent sections on specific synoptic patterns.

3.1.3.1 MID-LATITUDE CYCLONES

Mid-latitude cyclones originate at the polar front (along approximately 60^{o} N and S), which is the zone of separation between warm tropical air and cold polar air. Mid-latitude cyclones are intense low pressure cells that travel within the westerly wind belt between 30^{0} and 60^{0} latitude N/S. Mid-latitude cyclones affect the weather in South Africa predominantly during winter and early spring and it is then that the northward shift of the pressure results in these systems travelling along and up the coastline from Cape Town towards KwaZulu-Natal. During summer these systems exist too far south to have a regular impact on South Africa. Four main stages resulting in the formation of a mid-latitude cyclone are the initial, origin of wave, mature and occlusion stages (Preston-Whyte and Diab, 1980). Since it is only the last two stages of the cyclone that affects the weather and climate over South Africa only they are discussed below.

The mature stage of the cyclone is reached when a wave along the polar front has deepened or intensified. The isobars at the fronts form a 'V' shape (i.e. the isobars kink). This 'V' points away from the low pressure centre. It takes approximately 12 hours for this stage to develop from the origin of the wave at the polar front. The frontal zones at this stage slope upward on the cold side of their surface positions, so that in the upper troposphere, they lie several hundred kilometres poleward of their surface expressions. A temperature gradient exceeding 5 $^{\circ}$C per hundred kilometres is observed across the cold front, creating a sharp thermal boundary between the warm sector and the cold sector. In Figure 17 below, the arrow labelled A indicates the general direction in which the mid–latitude cyclone moves (west to east) across South Africa. This diagram shows the most intense stage in the development of the cyclone with the warm front, cold front, cold sector and warm sector being fully developed during this stage. The warm fronts rarely, if ever, pass over South Africa.

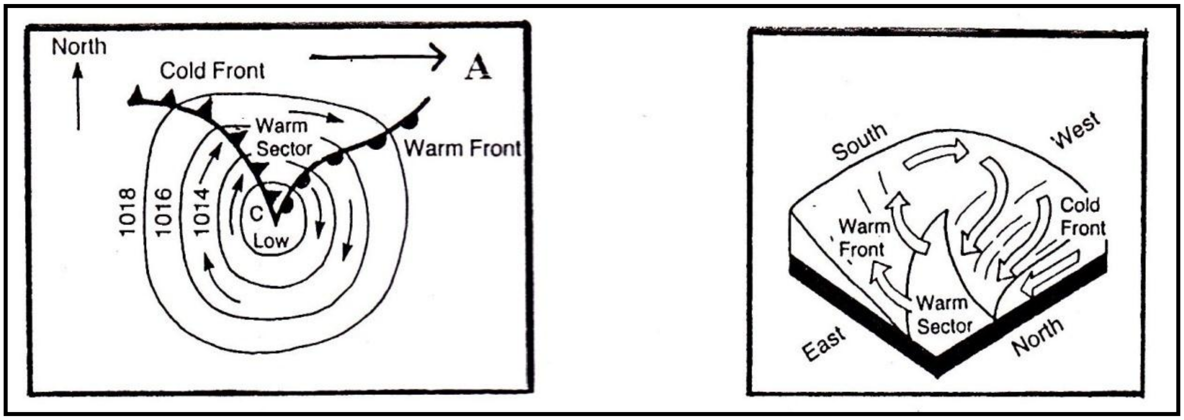

Figure 17: Diagram showing the mature stage of the Mid-latitude cyclone (Preston-Whyte and Diab, 1980).

The occlusion stage (shown in

Figure 18 below) is the final stage and is also known as the dissipating or degenerating stage. This stage is characterised by the presence of an occluded front. Cold fronts tend to move faster than warm fronts with the cold front eventually 'catching up' with the warm front and displacing it. The occluded develops from the apex of the wave since the distance between the fronts is shortest at this point. The process of occlusion continues until the entire front becomes what is known as an occluded front (Preston-Whyte and Diab, 1980).

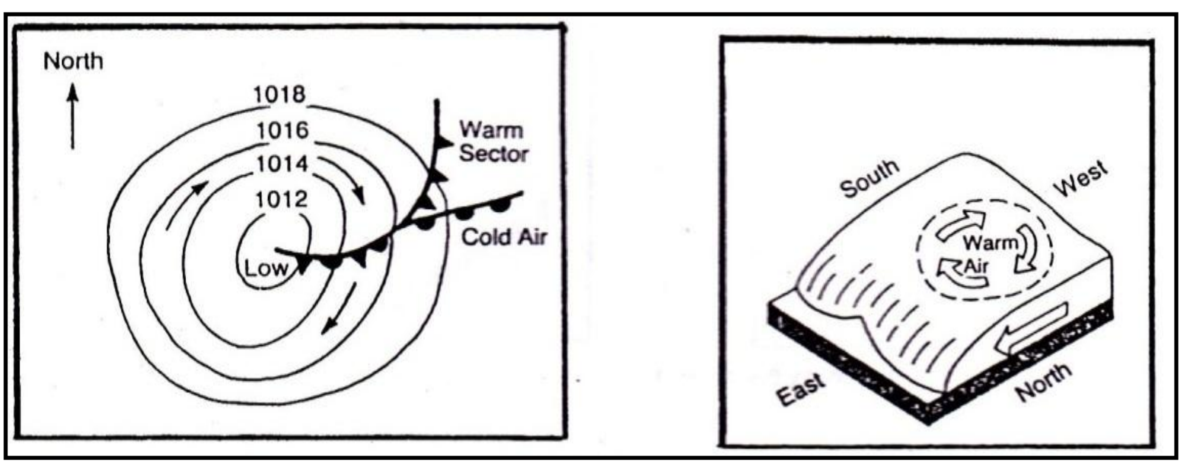

Figure 18: Diagram showing the occlusion stage of the Mid-latitude cyclone (Preston-Whyte and Diab, 1980).

3.1.3.2 PRE-FRONTAL CONDITIONS

The cold fronts that pass over Durban and Cape Town are responsible for altering air temperature, inversion characteristics, and mixing depths. A typical pre-frontal situation is shown in Figure 19 below, with a cold front approaching Durban following the passage of a coastal low.

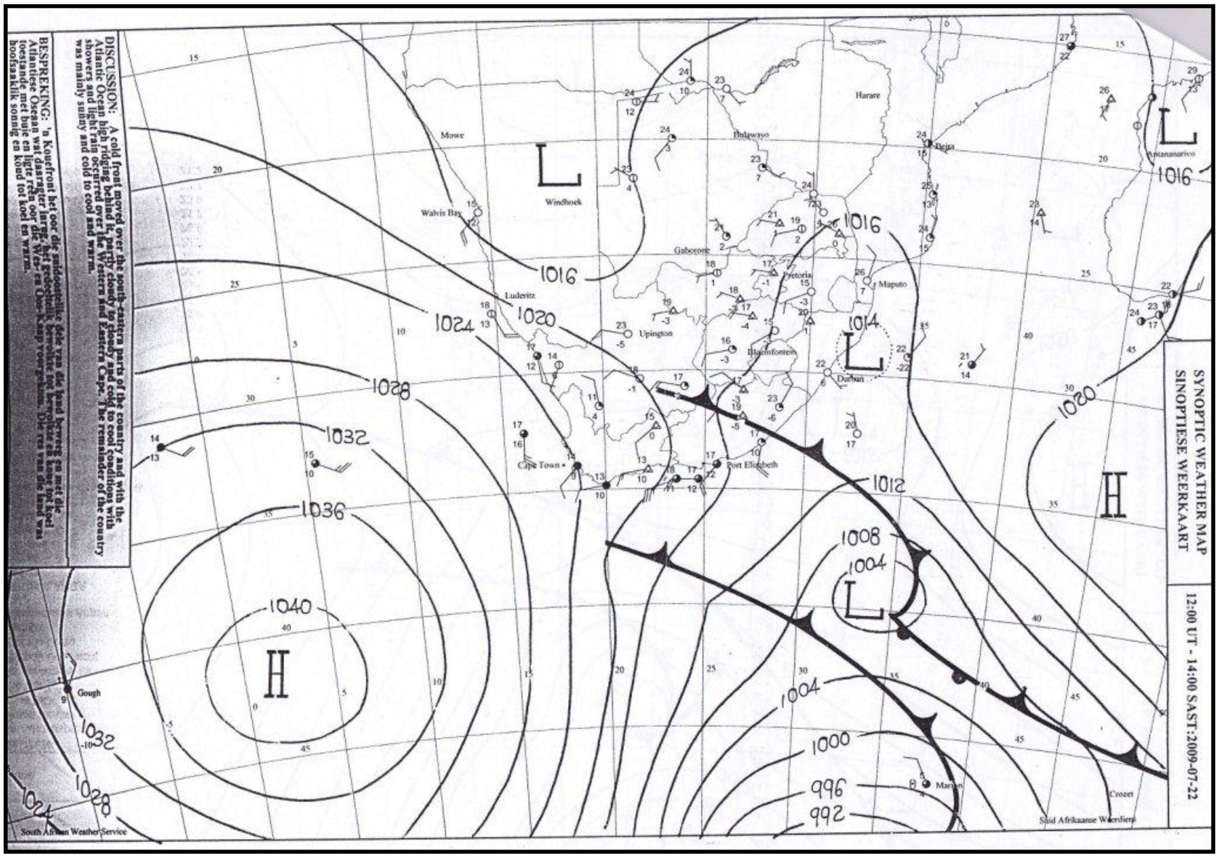

Figure 19: Synoptic chart showing pre-frontal conditions at Durban (SAWS, 2006 - 2010).

As the cold front approaches Durban there is a dramatic drop in atmospheric pressure, moderate easterly to north-easterly winds prevail and there is a narrowing of the mixing depth. Local subsidence inhibits the formation of clouds. Air pollution potential is highest under these conditions because of the lowering of the subsidence inversion and the consequent reduction in the depth of the mixing layer (Fouche, 1990). As the cold front traverses Durban, winds change direction from north-easterly to south-westerly and wind speeds increase.

3.1.3.3 POST-FRONTAL CONDITIONS

Post-frontal conditions occur once the cold front has passed over Durban as in Figure 20 below. As the front passes over, there is change of wind direction over Durban from north-easterly (pre-frontal) to south-westerly (post-frontal). In Cape Town, as the front passes over, the wind shifts from a north-westerly (pre-frontal) to south-easterly (post-frontal). Temperatures also fall sharply with the subsidence inversion layer being elevated or disappearing. Generally the South Atlantic High ridges over the south coast behind the cold front causing cool moist air to be advected onto the coastline.

Air pollution potential during these weather conditions is at its lowest since higher wind speeds and deeper mixing depths with dissipated inversion layers assist in the dispersion of air pollutants horizontally and vertically (Fouche, 1990). Rainfall is also likely to occur after the passage of the cold front and will wash pollutants out of the air.

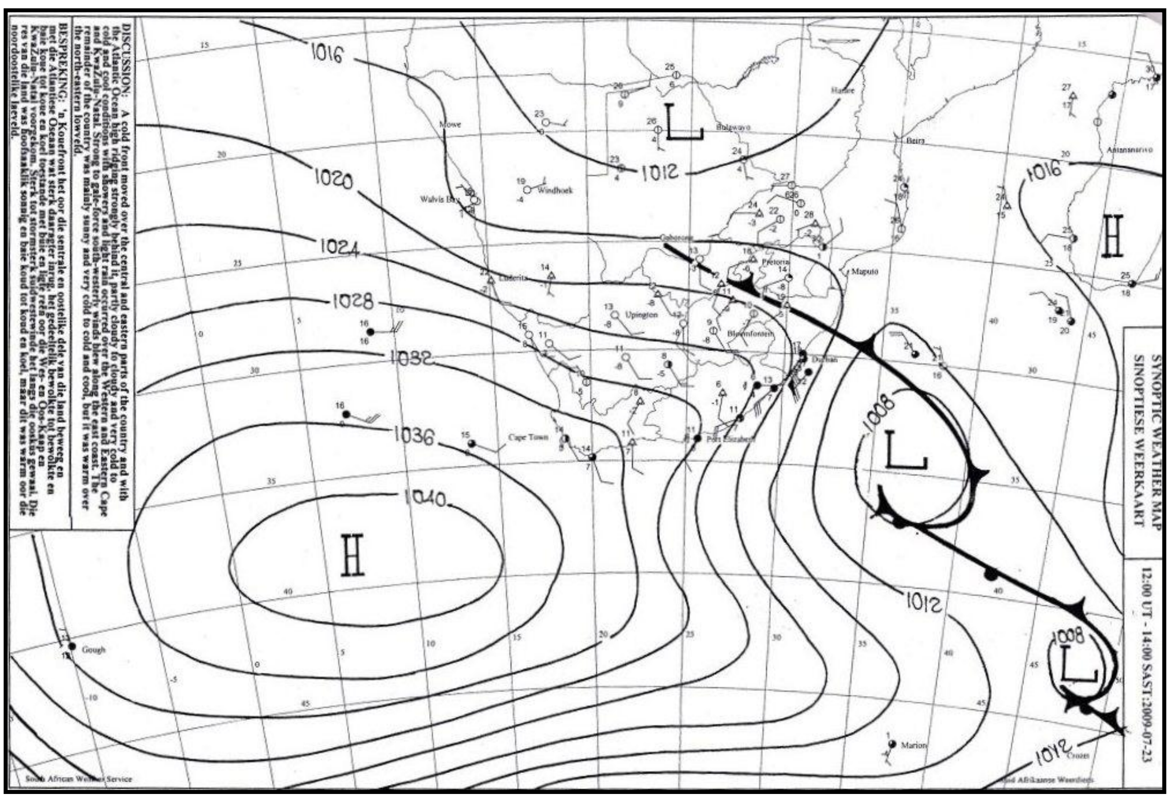

Figure 20: Synoptic chart showing post-frontal conditions over Durban (SAWS, 2006 - 2010).

3.1.3.4 DOWNWASH

The physical configuration of the stack and/or adjacent buildings can result in the plume not rising freely into the atmosphere. The aerodynamic effects of the way wind moves around adjacent buildings as well as the stack can force the plume downwards towards the ground instead of allowing to rise into the atmosphere (DEA, 2012). The movement of air around buildings and other structures causes turbulent wakes effecting ambient wind conditions. Depending on the ambient wind profile and exit velocity parts of the plume may be drawn down into the building cavity, low pressure region in the near wake of a building. This phenomenon is referred to as building downwash and can result in elevated air pollution concentrations (DEA, 2012).

Downwash also occurs due to topography as large hills or mountains can change the normal wind patterns of an area. If a stack is located closely downwind of a hill above the maximum height of the stack, the air flowing of the hills can cause the plume to reach the surface of the earth resulting in a fumigation effect (Preston-Whyte and Tyson, 2004).

Stack tip downwash occurs when the ratio of stack exit velocity (efflux rate) to wind speed is less than 1.5. Low pressure in the wake of the stack may cause the plume to be drawn downward on the lee side of the stack. The potential for air pollution dispersion is reduced and results in elevated pollutant concentrations immediately downwind of the source (Scire *et al*, 2000). Stack downwash in the DSB was described by Diab *et al.* (2002). The authors found that high levels of SO_2 in the DSB were associated with low wind speeds, with concentrations decreasing as wind speeds increased, until a critical wind speed threshold that lay between 3.5 m/s and 4.5 m/s when the trend reversed. These increased concentrations of SO_2 were associated with stack downwash (referred to in this paper as 'stack down-drafting') during strong south-westerly winds after the passing of the front.

3.2 DEFINING AIR POLLUION EVENTS

Preston-Whyte and Diab (1980) defined an air pollution event on the basis of vertical and horizontal mixing of air. These authors classified inversion conditions and wind speed values into different categories. For the basis of this dissertation, PM_{10} and SO_2 measurements will be used to identify an air pollution **incident**. It was decided that for an incident to have occurred, hourly air pollutant values must exceed the NEM:AQA standard of 134 ppb (Government Gazette, 2009) for SO_2 and/or a threshold of 100 $\mu g/m^3$ for PM_{10} for a sustained period of at least three hours over a 24-hour period. By classifying an air pollution incident as one during which three or more hours exceed the guideline value, one eliminates intermittent extreme values that may be the result of instrument problems rather than a sustained period of high pollution values. If a series of incidents were found to occur within 48 hours of one another, then these were classed together as a single **event**. The top ten PM_{10} events (in terms of peak concentrations from highest to lowest) were selected for detailed analysis and graphical presentation in the results section.

Air quality guidelines and standards are designed to offer guidance for the management of air pollution. Ever since the industrial revolution there has been an increased awareness amongst scientists to address the public health problems associated with air pollution. The World Health Organisation (WHO) offers a set of international guidelines. Air pollution levels and management resources, however, vary from country to country, and thus there is some variation in what is converted to a legally enforceable pollution standard in each country. Factors that are taken into account when setting standards include economic factors, technological feasibility, as well as a range of political and social factors (WHO, 2005). In South Africa, a set of air pollution standards were promulgated in line with section 9 of the NEM:AQA in 2004 and supplemented in 2009 (Government Gazette, 2009). Sulphur dioxide and particulate matter (as PM_{10}) are the focus of this study and these are described further below.

3.2.1 SULPHUR DIOXIDE

Sulphur dioxide emissions are primarily a function of sulphur content in a fuel used. During the combustion process, essentially all the sulphur in the fuel is oxidized to SO_2. In the air, oxidation of SO_2 results in the production of sulphur trioxide (SO_3) which reacts with water to create sulphuric acid (H_2SO_4), a contributor to acid rain (Naidoo and Batterman, 2007).

Sulphur dioxide is a colourless gas that has a pungent and irritating odour causing an irritation on the upper respiratory tract of humans. If it is absorbed on particulate matter or if it is converted into sulphuric acid, it can be inhaled deep into the lungs where it can injure delicate inner tissue. Prolonged exposure to relatively low levels of SO_2 can be associated with an increased number of deaths from cardiovascular disease in elderly people. Very heavy concentrations of SO_2 are known to cause coughing, sore throats, chest constriction, headaches, burning sensation of the eyes, nasal discharge and vomiting (Berry and Horton, 1974).

3.2.2 PARTICULATE MATTER LESS THAN 10 MICROMETERS

Particulate matter is made up of a complex mixture of organic and inorganic substances that form a mixture of particles in the solid or liquid phase. The major components include sulphates, nitrates, ammonia, sodium chloride, carbon, mineral dust, water, metals and polycyclic aromatic hydrocarbons. These particles vary in size, composition and origin. Particles with an aerodynamic diameter less than 10 microns are called PM_{10}. When inhaled, these particulates can reach the depths of the lungs. Smaller particles with an aerodynamic diameter less than 2.5 microns are called $PM_{2.5}$ and are more dangerous than PM_{10} since they can travel deeply into the lungs and enter the bloody stream through the capillaries lining the alveoli of the lungs (Martuzzi and Mits, 2006).

Smaller particles, such as $PM_{2.5}$, can remain suspended in the air for days up to weeks and be transported over long distances, whereas larger particles (such as PM_{10}) remain in the atmosphere for a few hours before they are deposited to the earth’s surface (Perkins, 1974). Particulate matter can be classified as primary or secondary depending on the method in which they were created. Primary particulates are emitted directly into the atmosphere via anthropogenic and natural processes. Examples of these are motorcar exhaust fumes, burning of fossil fuels, industrial activities, and actions that create dust (Martuzzi and Mits, 2006). Secondary particulates can form through the interaction of other primary pollutants in the atmosphere.

3.2.3 NATIONAL ENVIRONMENTAL MANAGEMENT: AIR QUALITY ACT 39 OF 2004

Air quality guidelines are designed to offer guidance in reducing the health impacts of air pollution based on expert evaluation of current scientific evidence (WHO, 2005). Subsequent to the publication of the original World Health Organisation (WHO) guidelines in 1995, there has been a global increase in awareness amongst scientists and policymakers of public health problems that are caused by air pollution.

The National Environmental Management: Air Quality Act 39 of 2004 (NEM:AQA) came into effect in September 2005 (Guastella and Knudsen, 2007). NEM:AQA was formulated to update and replace the previous Atmospheric Pollution Prevention Act 45 of 1965 (APPA) and various other laws that addressed air pollution in South Africa

NEM:AQA designates responsibility for the implementation and enforcement of various aspects of the AQA to the Department of Environment Affairs and Tourism (DEAT), the provincial environmental departments and local authorities. Each of these spheres of government is obliged to appoint an Air Quality Manager and to co-operate with each other and co-ordinate their activities through mechanisms provided for in the National Environmental Management Act (DEAT, 2007).

The purpose of the Act is to set norms and standards that relate to:

- air quality management planning;
- air quality monitoring and information management;
- general compliance and enforcement;

- institutional frameworks, roles and responsibilities; and
- air quality management measures

These norms and standards are set to achieve the following main objectives:

- to increase public participation in the protection of air quality and to improve public access to relevant and meaningful information about air quality;
- to reduce the risk on human health and the prevention of the degradation of air quality;
- to protect, restore and enhance the air quality of South Africa; and
- to reduce the of risks of human health and to prevent the degradation of air quality.

The Act provides for the identification of priority pollutants and the setting of national ambient air quality standards (NAAQS) with respect to these pollutants (NEM:AQA, 2004). The NAAQS are targets for air quality management plans and are used to ascertain the effectiveness of management plans. On the 24 December 2009 the NAAQS provided in Table 1 and Table 2 below were published (Standards South Africa, 2005).

Table 1: National ambient air quality standards (NAAQS) for SO_2 (Government-Gazette, 2009).

Averaging Period	Concentration	Frequency of Exceedence p.a	Compliance Date
10 minutes	500 ($\mu g/m^3$(191 ppb)	526	2009
1-hour	350 $\mu g/m^3$ (134 ppb)	88	2009
24-hours	125 $\mu g/m^3$ (48 ppb)	4	2009
1 year	50 $\mu g/m^3$ (19 ppb)	0	2009

Table 2: National ambient air quality standards for PM_{10} (Government-Gazette, 2009).

Averaging Period	Concentration	Frequency of Exceedence p.a	Compliance Date
24-hours	120 µg/m^3	4	31 December 2009- 31 December 2014
24-hours	75 µg/m^3	4	1 January 2015
1 year	50 µg/m^3	0	31 December2009- 31 December 2014
1 year	40 µg/m^3	0	1 January 2015

It is important to note that there is no hourly standard for PM_{10} – only annual and 24-hour standards. Since this study is based on data with an hourly resolution, an hourly PM_{10} threshold value of 100 µg/m^3 was decided upon. This value is less than the current 24-hour standard.

Pollution values above the NAAQS indicate a significant likelihood of health impacts on humans. Exact health impact thresholds, however, are impossible to identify since they are dependent on a range of environmental and socio-political factors, and vary from individual to individual. Ultimately, these standards (and the guidelines of the WHO) represent what is considered an 'acceptable' risk based on the results of various experimental and epidemiological studies, largely conducted in North American and European contexts (Ramsay, 2010).

3.3 CHAPTER SUMMARY

This chapter highlights the need for a broad knowledge of local meteorology and climatology before the local air quality situation can be understood. This first section of *Chapter 3* describes how dispersion and accumulation of air pollution are dependent on prevailing meteorological conditions. This section was followed by a definition of air pollution events as used in this study and a description of applicable air quality guidelines and standards, specifically those those stipulated under NEM:AQA. It was decided that when three or more consecutive hourly averaged air pollution values exceeded the thresholds selected (i.e. 134 ppb for SO_2 and 100 μg/m^3 for PM_{10}), then an air pollution incident is said to have occurred. If more than one incident occurred within 24 hours of each other, they were combined as a single air pollution event. The methodological approach applied to meet the objectives of this study is discussed in the next chapter.

Veiw of SAPREF from the Bluff (SAPREF, 2010).

4 DATA ACQUISITION AND METHODOLOGY

4.1 DATA AQUISITION

To successfully meet the aims of this study as presented in *Chapter 1,* air pollution and meteorological datasets were sourced for the study and comparison site, Cape Town. Each of these cities has an air quality monitoring networks that is run by its respective municipality. These monitoring networks include weather stations that collect meteorological datasets. A comprehensive discussion of datasets used in this study and the analytical methods implemented follows.

4.1.1 AIR QUALITY MONITORING NETWORK - DURBAN SOUTH BASIN

The eThekwini Municipality established an advanced real time air quality monitoring network during 2003 to supplement its existing bubbler network. This air quality monitoring network was established to fulfil the requirements of the Multi-Point Plan (MPP). The principle aim of the MPP was to improve air quality in the Municipality by continuously monitoring ambient concentrations of key pollutants. This allowed for an assessment of whether health-based standards were regularly exceeded, and to identify key sources of air pollution so that these could be addressed. The monitoring network was designed by a professional team of scientists from the eThekwini Health Department and were under the technical guidance of the Norwegian Institute for Air Research (NILU) (eThekwini Department of Health, 2009).

The eThekwini air quality monitoring network currently comprises of twelve air quality monitoring stations and five meteorological stations, predominantly within the DSB but also at other key points in the city. Pollutants measured include SO_2, TRS, NO_x, PM_{10}, $PM_{2.5}$, O_3 and CO using United States Environmental Protection Agency (USEPA) approved methods. The network incorporates the latest technology in continuous air quality monitoring (Zanokuhle Environmental Services, 2007). Unfortunately, instrument calibration schedules, minimum detection limits, errors expected when using these types of instruments could not be provided by the local municipality.

The air quality data collected by these stations were requested from the eThekwini Health Department for the period 2006 to 2010 (five consecutive years). This study focuses on PM_{10} and SO_2 as proxies for overall pollution levels, thereby assuming that other major pollution concentrations would correlate with these (specifically, SO_2 with other industrial pollutants, and PM with both industrial and vehicular pollutants). The data provided by the Health Department had gone through various stage of quality control before storage on a secure database. Samplers used in the monitoring stations are tested on a weekly basis using gases of known concentration to gauge their accuracy and precision. These readings are also checked for instrument drift and adjusted accordingly (eThekwini Department of Health, 2009). Data from five stations were considered in this study as the remainder of the stations do not record the pollutants of interest or are outside the DSB and is presented in Table 3 below.

Table 3: Summary of air pollutants recorded by each monitoring station in the DSB used in this study.

Monitoring Station	SO_2	PM_{10}
Ganges	✓	✓
Wentworth	✓	✓
Southern Works	✓	✓
Jacobs	✓	✗
Settlers	✓	✗

4.1.1.1 GANGES

The Ganges station shown in Figure 21 is located at Ganges Secondary School, Jammu Road, Merebank, along the Southern Freeway (northbound). This station is positioned 20 meters above sea level and measures the air quality of this suburban traffic zone. The main reason for the location of the station in this area is obtain data on the levels of NO_2 and PM_{10} from traffic and SO_2 from the small- and medium-scale industries in the Merebank, Mobeni and Jacobs areas (Department of Health and eThekwini, 2008).

Figure 21: Air quality monitoring station in Ganges (Department of Health, 2008).

4.1.1.2 WENTWORTH

The Wentworth station shown in Figure 22 below is located at the Wentworth Reservoir along Boston Road, near the Wentworth Hospital. The station is 78 meters above sea level and monitors air typical of the DSB's residential environment. This station is responsible for measuring industrial pollution that comes from the Merbank, Jacobs, Mobeni and Clairwood areas. The following pollutants are measured at this station: SO_2, NO_x, PM_{10} and O_3 (Department of Health and eThekwini, 2008).

Figure 22: Air quality monitoring station in Wentworth (Department of Health, 2008).

4.1.1.3 SOUTHERN WORKS

This station is located at 2 Bayfield Road, Merebank, within the Southern Sewage Works site, adjacent to the residential areas of Merebank and Wentworth. The station is shown in Figure 23 below and is positioned at an elevation of 13 meters above sea level. It records the highest levels of air pollution in the DSB, predominantly from industrial sources. It has been specifically located to distinguish the emissions from SAPREF and Mondi according to prevailing wind directions. This station measures a range of pollutants including SO_2, NO_x, TRS and PM_{10}. The meteorological parameters measured at the station are wind speed, wind direction, ambient temperature, delta temperature, solar radiation and barometric pressure.

Figure 23: Air quality monitoring station in Southern Works (eThekwini Department of Health, 2008).

4.1.1.4 JACOBS

This air quality monitoring station (shown in Figure 24 below) is located at the South African Police Station (SAPS) vehicle depot in Balfour Road. This station was positioned in the Jacobs area to measure air pollutants from small and medium sized industries. It has an elevation of 16 meters above sea level and serves as an industrial background station. The parameters measured at the station are SO_2 and NO_x (eThekwini Department of Health, 2008).

Figure 24: Air quality monitoring station in Jacobs (eThekwini Department of Health, 2008).

4.1.1.5 SETTLERS

This air quality monitoring station is located at Settlers School and monitors air that is being inhaled by the school children. This station is positioned at the lowest level of the basin and records concentrations from stack emissions and ground level industrial sources. A tall stack from Engen refinery can be seen in the top right hand corner of Figure 25, showing the close proximity of industry. The pollutants measured at the station are SO_2, TRS and benzene, toluene, ethyl-benzene and xylene (BTEX).

Figure 25: Air quality monitoring station at Settlers School (eThekwini Department of Health, 2009).

4.1.2 AIR QUALITY MONITORING NETWORK - CAPE TOWN

In the year 2008, the City of Cape Town published an Air Quality Management Plan (AQMP) with the aim of protecting human health and the environment of the City. The vision of Cape Town's AQMP is to be the least polluted city in Africa. The City of Cape Town operates a network of 15 automated air quality monitoring stations with the first being commissioned in 1984. The network monitors concentrations SO_2, NO_x, O_3, CO, H_2S and PM using United States Environmental Protection Agency (USEPA) approved methods. The data obtained from the network is evaluated against local standards and international guideline values on a regular basis by the local municipality. The location of each monitoring station is provided in Figure 26 below (City of Cape Town, 2011).

Figure 26: Map showing the location of City of Cape Town's air quality monitoring stations (City of Cape Town, 2011).

These monitoring stations are strategically positioned to cover a wide spatial extent across the City. Table 4 below summarises the locations of each monitoring site and classifies them by spatial setting. Stations highlighted in green were selected for this study. The Bellville and Goodwood monitoring stations were selected for further analysis as these measure industrial sources. Data from the Kayelitsha monitoring station was sourced to assess ambient air quality in a residential region.

Table 4: Brief summary for the location of each air quality monitoring station in Cape Town (City of Cape Town, 2011).

Spatial Setting	Classification	Sources	Location of Monitoring Station
Micro Scale - 0 - 100 m from source	• To characterize emissions from nearby source.	• Vehicular emissions. • Dust from construction.	• City Hall • Foreshore
Middle Scale - 0.1 - 0.5 km from source	• Used to assess effects of control strategies and monitor air pollution episodes.	• Industry wants to monitor impacts on air quality after installing scrubbers on stack.	• Atlantis • **Bellville** • Killarney • Potsdam
Neighbourhood 0.5 – 4 km from source	• Suburban areas around urban centre. • Population exposure to ambient air pollution.	• Small emitters in a neighbourhood. • Residential heating. • Dust from congested traffic.	• **Khayelitsha** • Wallacedene
Urban - > 4 km from source	• Characterise conditions over an entire metropolitan area. • Used to assess trends in citywide air quality.	• A mixture of particles from many sources. • Conglomeration of emissions from many sources.	• Bothasig • Table View • Somerset West
Regional Many kilometres from source.	• Characterize air in large homogeneous area. • Background air quality.	• Pollution generated in urban and industrial areas many kilometres away. • Naturally occurring pollution.	• **Goodwood** • Molteno

Air pollution data was requested from the Cape Town Air Quality Management Unit for the period 2006 to 2010. This is five years of air pollution data and is sufficient to identify trends and to statistically assess synoptic controls on air pollution dispersion. The pollutants measured at each station are presented in Table 5.

Table 5: Summary of the pollutant data recorded by the Bellville, Goodwood and Khaylitsha monitoring stations in Cape Town (City of Cape Town, 2011).

Monitoring Station	SO_2	PM_{10}
Bellville South	✓	✓
Goodwood	✓	✓
Khayelitsha	✗	✓

4.1.3 METEOROLOGICAL DATA - DURBAN SOUTH BASIN AND CAPE TOWN

Despite that both the Cape Town and Durban air quality monitoring networks include meteorological stations, it was decided that the South African Weather Services provided the most reliable meteorological data for these regions. The weather station in the DSB is located at the former Durban International Airport while the weather station in Cape Town is located at the Cape Town International Airport. The change in air temperature with height, however, is not measured by the SAWS and was obtained from the eThekwini Municipality. Delta Temperature data for Cape Town could not be obtained. The following meteorological variables were used in this study.

4.1.3.1 ATMOSPHERIC PRESSURE

Atmospheric pressure is the force of a column of air acting on a unit area. Atmospheric pressure can be used to track the passage of synoptic weather systems. For example, since cold fronts are associated with low pressure, steadily decreasing pressure values recorded at the monitoring station on the ground may signify that a cold front (or coastal low) is approaching.

4.1.3.2 DELTA TEMPERATURE

Delta temperature is the change in temperature with height and used to determine whether stable or unstable conditions prevail. The height of the tower at eThekwini's Southern Works station is 25 m and air temperature is measured at 3 and 23 m above the ground (Naidoo and Batterman, 2007). While the South African Weather Services also operate a radiosonde station at the old Durban International Airport measuring upper air meteorological parameters, delta temperature data from the Southern works station was used as was sufficient to track the presence of radiative inversion layers. The effect of this radiative inversion is noted in the results section with elevated pollutant concentrations being measured by the monitoring station during early morning peak traffic periods

A positive delta temperature indicates an atmospheric inversion and stable conditions. The strength of the inversion layer can be determined from this change in temperature with height as the more positive the value, the stronger the inversion. A negative delta temperature indicates lapse conditions and a more unstable environment.

4.1.3.3 WIND DIRECTION AND SPEED

Wind speed and direction is recorded at an hourly resolution by SAWS. As described by Preston-Whyte and Diab (1980), the passing of a cold front is associated with an increase in wind speed together with a change in wind direction. In Durban the wind direction backs from north-easterly to south-westerly. In Cape Town however, the wind direction change is from north-westerly to south-easterly. Wind direction and speed data thus were useful for detecting the passing of a front (SAWS, 2010).

4.2 METHODOLOGY

Pollution incidents are defined in the study as three or more consecutive hours when PM_{10} concentrations are above the 100 μg/m^3 threshold defined in this study and/or three more consecutive hours when SO_2 concentrations are above the 134 ppb NAAQS. If two such incidents occurred within 24 hours of each other, they were grouped together as a **pollution event**. Events that comprised of two elevated peak concentrations separated by low values needed to be classed together as the first peak could have occurred due to a pre-frontal post subsidence inversion and the second peak could be due to post frontal (stack tip downwash) conditions (i.e. influenced by a single synoptic system.

To accurately extract the air pollution events recorded by each station over the five year period (2005 – 2010) record, a simple computer application program was developed. Figure 27 below shows a screenshot of the computer application interface where the user inputs the raw data (in excel spread sheet format) into a designated folder and selects the air quality stations from which the air pollution events are to be extracted from. The associated air quality standard needs to be set and the program identifies pollution events (defined above) and produces output graphs which clearly show the time and duration of air pollution events together with meteorological conditions for further analysis. Excel spread sheets presenting a summary of each air pollution event are outputted from the program containing the relevant data for further analyses. Developing this program enabled air pollution events to be effectively screened out from a large dataset.

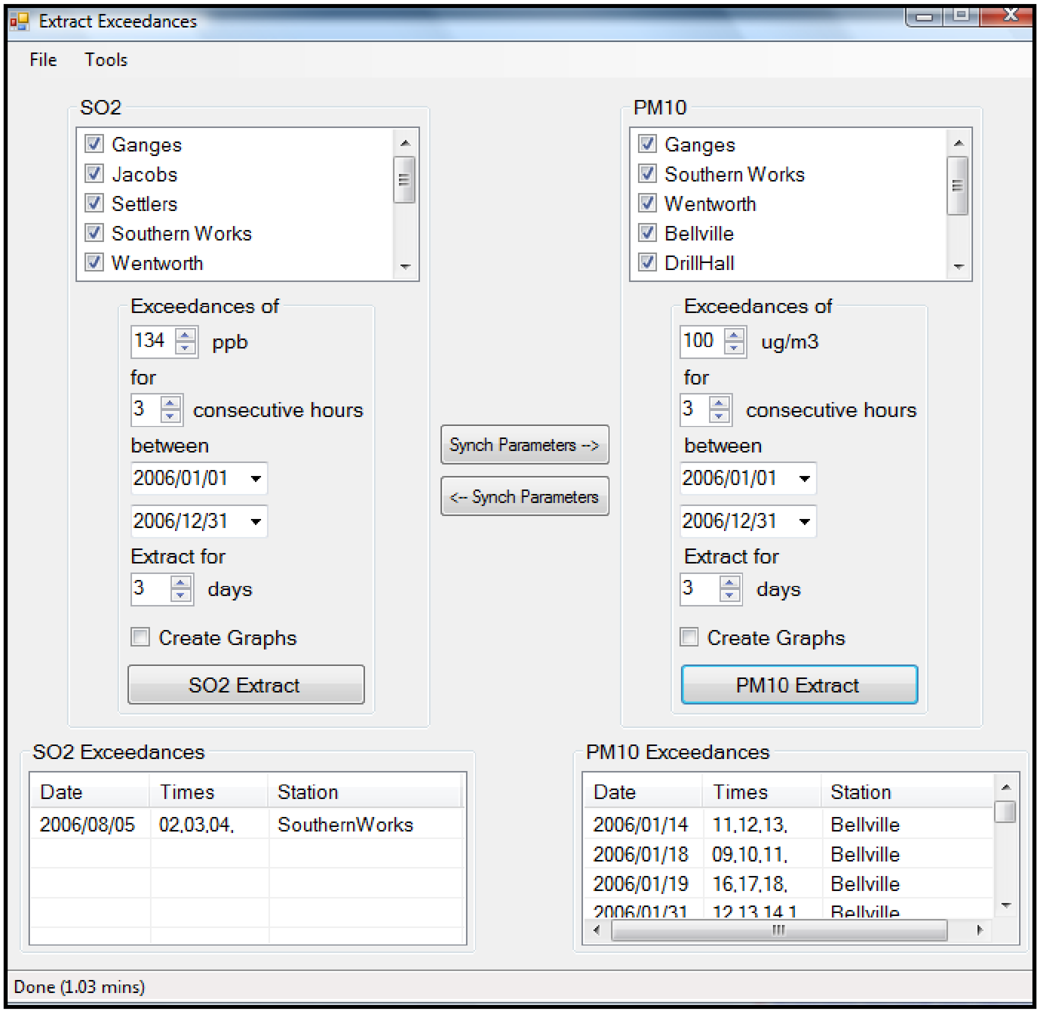

Figure 27: Screenshot of the air pollution event application that extracted SO_2 and PM_{10} exceedences from the air pollution datasets.

The WHO (2005) guidelines do not include an hourly guideline for PM_{10}, but instead provide guidelines for annual and 24-hour averages. Similarly, NEM:AQA (2009) provides standards with these averaging periods. The 24-hour WHO guideline is 50 μg/m^3, and an hourly guideline (if provided) would be higher than this. It is suggested that for the purposes of this study, a 100 μg/m^3 value is a suitable hourly guideline for identification of PM_{10} pollution events in hourly resolution pollutant concentration data provided by eThekwini Municipality.

The SO_2 data was also compared to the available standards. WHO guidelines only provide standards for 10 minute and 24-hour averaging periods. NEM:AQA (2009), however, provides a 134 ppb hourly standard and this was used for this study. The air pollution application was pre-set to extract PM_{10} and SO_2 exceedences which prevailed for a period equal to or greater than three consecutive hours from each monitoring station over the five year study period. Air pollution concentrations and selected meteorological parameters were graphically presented for the day on which the air pollution event had occurred as well as a day before and after the event.

In the results chapter that follows, the ten highest hourly PM_{10} exceedences of the defined hourly threshold of 100 $\mu g/m^3$ that occurred between 2006 and 2010 were selected for detailed analysis. The 24-hour average PM_{10} concentrations for the duration of the air pollution event are tabulated. Thereafter, each air pollution event is graphically displayed with the following meteorological variables:

- wind speed;
- wind direction;
- pressure; and
- delta temperature (change in temperature with height).

The wind speed data was classified into very strong, strong, medium, gentle and calm wind speeds. If wind speed was less than 1 m/s (threshold for SAWS weather station to measure wind speed) then stagnant (calm) conditions prevailed limiting the horizontal transport of air pollutants. Table 6 below shows the classification system of wind speeds selected for this study. These specific wind speed values were selected as they had been previously utilised in a study by Diab and Preston Whyte (1980).

Table 6: Classification of wind speeds for the purpose of this study.

Wind Speed (m/s)	Wind Speed Range
> 6	Very strong
≤ 6	Strong
≤ 4	Medium

Wind Speed (m/s)	Wind Speed Range
≤ 2	Gentle
≤ 1	Calm

Delta temperature was used as a proxy variable for mixing depth and atmospheric stability for each air pollution event was categorised into different classes as very strong, strong, medium or weak (refer to Table 7 below). If delta temperature was less than zero, then lapse conditions occurred and pollutants would be better dispersed vertically. These specific delta temperature values were selected as they had also been previously used in a study conducted by Preston Whyte and Diab (1980).

Table 7: Classification of inversion layers for the purpose of this study.

Inversion Strength	Temperature Inversion Range
Very strong	Temp $\Delta \geq 5\ ^0$C
Strong	Temp $\Delta \geq 3\ ^0$C and $\leq 5\ ^0$C
Medium	Temp $\Delta \geq 2\ ^0$C and $\leq 3\ ^0$C
Weak	Temp $\Delta \geq 0\ ^0$C and $\leq 2\ ^0$C

To identify any synoptic controls on the air pollution events, daily synoptic charts were obtained from the SAWS office at King Shaka International Airport (KSIA) and the Pietermaritzburg City Library.

4.2.1 CLASSIFICATION OF SYNOPTIC SCENARIOS AND RECORD OF COMMUNITY COMPLAINTS FROM THE SDCEA

The synoptic chart for the day each air pollution event occurred, and the days preceding and succeeding it, was sourced and analysed. This analysis revealed that the identified pollution events fell into one or more of the following three categories:

1. Pre-frontal air pollution event;
2. Low wind speed and weak inversion conditions;
3. Post-frontal pollution event;

In addition, the SDCEA register of reported air pollution events was analysed to determine whether these events coincided with those identified in this study. The complaints database obtained from SDCEA comprised the following information for each reported event:

- location
- date
- approximate time
- most likely polluter

4.2.2 DATA ANALYSIS

To meet the study objectives, it was necessary to clearly identify the prevailing synoptic conditions during each identified air pollution incident. As mentioned previously, daily synoptic charts were the first source of information. However, these did not provide the exact time at which a front passed over Durban. To determine the exact time, a careful analysis of various hourly meteorological variables was necessary. As a front passes over, one expects a number of meteorological changes. First, air temperature tends to drop. Second, atmospheric pressure decreases as the front approaches but increases once the front moves over. Third, one expects the inversion layer to strengthen as the front approaches and then to dissipate as the front passes over or, in other words, one expects an increase in delta temperature followed by a rapid decrease to delta temperature values below zero (Preston-Whyte and Diab, 1980). Finally, one expects winds to back towards the south-west as the front passes over and wind speeds to increase at the squall front. By screening the synoptic chart for the day of the pollution event, it was possible to roughly estimate the time that the front passed over Durban. Following this, a simple checklist was developed to narrow down the time of the passing of a cold front:

1) When does delta temperature peak followed by a sustained decrease?
2) When does wind speed increase?
3) When does wind back towards the south-west?
4) When does the atmospheric pressure minimum occur?

In many cases it was clear when the front passed over from the meteorological data. However, when discretion was required, the front was placed at the pressure minimum prior to the backing of the wind.

4.2.3 GRAPH INTERPRETATION

A specific graphical framework was developed to display the results of this study (see Figure 28 below as an example). PM_{10} and SO_2 concentration data are plotted with various meteorological variables. Each graph shows at least a three day period – the day on which the pollution event occurs, and then a day on either side of this incident. The estimate time of the passing of a cold front (as determined using the checklist described above) is shown by a vertical black line on the graph. The graph legend is found above the graph. 'PM_{10}' represents ambient PM_{10} concentrations; 'SO_2' represents ambient SO_2 concentrations. Concentration on the primary Y-axis refers to the concentration of SO_2 in ppb and PM_{10} in µg/m^3 as measured by the air quality monitoring stations. "Pressure" on the secondary Y-axis refers to atmospheric pressure in hectapascals (hPa). On a separate set of axis the same pollution data is plotted with "Delta Temperature" (in degrees Celsius) replacing pressure on the secondary y-axis. The X-axis of the graphs show time of day (hour), wind direction, and wind speed (m/s) respectively. For example '15–N–1.6' means the following:

- 15 = time of day which is 15h00;
- N = wind direction which in this case is northerly; and
- 1.6 = wind speed in m/s.

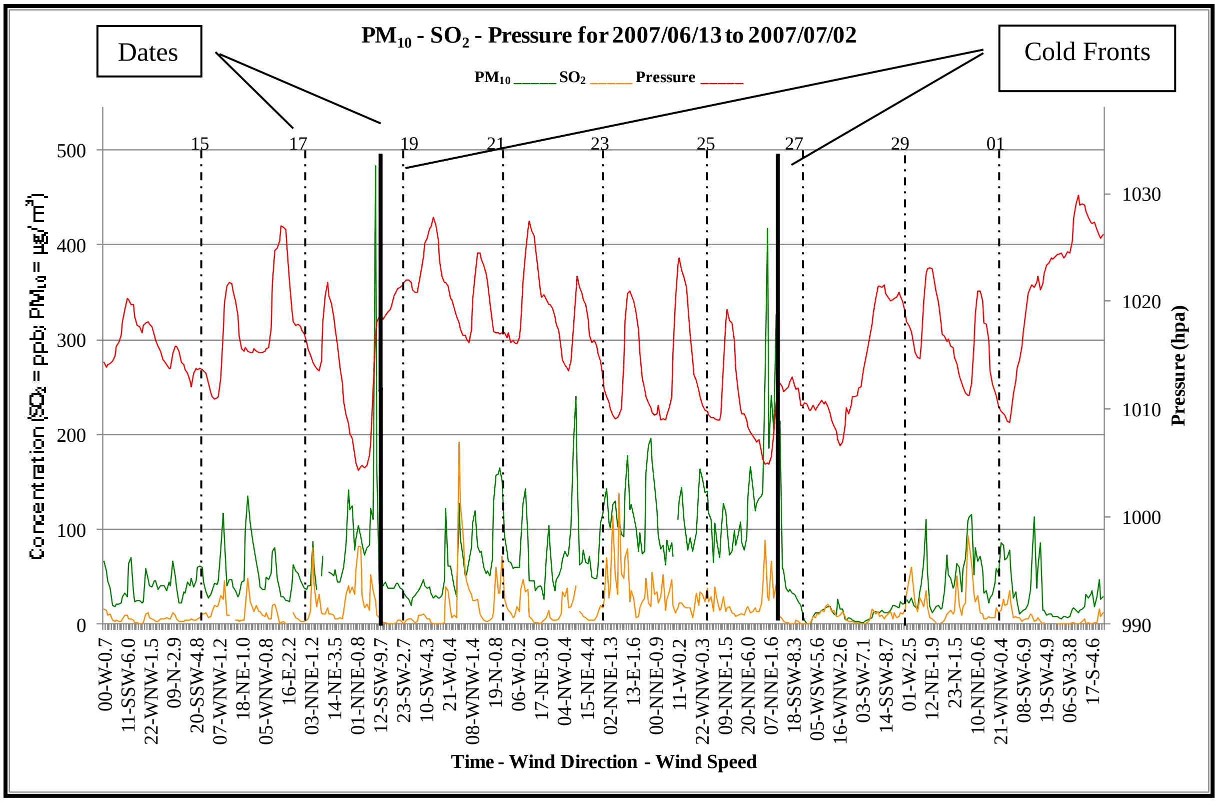

Figure 28: Example of PM_{10} and SO_2 relationship with air pressure for the period 13th July 2009 to 3th July 2007.

Of the 96 air pollution event days that were classified for the period 2006 to 2010, only the top ten air pollution event days were selected for detailed analysis. In Chapter 5 that follows, the description of events is arranged according to peak pollution concentration values with Day 1 as the event with the highest PM_{10} value across the record.

4.2.4 STATISTICAL ANALIYSIS

Statistical tests are used to assess relationships between variables or trends within datasets. To meet the objectives of this study, Pearson product-moment correlations, Analysis of Variance (ANOVA) and multivariate regression analyses were conducted. All analyses were conducted in SPSS Version 21.

4.2.4.1 PEARSON PRODUCT-MOMENT CORRELATION

This analysis quantifies the degree to which two variables are related. The Pearson's 'R' value between -1 and 1 indicates the degree of the relationship (Cohen *et al.*, 2003). The significance of each correlation was assessed using a two-tailed t-test.

4.2.4.2 ANALYSIS OF VARIANCE (ANOVA)

This statistical test assesses whether the means of several groups are equal, and therefore generalizes a t-test to more than two groups. Doing multiple two-sample t-tests would result in an increased chance of committing a type I error. For this reason, ANOVAs are useful in comparing the means of three or more variables. The F-ratio provided is calculated by dividing mean square between-groups by mean square within-groups. The significance of the F ratio is assessed by comparing the provided p-value with an alpha level (e.g. 0.05).

4.2.4.3 MULTIVARIATE REGRESSION

A multivariate regression analysis reveals the effect on one variable (dependent) from variations of several other potential explanatory variables (independent) (Denis, 2011). SPSS Version 21 was used to carry out multivariable regressions to determine whether air pollution concentrations in the DSB could be explained on the basis of meteorological variables and traffic levels. It was not possible to account for variations in industrial emissions due to lack of data. The larger industries, however, do not experience significant variations in their emissions unless operating under upset conditions or during start up.

Traffic data was sourced from the eThekwini Municipality for major intersections in the DSB. This data was analysed to determine periods of the day during which the highest and lowest levels of traffic are observed. Thereafter a coding system was developed to represent traffic levels associated with that time of day using values of 1 to 5 (1 = lowest traffic and 5 = highest traffic). Further analysis indicated that Saturday traffic values were half the weekday values, while Sunday traffic values were a quarter of the weekday traffic values. Table 8 below shows how traffic levels were classified for each hour of the day.

Table 8: Classification of traffic levels at different times of the weekday

Hour of the Day (Time)	Traffic Index Value
0h00	1
1h00	1
2h00	1
3h00	1
4h00	1
5h00	2
6h00	3
7h00	5
8h00	5
9h00	5
10h00	4
11h00	4
12h00	4
13h00	4
14h00	4
15h00	4
16h00	5
17h00	5
18h00	4
19h00	3
20h00	3
21h00	2
22h00	2
23h00	1

In the regression outputs the beta and standardised beta values reported for the independent variables provides a measure how strongly each independent variable influences the dependant variable. The standardised beta values allow for comparisons across variables as to the strongest explanatory variable. The R square (R^2) value is the square of the measure of correlation and indicates the proportion of the variance in the independent variables accounted for in the model. The variance inflation factor (VIF) was reported to assess multicollinearity between the explanatory variables. VIF provides an index of the amount that the variance of each regression coefficient is increased relative to a situation in which all of the predictor variables are uncorrelated (Cohen *et al.*, 2003).

4.3 CHAPTER SUMMARY

Chapter 4 provided a description of the monitoring networks operating in the DSB and in Cape Town. The types of data (pollution concentration and meteorological) used in the study as well as the source of each dataset were clearly outlined. The analytical approaches to assess these data were also presented. These approaches include graphical presentations of available data as well as multivariate statistical analyses to confirm any presumed relationships between variables. The statistical method used for an initial assessment of any relationships between the air pollution concentrations in Cape Town and Durban and traffic levels was the Pearson product-moment correlation, while the potential explanatory power of meteorological variables with respect to pollution concentrations in the DSB was assessed using a multivariate linear regression analysis.

A fire breaks out at Engen Refinery along Tara Road (SDCEA, 2009b).

5 RESULTS

This chapter presents the findings of this study. The PM_{10} and SO_2 data obtained from each selected monitoring station located in the Durban South Basin and Cape Town were analysed using the methodology described in the previous chapter. This chapter comprises six main sections. The first is an overview of the air pollution monitoring results recorded in the Durban South Basin and Cape Town for the period 2006 to 2010. This is followed by a graphical depiction of the DSB's top ten air pollution events and associated meteorology. These air pollution events are then classified into their associated meteorological scenario and their timing is assessed to determine whether they coincide with a reported pollution event or occur during peak traffic hours. Finally, a statistical assessment of possible predictor variables for elevated air pollution concentrations in the DSB is presented.

5.1 MONITORING RESULTS - DURBAN SOUTH BASIN

The SO_2 and PM_{10} concentrations recorded by the eThekwini monitoring stations in the DSB are graphically presented and compared against their respective NAAQS. This is to assess whether ambient pollutant levels exceed legislated standards in the DSB.

5.1.1 ANNUAL AVERAGE PM_{10} CONCENTRATIONS

Annual average PM_{10} concentrations from the Ganges, Wentworth and Southern Works stations for the period 2006 to 2010 are graphically presented in Figure 29 below. The current annual PM_{10} NAAQS of 50 µg/m^3 has also been plotted (red line) for comparison.

Key points to note from Figure 30 below include the following:

- The annual average PM_{10} concentrations recorded at each monitoring station for the period 2006 to 2010 demonstrate full compliance with the annual PM_{10} NAAQS.
- The Ganges station recorded the highest PM_{10} concentrations while the Southern Works station recorded the lowest for the period 2007 to 2010.
- A decreasing trend in annual average particulate matter concentrations is evident for the period of 2007 to 2010.

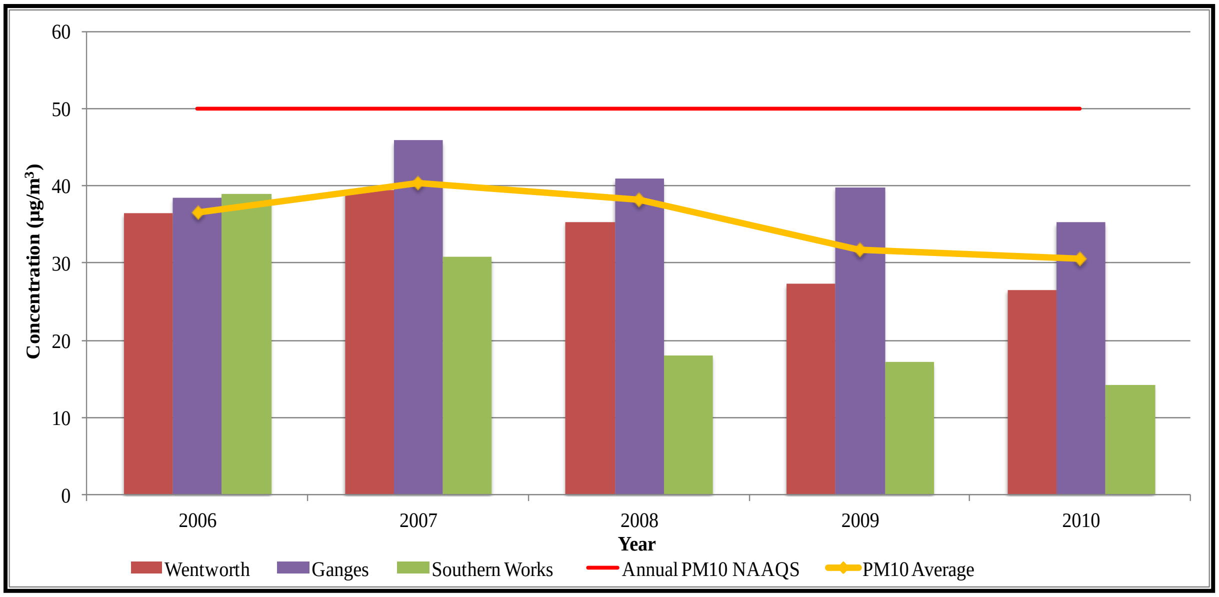

Figure 29: Graph showing annual average PM_{10} concentrations at three air quality monitoring stations in the DSB and the annual PM_{10} NAAQS.

5.1.2 ANNUAL AVERAGE SO_2 CONCENTRATIONS

Annual average SO_2 concentrations recorded at the Ganges, Wentworth and Southern Works stations for the period 2006 to 2010 are graphically presented in Figure 30 below. The current SO_2 annual NAAQS of 19 ppb has been plotted (red line) for comparison.

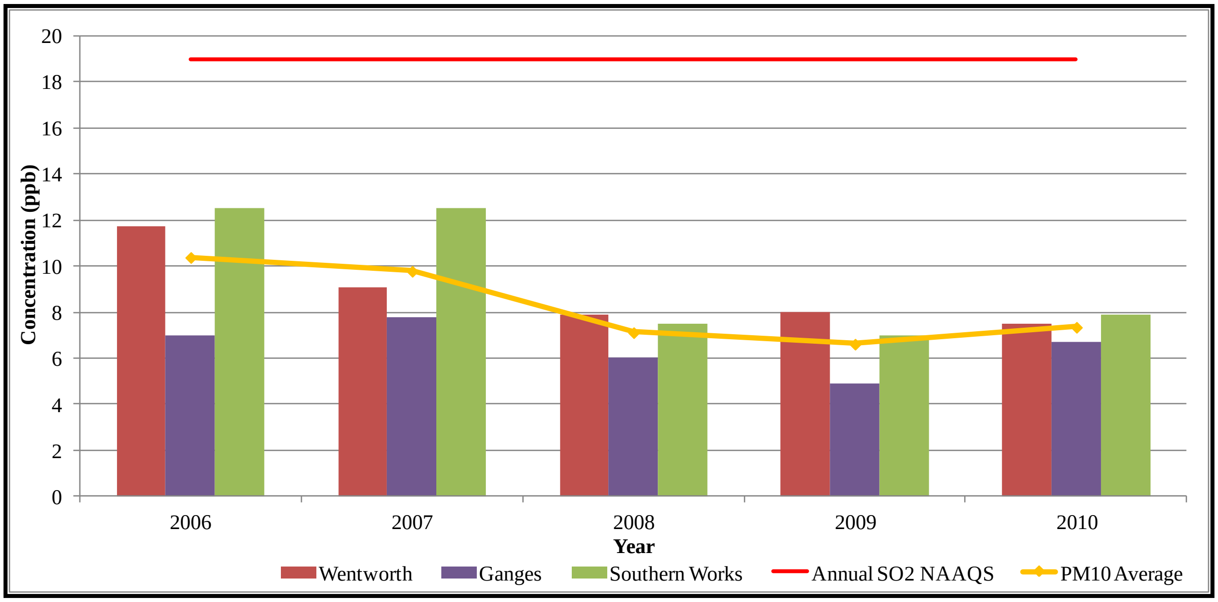

Figure 30: Graph showing annual average SO_2 concentrations at three air quality monitoring stations in the DSB and the annual SO_2 NAAQS.

Key points to note from Figure 30 above include the following:

- The annual average SO_2 concentrations measured at all stations for the period 2006 to 2010 are compliant with the annual SO_2 NAAQS.
- The lowest annual average SO_2 concentrations were recorded at the Ganges station from 2006 to 2010.
- Similar annual average SO_2 concentrations are recorded at the Wentworth and Southern Works stations.
- The yellow line shows a decreasing trend in SO_2 concentrations from 2006 to 2009, with a slight increase from 2009 to 2010.

5.1.3 24-HOUR AVERAGE PM_{10} AND 1-HOUR AVERAGE SO_2 CONCENTRATIONS

The graphs presented in Figure 1 to Figure 6 in Appendix A show the 24-hour averaged PM_{10} concentrations and hourly averaged SO_2 concentrations measured at the various monitoring stations in the DSB for the period 2006 to 2010.

Key points to note from these graphs are as follows:

- A clear seasonal variation in SO_2 and PM_{10} concentrations is evident in the monitoring records.

- The highest PM_{10} and SO_2 concentrations were recorded between May and August of each year of the study period (late autumn and winter).

The number of exceedences of the hourly SO_2 standard and the number of allowable exceedences (red line) in terms of the NAAQS are graphically presented below in Figure 31. The maximum number of times the hourly SO_2 standard is allowed to be exceeded is 88 times per annum under NEM:AQA.

Key points to note from Figure 31 below include:

- The number of SO_2 exceedences recorded at each monitoring station is less than the maximum allowable number of exceedences in terms of the NAAQS.
- The highest number of exceedences per annum occurred at the Southern Works monitoring station during 2006, 2007 and 2010.

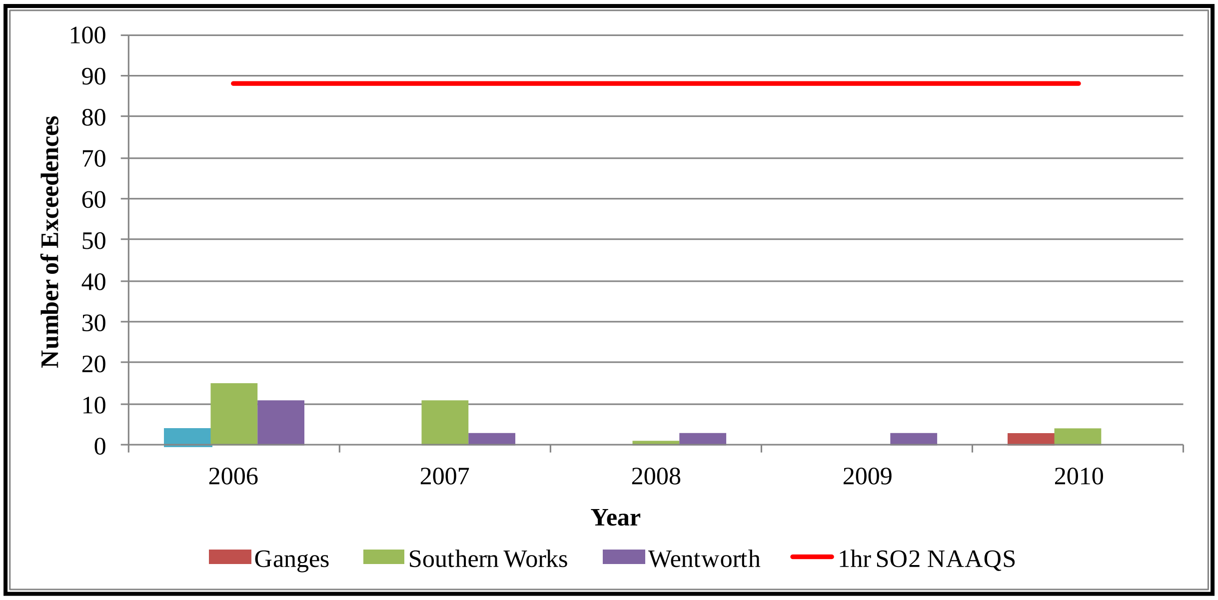

Figure 31: Graph showing number of SO_2 exceedences of the hourly standard at three air quality monitoring stations in the DSB for the period 2006 to 2010 and the number of allowable exceedences in terms of the NAAQS (red line).

The number of exceedences of the 24-hour PM_{10} standard and the number of allowable exceedences (red line) in terms of the NAAQS are graphically presented below in Figure 32. The maximum number of times the 24-hour PM_{10} standard is allowed to be exceeded is four times per annum under NEM:AQA.

Key points to note from Figure 32 below include:

- The total number of exceedences of the NAAQS measured at the Ganges station are 3, 11, 4 and 5 for 2006, 2007, 2008 and 2009 respectively. This is beyond the allowable number in 2007 and 2009.
- The total number of exceedences of the NAAQS measured at the Southern Works station was 1 in 2006 and 5 and 2007. This is beyond the allowable number in 2007.
- 1 exceedence of the NAAQS was observed at Wentworth station in 2006 and 2007.
- During 2010, no exceedences of the 24-hour NAAQS occurred at either station.

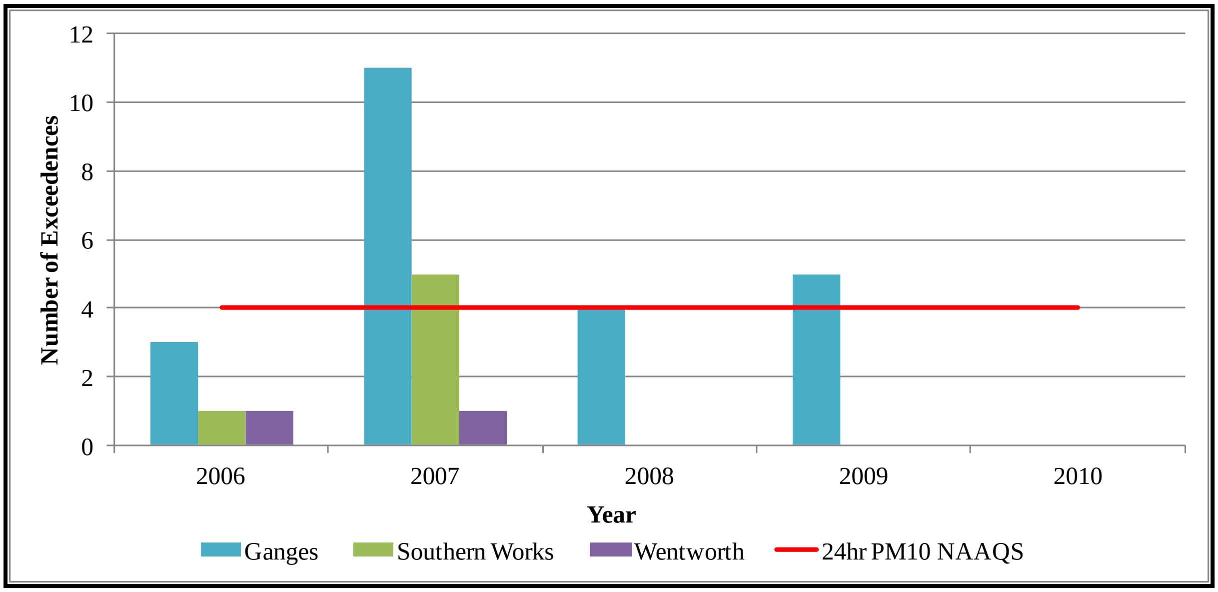

Figure 32: Graph showing the number of 24-hour average PM_{10} exceedences for the period 2006 to 2010 at three air quality monitoring stations in the DSB and the number of allowable exceedences in terms of the NAAQS (red line).

5.2 MONITORING RESULTS - CAPE TOWN

The SO_2 and PM_{10} concentrations recorded by each monitoring station in the City of Cape Town have been graphically presented and are assessed in the sections that follow.

5.2.1 ANNUAL AVERAGE PM_{10} CONCENTRATIONS

Annual average PM_{10} concentrations at the Goodwood, Bellville and Khayelitsha monitoring stations for the period 2006 to 2010 are graphically presented below in Figure 33. The annual PM_{10} NAAQS of 50 µg/m^3 has also been plotted as a red line for comparison purposes.

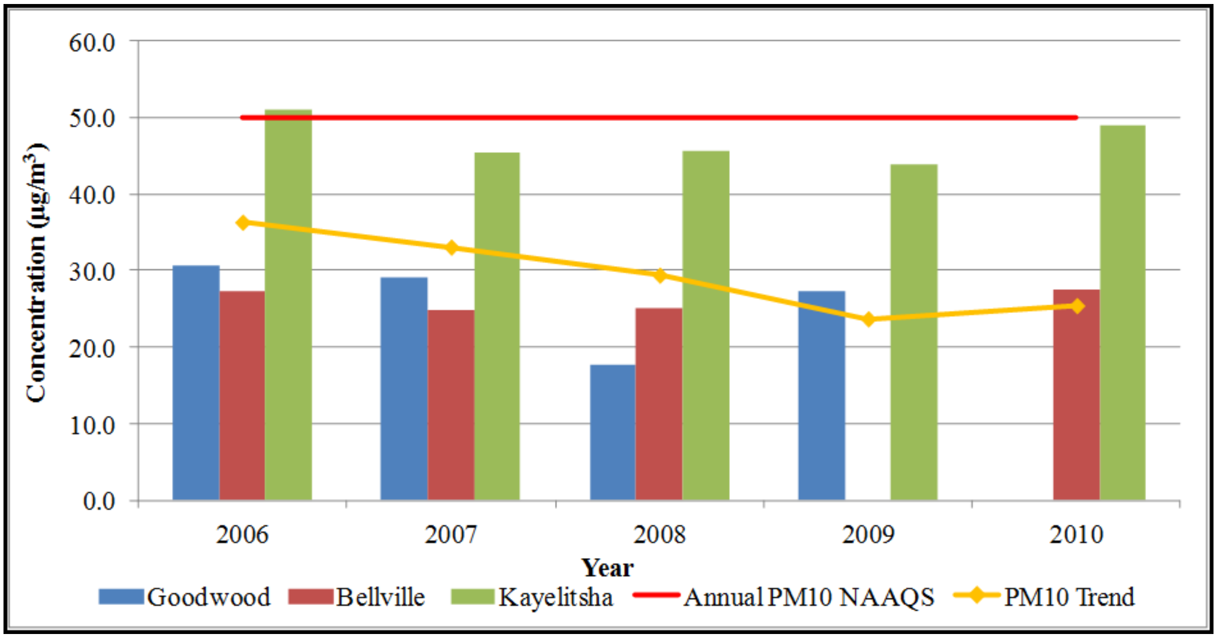

Figure 33: Graph showing annual average PM_{10} concentrations at three air quality monitoring stations in Cape Town and the annual PM_{10} NAAQS.

Key points to note from Figure 33 above:

- In 2006, the annual average PM_{10} concentration at the Khayelitsha monitoring station was in exceedence of the annual NAAQS. The Goodwood and Bellville monitoring stations showed compliance.
- For the period 2007 to 2010, all monitoring stations produced annual average PM_{10} concentrations that were below the annual PM_{10} NAAQS.
- Highest annual average PM_{10} concentrations were recorded at the Khayelitsha monitoring station for 2006 to 2010.

5.2.2 ANNUAL AVERAGE SO_2 CONCENTRATIONS

Annual average SO_2 concentrations at the Goodwood and Bellville monitoring stations for the period 2006 to 2010 are graphically presented below in Figure 34. The Khayelitsha monitoring station does not measure SO_2. The annual SO_2 NAAQS of 19 ppb has also been plotted (red line) for comparison.

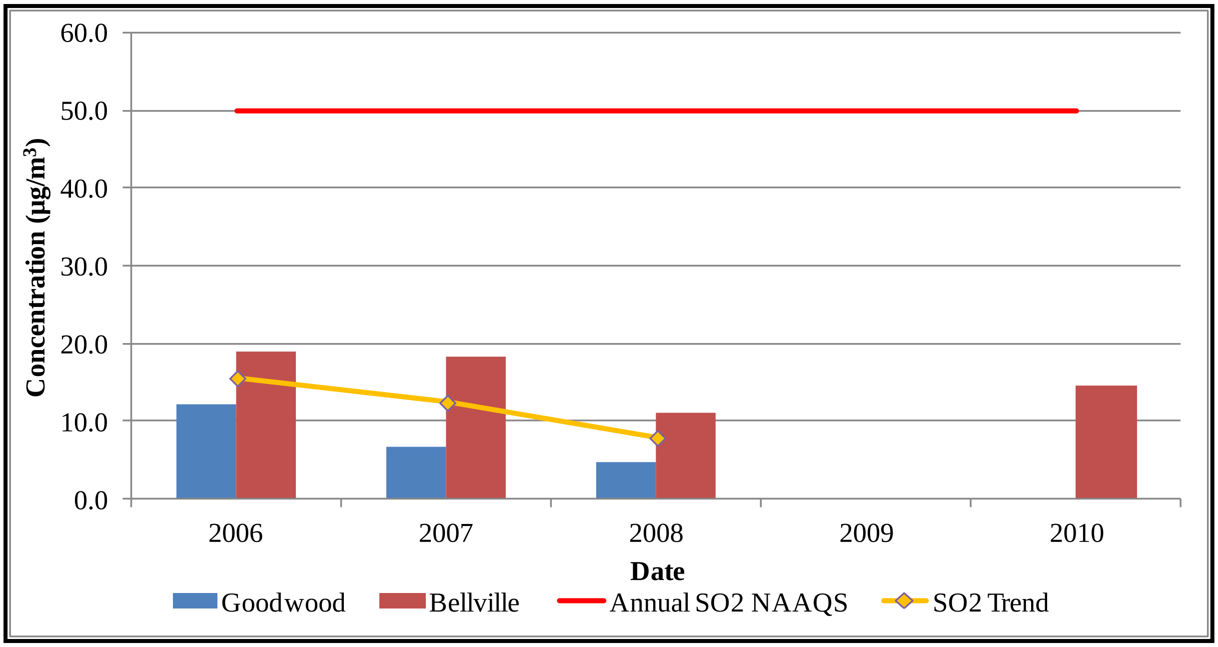

Figure 34: Graph showing annual average SO_2 concentrations at three air quality monitoring stations in Cape Town and the current annual SO_2 NAAQS.

Key points to note from Figure 34 above:

- Annual average SO_2 concentrations demonstrate compliance with the annual SO_2 NAAQS.
- The Bellville monitoring station measured higher SO_2 concentrations than the Goodwood station for the period 2006 to 2008.
- There is an overall decrease in SO_2 concentrations between 2006 and 2008.
- The Goodwood station was decommissioned for the period 2009 and 2010 while the Bellville station was decommissioned for 2009 only.

5.2.3 24-HOUR AVERAGE PM_{10} AND 1-HOUR AVERAGE SO_2 CONCENTRATIONS

Figure 7 to Figure 11 in Appendix A show the 24-hour PM_{10} concentrations and hourly SO_2 concentrations for the period 2006 to 2010 at the Cape Town monitoring stations.

Key points to note from Figure 7 to Figure 11 in Appendix A below are as follows:

- SO_2 concentrations at the Bellville and Goodwood monitoring stations show a clear seasonal pattern with higher average concentrations during winter.
- Whilst elevated PM_{10} concentrations were detected during winter, clear spikes in ambient concentrations also occurred during other parts of the year.

The number of exceedences of the hourly SO_2 NAAQS and the number of allowable exceedences (red line) in terms of the NAAQS are graphically presented below in Figure 35. The maximum number of times the hourly SO_2 standard is allowed to be exceeded is 88 times per annum under NEM:AQA. Key points to note from Figure 35 below include:

- The number of SO_2 exceedences recorded at each monitoring station was lower than the maximum allowable number of exceedences.
- More SO_2 exceedences occurred at the Bellville monitoring station than at the Goodwood monitoring station each year.

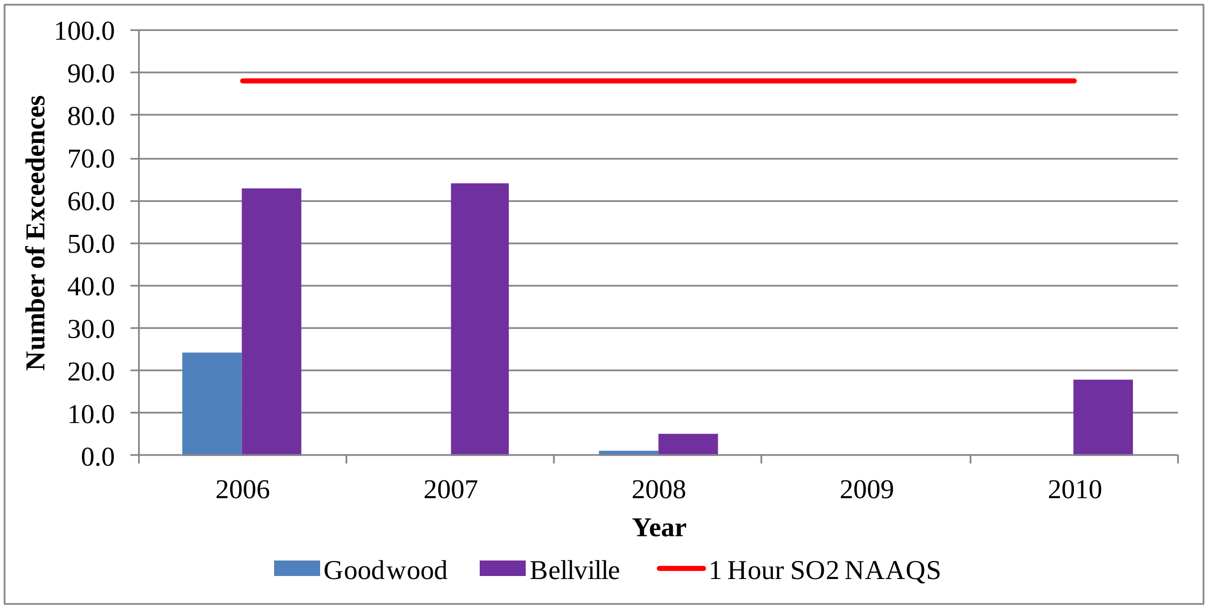

Figure 35: Graph showing the number of hourly SO_2 exceedences at three air quality monitoring stations in Cape Town for the period 2006 to 2010.

The number of times 24-hour average PM_{10} concentrations exceeded the hourly SO_2 standard as well as the permitted number of exceedences in terms of the NAAQS is shown in Figure 36 below. The maximum number of times the 24-hour PM_{10} standard is allowed to be exceeded in terms of the NAAQS is four times per annum.

Key points to note from Figure 36 below include:

- No 24-hour average PM_{10} exceedences were detected at the Goodwood and Bellville monitoring stations for the period 2006 to 2010.
- The Khayelitsha monitoring station detected 24-hour PM_{10} exceedences every year between 2006 and 2010. In 2006 and 2010, the total number of PM_{10} exceedences was 5 and 8 respectively, exceeding the permitted allowance at the site.

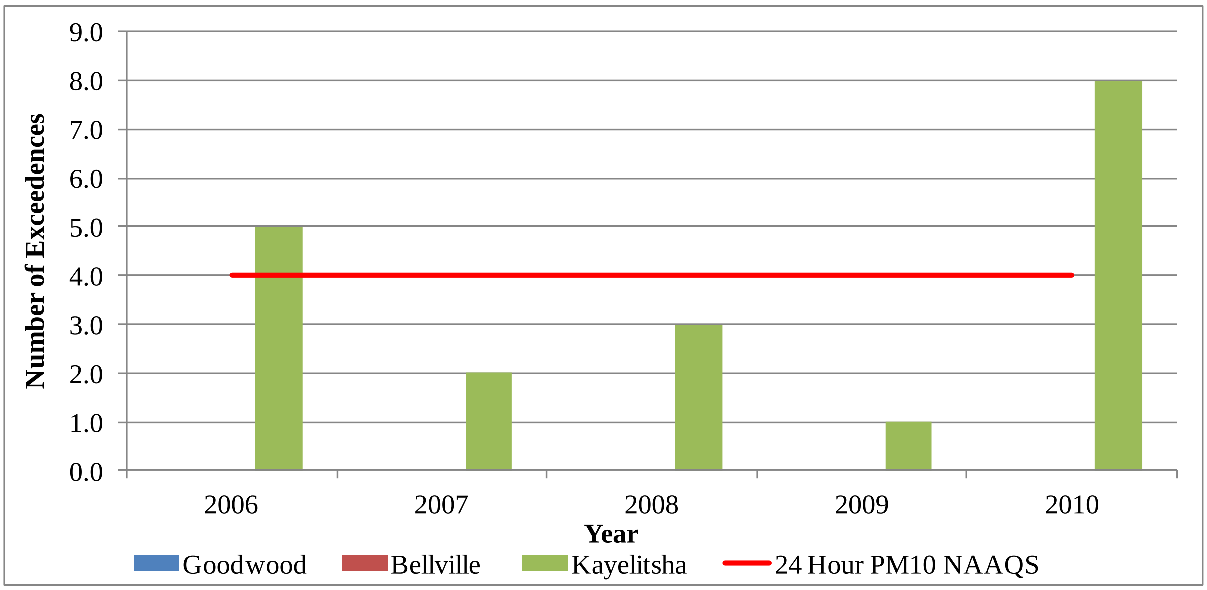

Figure 36: Graph showing the number of 24-hour average PM_{10} exceedences at three air quality monitoring stations in Cape Town for the period 2006 to 2010.

5.3 TOP TEN AIR POLLUTION EVENTS IN THE DSB BETWEEN 2006 AND 2010

The PM_{10} and SO_2 data obtained from the eThekwini Municipality from selected air pollution monitoring stations was analysed using the methodology described in the previous chapter. Only five SO_2 incidents (one at Ganges, two at Settlers and two at Southern Works monitoring station) were found to occur in the five year study period, none of which coincided with the PM_{10} incidents or with significant meteorological events. As mentioned in the methodology, a pollution incident is defined for the purposes of this study as at least three consecutive hours of pollution concentrations beyond the critical value (100 µg/m^3 for PM_{10} and 134 ppb for SO_2). It is suggested that these incidents were emission events, likely to correlate with upset process conditions at one of the key SO_2 emitters in the region (such as Engen, SAPREF or Mondi).

It is important to note that if a series of incidents were found to occur within 48 hours of a previous incident, then these were classed together as a single event. Events that comprised of two elevated peak concentrations separated by low values needed to be classed together as the first peak could have occurred due to a pre-frontal post subsidence inversion and the second peak could be due to post frontal (stack tip downwash) conditions (i.e. influenced by a single synoptic system. Furthermore, diurnal fluctuations can exacerbate or limit pollution peaks at certain times of the day. To limit subdivision of a single event as a result of midday pollution level troughs due to increased instability (for example), more than one set of peaks was combined with another if within 24 hours of each other.

The top ten PM_{10} events (in terms of peak concentrations from highest to lowest) were selected for detailed analysis and graphical presentation below. As such the top ten air pollution events discussed below lasted for varying durations until an hourly air pollution exceedence failed to occur in 48 hours since the last exceedence occurred. Some events contained more than one of the highest hourly values, but the top ten PM_{10} events (as opposed to top ten hourly concentrations) were selected for study. The following variables were analysed for the course of the event:

- wind speed;
- wind direction;
- pressure;
- delta temperature;
- time of day; and
- any reported emission events.

A description of each of these events now follows.

5.3.1 AIR POLLUTION EVENT 1 (16 AUGUST 2007) - WENTWORTH

This event includes the highest hourly averaged PM_{10} concentration (544.1 µg/m^3 at 10h00 on 16 August 2007) recorded across all air quality monitors over the period of this study. Elevated concentrations of PM_{10} above the defined threshold of 100 µg/m^3 prevailed from 04h00 to 14h00, except for the hours of 07h00 and 08h00 on this day. On 20 August 2007, elevated PM_{10} concentrations once again were above the hourly threshold between 02h00 and 11h00. Furthermore, on 21 August 2007, an undisrupted period of elevated PM_{10} concentrations above the hourly threshold occurred between 07h00 and 17h00. The monitoring station failed to record PM_{10} and SO_2 concentrations from 18h00 on 21 August 2007 until late evening of 22 August 2007. The daily PM_{10} averages for this air pollution event have been tabulated below. Table 9 shows that there were no exceedences of the 24-hour PM_{10} NAAQS over the duration of Event 1. All hourly SO_2 concentrations were compliant with the hourly SO_2 NAAQS of 134 ppb, with a peak value of 133.4 µg/m^3 at 03h00 on 20 August 2007. Figure 37 shows that SO_2 concentrations fluctuate in a similar pattern to the PM_{10} concentrations over this period.

Table 9: Daily averages for the period during which air pollution Event 1 had occurred

Date	Daily Average PM_{10} (µg/m^3)
2007/08/14	48.44
2007/08/15	36.81
2007/08/16	95.74
2007/08/17	26.25
2007/08/18	31.18
2007/08/19	61.98
2007/08/20	76.12
2007/08/21	113.89
2007/08/22	55.08
2007/08/23	72.56

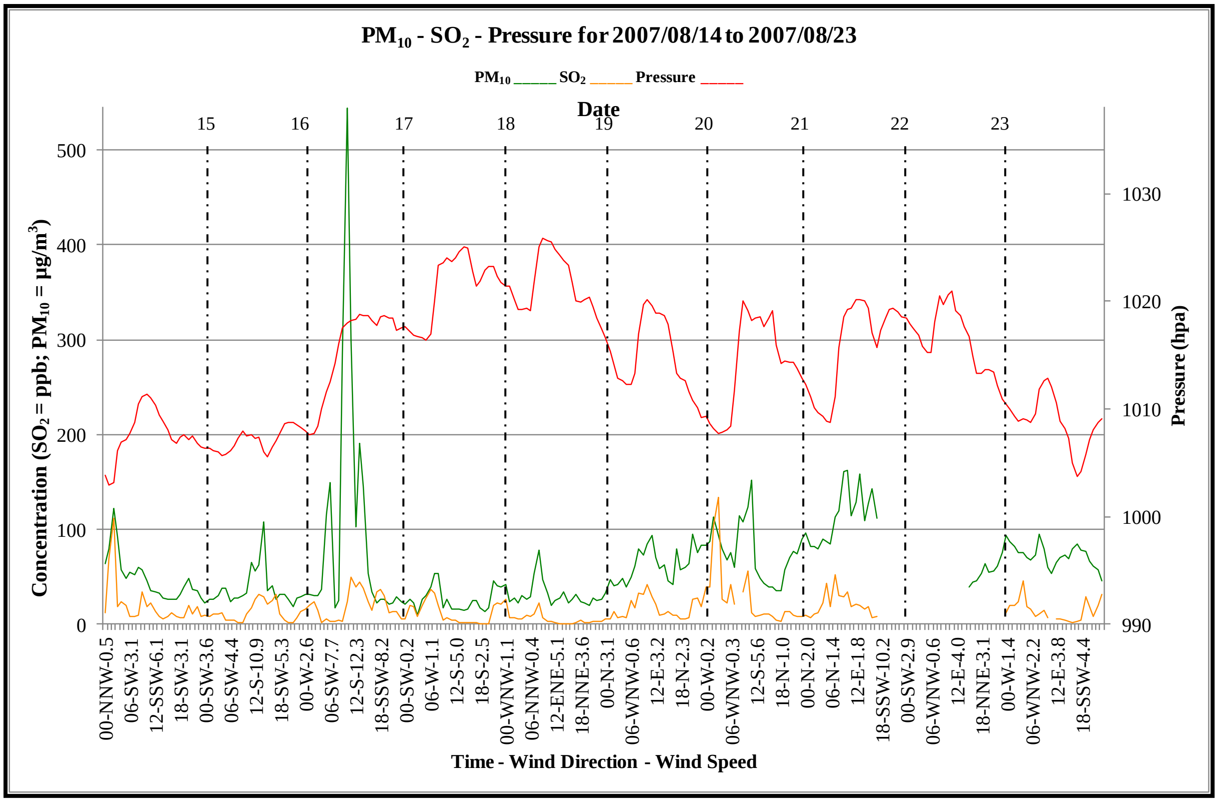

Figure 37: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Wentworth station with changes in pressure for period 14 August 2007 to 23 August 2007.

5.3.1.1 SYNOPTIC SITUATION

Daily synoptic charts for South Africa indicated that on 14 August 2007, two mid-latitude cyclones approached South Africa from the west while three coastal lows were evident along the east coast of South Africa. According to Tyson and Preston-Whyte (2004), coastal lows produce warm offshore airflow ahead of them and cool onshore airflow behind the system.

The wind shifts associated with coastal lows resemble those of a cold front, although meteorological changes are not usually as intense. However, the limited availability of synoptic charts (one for every 24-hour period) and the presence of the coastal lows mean that it was not possible to determine the exact timing of the passage of each cold front across Durban.

On 16 August 2007, PM_{10} concentrations exceeded the stated hourly threshold with the highest PM_{10} concentration recorded at 10h00. Unfortunately data pertaining to delta temperature is missing between 08h00 and 15h00 for this day and the relationship between the two cannot be fully determined (Figure 38 below). It is surmised that this air pollution event is the result of high emissions associated with rush hour traffic that morning combined with a narrowing of the atmospheric mixing layer as a cold front approached (Preston-Whyte and Tyson, 2004).

On 20 and 21 August 2007 a coastal low is evident along the east coast of South Africa. This coastal low caused barometric pressure to drop and delta temperature to increase. At midday on 20 August 2007 and during the morning and well into the afternoon of 21 August 2007, hourly PM_{10} concentrations were found to exceed the hourly PM_{10} threshold adopted for this study. However the concentrations at these times were not as extreme as those measured two days prior.

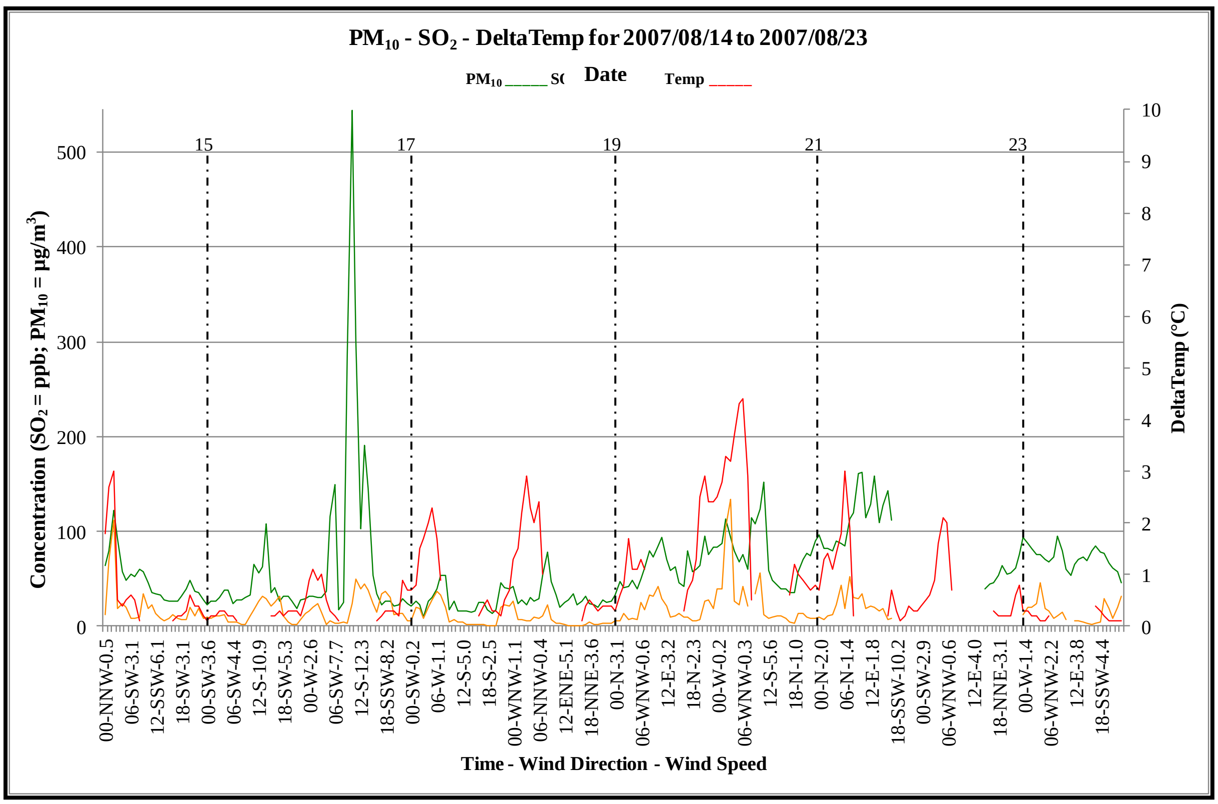

Figure 38: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Wentworth station with changes in delta temperature for the period 14 August 2007 to 23 August 2007.

5.3.2 AIR POLLUTION EVENT 2 (18 JUNE 2007) - WENTWORTH

Event 2 occurred between 13 June 2007 and 2 July 2007. The second highest hourly PM_{10} value in the study dataset (483.7 µg/m^3) occurred at 10h00 on the 18 June 2007. On 26 June 2007 another very high PM_{10} concentration (417.7 µg/m^3) was measured. Between these two major PM_{10} exceedences, there were numerous other hourly PM_{10} exceedences of the 100 µg/m^3 threshold value as defined for this study.

The 24-hour average PM_{10} concentrations for each day during Event 2 have been tabulated below. Exceedences of the 24-hour PM_{10} NAAQS of 120 µg/m^3 have been highlighted in red. On 23 and 26 June 2007 the 24-hour average PM_{10} concentrations were in exceedence of the 24-hour PM_{10} NAAQS due to sustained periods of elevated hourly average concentrations.

Table 10: Daily averages for the period during which air pollution Event 2 had occurred.

Date	24-hour Average PM_{10} (µg/m^3)
2007/06/13	36.53
2007/06/14	43.47
2007/06/15	57.67
2007/06/16	47.35
2007/06/17	64.70
2007/06/18	85.72
2007/06/19	40.04
2007/06/20	88.36
2007/06/21	67.08
2007/06/22	84.01
2007/06/23	**123.29**
2007/06/24	103.34
2007/06/25	104.59
2007/06/26	**127.66**
2007/06/27	11.29

Date	24-hour Average PM_{10} ($\mu g/m^3$)
2007/06/28	11.30
2007/06/29	34.63
2007/06/30	61.25
2007/07/01	37.57
2007/07/02	18.66

5.3.2.1 SYNOPTIC SITUATION

A review of the synoptic charts for this period shows cold fronts traversing the east coast of South Africa and reaches Durban on 18, 26 and 30 June 2007. The effects that these cold fronts had on air pressure, delta temperature and air pollution concentrations are evident in Figure 39 and Figure 40 below. There is decreasing air pressure and increasing delta temp as the front approaches, and then the backing of the wind and increase in wind occurs as the front passes over Durban. Increases in ambient PM_{10} are evident as the front approaches (but with a clear diurnal cycle), followed by a sudden pollution peak either as the front passed over, or immediately after the front passed (due to the resolution of the data it is difficult to pinpoint the exact time of the front passing). These peaks are likely to be associated with stack tip downwash as wind speeds reached levels beyond critical wind speed of 3.5 - 4.5 m/s as described by Diab *et al* (2002). In addition to these peak values, a number of high PM_{10} concentrations are evident that coincide with peak traffic hours in the morning (07h00 and 09h00), likely also influenced by morning surface inversion conditions and/or fumigation conditions as the surface inversion is eroded from the bottom up after sunrise (*cf.* Diab *et al.* 2002). Once the cold fronts traverse across Durban, a lifting of the inversion layer facilitates air pollution dispersion (Diab and Preston-Whyte, 1980) in the region as is evident in the lower concentrations within a few hours of the passing of each front in Figure 39 below.

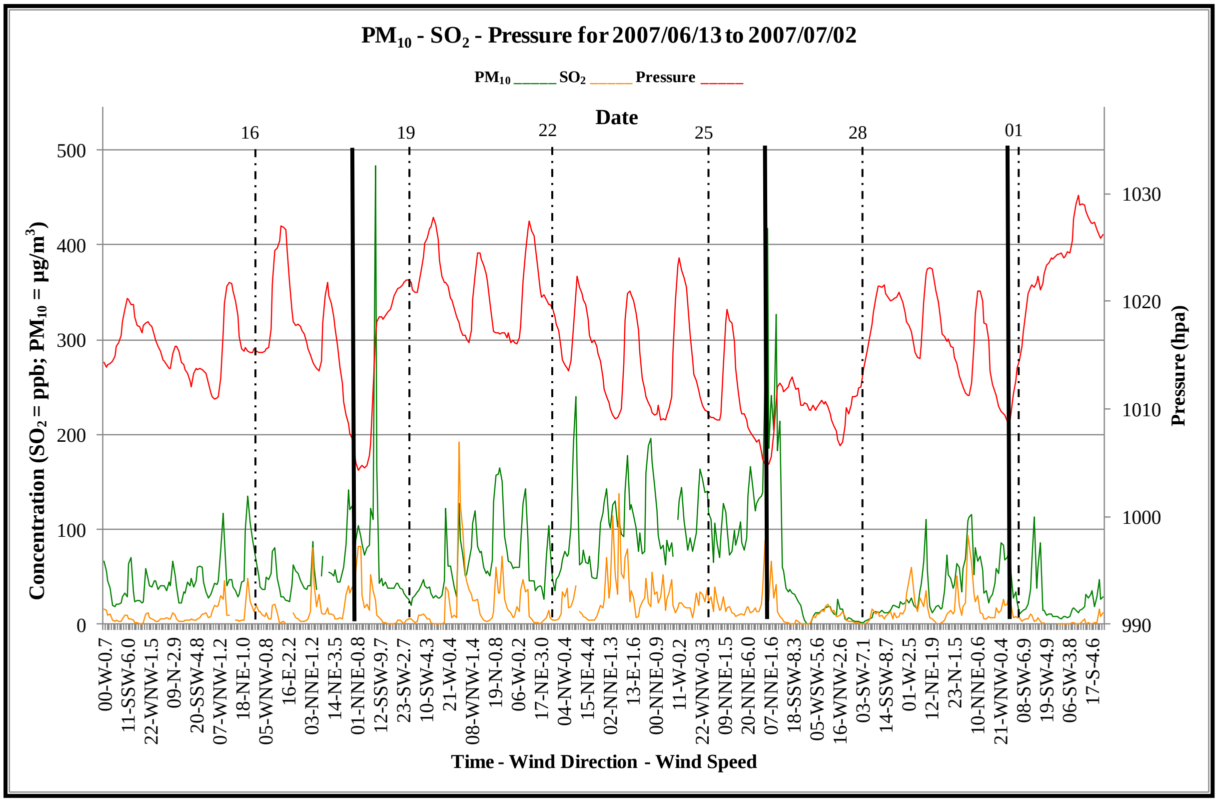

Figure 39: Graph showing relationship of hourly SO_2 and PM_{10} concentrations at Wentworth station with changes in pressure for period 13 June 2007 to 02 July 2007. The vertical black lines represent the cold fronts.

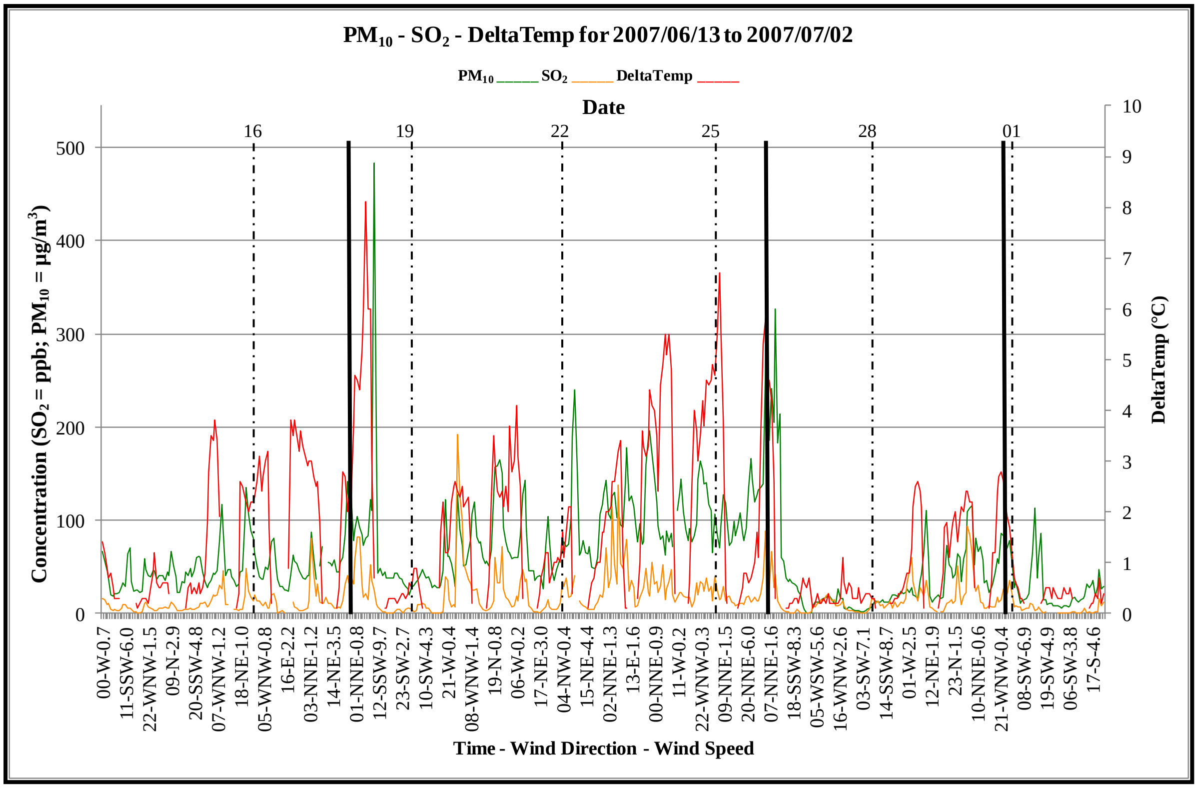

Figure 40: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Wentworth station with changes in delta temperature for the period 13 June 2007 to 02 July 2007. The vertical black lines represent the cold fronts.

5.3.3 AIR POLLUTION EVENT 3 (10 JULY 2009) - GANGES

The third highest PM_{10} concentration recorded by the DSB monitoring stations was 453.1 µg/m^3 at 21h00 on 10 July 2009. Table 11 below presents the daily average PM_{10} concentrations for this air pollution event (period 30 June 2009 to 14 July 2009). Exceedences of the 24-hour PM_{10} NAAQS of 120 µg/m^3 have been highlighted in red. Daily average PM_{10} concentrations between 09 July 2009 and 11 July 2009 were non-compliant with the 24-hour NAAQS. Elevated concentrations occurred on 2 July 2009 and 3 July 2009 but were compliant with the 24-hour NAAQS.

Table 11: Daily averages for the period during which air pollution Event 3 had occurred.

Date	Daily Average PM_{10} (μg/m^3)
2009/06/30	43.51
2009/07/01	63.92
2009/07/02	99.30
2009/07/03	102.69
2009/07/04	48.45
2009/07/05	41.43
2009/07/06	84.12
2009/07/07	57.81
2009/07/08	82.71
2009/07/09	**180.64**
2009/07/10	**205.20**
2009/07/11	**158.68**
2009/07/12	67.84
2009/07/13	42.57
2009/07/14	30.58

The hourly SO_2 data remains below the NEM:AQA guideline of 134 ppb with the highest value (63.8 ppb) over this period recorded at 08h00 on 09 July 2009.

5.3.3.1 SYNOPTIC SITUATION

The synoptic chart for 9 July 2009 shows a family of three mid-latitude cyclones approaching South Africa. The South Indian High was situated over the east coast of southern Africa and shifted easterly away from the coastline on 10 July 2009 as the cold fronts approached. The synoptic charts for the period 10 July 2009 to 13 July 2009 reveal the weakening and merging of two of the lows. During early morning of 12 July 2009, a cold front reached Durban with the South Atlantic high ridging over the southern parts of South Africa. Unfortunately wind speed and direction data is missing for this period but the pressure minimum is evident at this time (Figure 41). Figure 42 below shows a strengthening of the inversion (increasing delta temperatures) as the lows slowly approached Durban, followed by a rapid decrease in delta temperature (i.e. lifting of the inversion) as the cold front passed over.

Prior to arrival of the cold front, strong inversions are evident but with a clear diurnal cycle. Interestingly, the highest air pollution concentration defining this event was recorded at 21h00 on 10 July 2007 did not occur during the strongest inversion conditions or at a pressure minimum. This suggests that this event could be attributed to an emission event (possibly an industrial emission event) that coincided with stable atmospheric conditions and gentle wind speeds. The missing wind speed and direction parameters have resulted in errors (99 and 99.0) along the x-axis.

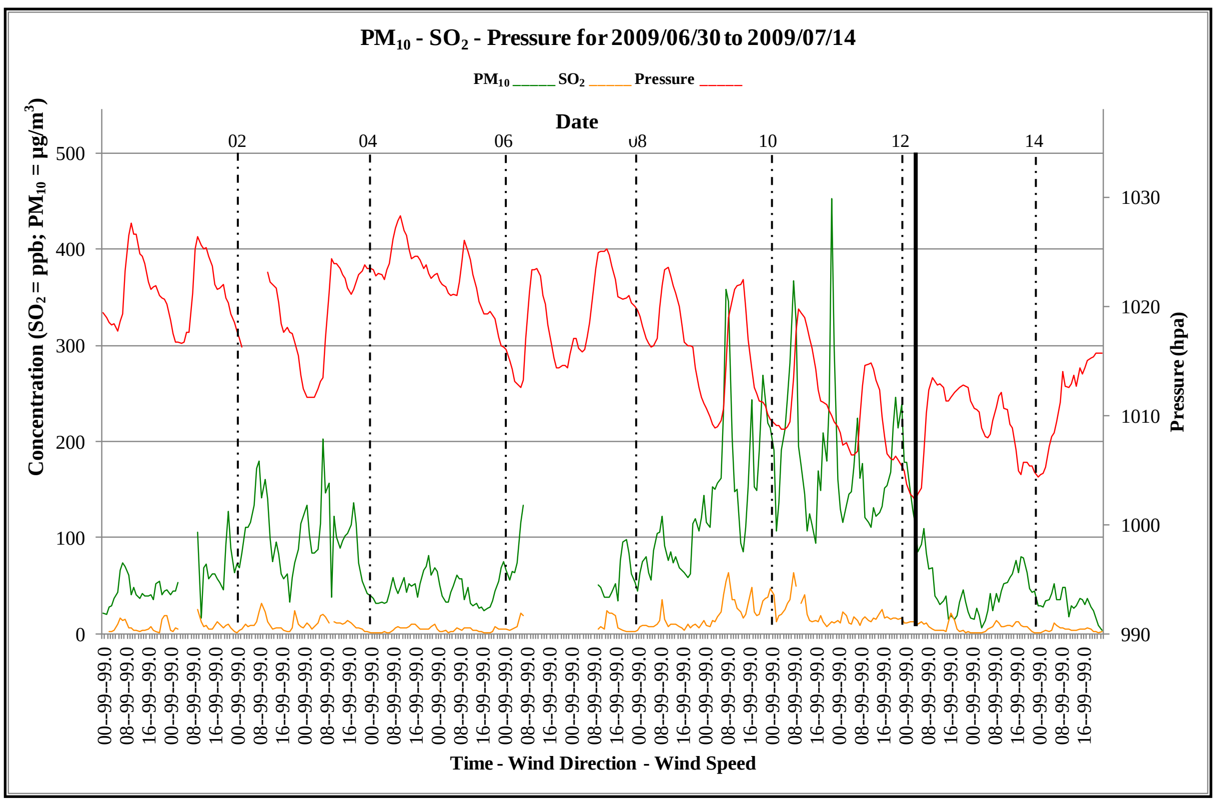

Figure 41: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in pressure for period 30 June 2009 – 14 July 2009. The vertical black line represents the cold front.

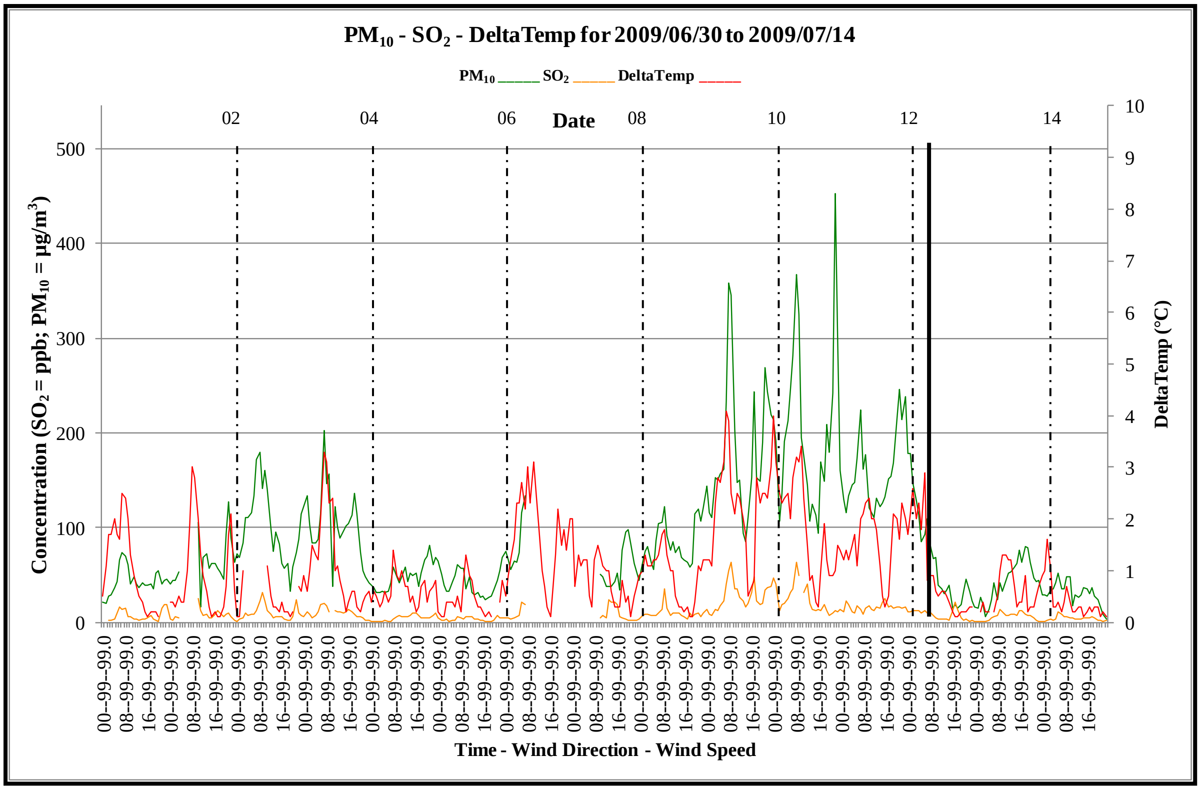

Figure 42: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in delta temperature for the period 30 June 2009 - 14 July 2009. The vertical black line represents the cold front.

5.3.4 AIR POLLUTION EVENT 4 (26 JULY 2008) - WENTWORTH

The fourth highest hourly PM_{10} concentration detected over the five year study period was 420 µg/m^3 at 02h00 on 26 July 2008 at Wentworth. Many other exceedences of the hourly PM_{10} threshold occurred around the duration of this peak. Table 12 below presents the 24-hour average PM_{10} concentrations. Exceedences of the 24-hour PM_{10} NAAQS (120 µg/m^3) are highlighted in red. The highest 24-hour average PM_{10} concentration of 121.38 µg/m^3 was recorded on 31 July 2008 and was above the 24-hour NAAQS for PM_{10}.

Table 12: Daily averages for the period during which air pollution Event 4 had occurred.

Date	24-hour Average PM_{10} (µg/m^3)
2008/07/20	54.67
2008/07/21	46.65
2008/07/22	78.50
2008/07/23	65.54
2008/07/24	45.87
2008/07/25	73.68
2008/07/26	82.26
2008/07/27	79.69
2008/07/28	28.62
2008/07/29	41.17
2008/07/30	96.56
2008/07/31	**121.38**
2008/08/01	48.27
2008/08/02	40.41
2008/08/03	23.74
2008/08/04	25.70
2008/08/05	74.44
2008/08/06	36.67
2008/08/07	54.32

SO_2, concentrations remain below the hourly NAAQS of 134 ppb with the highest value (118.9 ppb) occurring at 07h00 on 23 July 2008. The SO_2 concentrations can be seen to fluctuate with PM_{10} concentrations in Figure 43 and Figure 44 below.

The effect of pollution concentrations with fluctuations in atmospheric pressure and the passage of cold fronts are shown in Figure 43 below. Delta temperature data was missing for the period

20 July 2008 to 01 August 2008 and therefore the effect of this meteorological variable on air pollution concentrations could not be assessed.

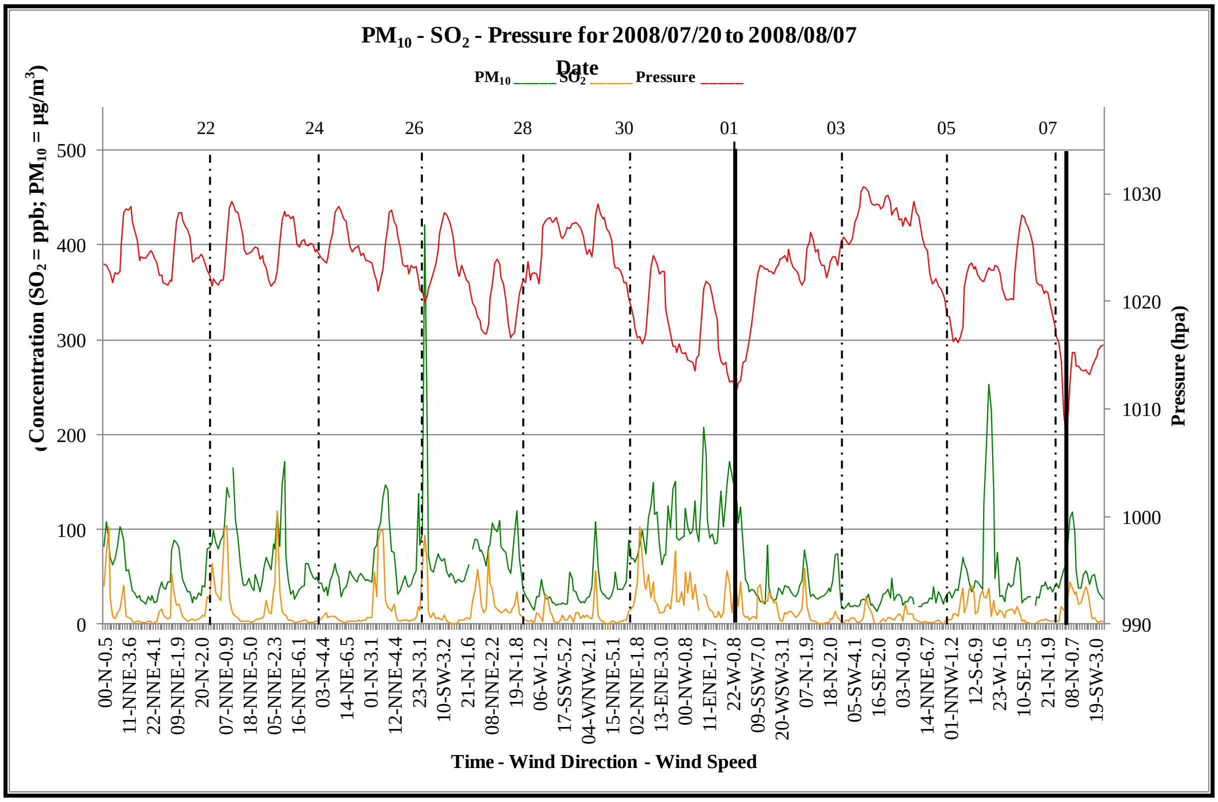

Figure 43: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges Station with changes in pressure for period 20 July 2008 to 07 August 2008. The vertical black lines represent cold fronts.

5.3.4.1 SYNOPTIC SITUATION

On 25 July 2008, two cold fronts passed over Cape Town and weakened as they travelled towards Durban. The synoptic chart for 26 July 2008 showed a weak coastal low over Port Elizabeth and a dominant South Indian High extending over the eastern interior of the country. The pollution peak of 420 µg/m^3 at 02h00 on 26 July 2008 does not coincide with the passing of a front. It is suggested that this peak is the result of an industrial emission event under a stable scenario (unfortunately this cannot be assessed further due to the lack of delta temperature data). On 30 July 2008, a weak coastal low is evident over Durban, with a cold front approaching Port

Elizabeth and another approaching Cape Town. On 31 July 2008, the coastal low remained over Durban while the two approaching cold fronts weakened. Light north-easterly winds prevailed over Durban and delta temperature was high, indicating limited vertical mixing. These conditions resulted in the numerous hourly PM_{10} exceedences as well as an increase in SO_2 concentrations over this period. The first cold front had passed over Durban at 01h00 on 01 July 2008 resulting a lifting of the inversion layer and pollution concentrations to decrease.

On 07 August 2008, another coastal low is evident over Durban together with a cold front following closely behind. Air pressure is seen to decrease while delta temperatures increases, indicating increased stability, with gentle winds, limiting the horizontal dispersion of air pollutants. However, pollutant concentrations are not particularly high over this period. At 07h00 the cold front passed over Durban, causing south-westerly winds and a subsequent increase in air pressure. At this point, PM_{10} levels decrease with an increased dispersion potential.

Graph presented overleaf

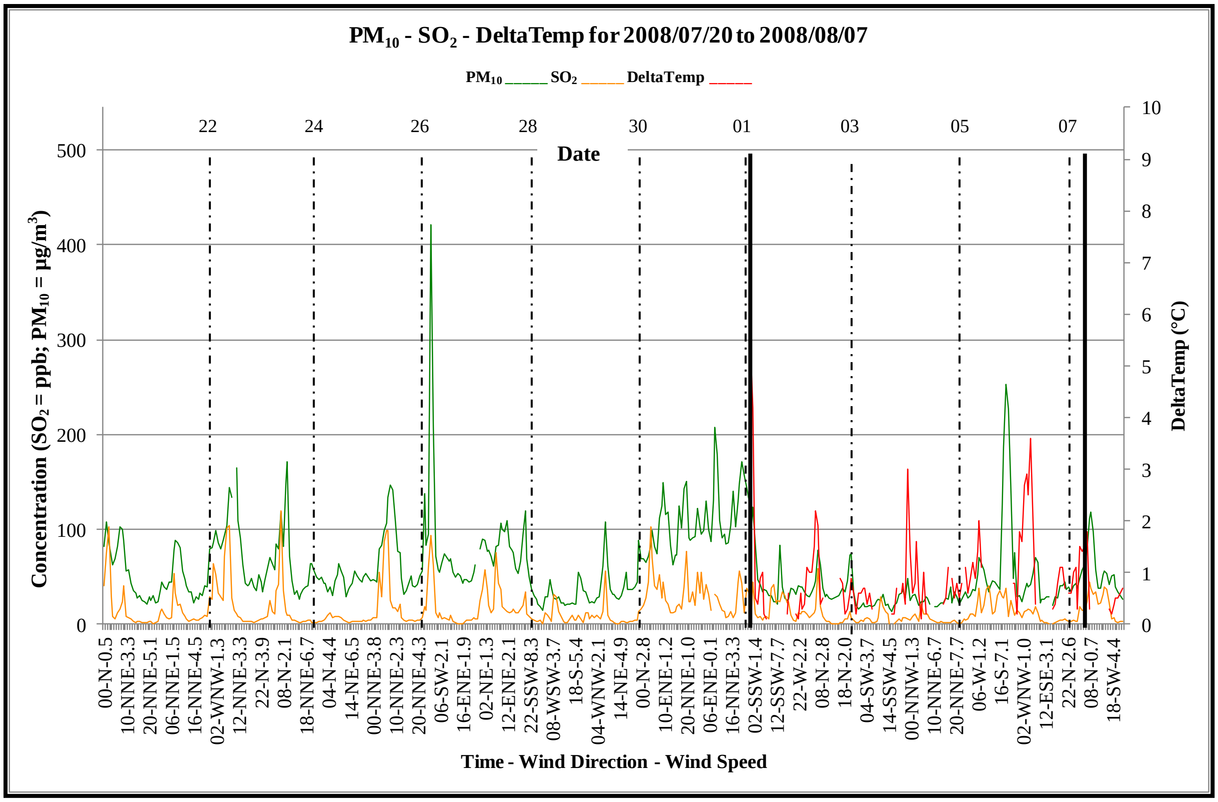

Figure 44: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in delta temperature for the period 20 July 2008 to 07 August 2008. The vertical black line represents the cold front.

5.3.5 AIR POLLUTION EVENT 5 (12 JULY 2006) - WENTWORTH

Between 10 and 15 July 2006 numerous exceedences of the hourly PM_{10} threshold were recorded by the Wentworth station. The fifth highest hourly PM_{10} concentration of 388.5 µg/m^3 was recorded at 20h00 on 12 July 2006. The hourly SO_2 concentration at this time was 151 ppb and was therefore above the hourly SO_2 NAAQS. The 24-hour average PM_{10} concentrations over the duration of event 5 are presented in Table 13 below. Exceedences of the 24-hour PM_{10} NAAQS of 120 µg/m^3 are highlighted in red. As evident in Table 13 below, 24-hour PM_{10} concentrations on 11 and 12 July 2006 are in exceedence of the 24-hour NAAQS. SO_2 concentrations follow a similar trend to PM_{10} concentrations as shown in Figure 45 and Figure 46 that follow.

Table 13: Daily averages for the period during which air pollution Event 5 had occurred.

Date	24-hour Average PM_{10} ($\mu g/m^3$)
2006/07/03	47.72
2006/07/04	46.41
2006/07/05	79.69
2006/07/06	83.53
2006/07/07	43.74
2006/07/08	35.34
2006/07/09	62.79
2006/07/10	82.23
2006/07/11	**120.68**
2006/07/12	**164.12**
2006/07/13	70.08
2006/07/14	75.48
2006/07/15	70.76
2006/07/16	39.71
2006/07/17	56.15

5.3.5.1 SYNOPTIC SITUATION

On 5 and 6 of July 2006 elevated PM_{10} concentrations in exceedence of the hourly threshold were measured at the Wentworth monitoring station. The synoptic chart for 5 July 2006 shows a cold front approaching Cape Town as well as a coastal low travelling along the south coast of South Africa towards Durban. As these systems approached Durban, air pressure decreased and wind speeds increased. Positive delta temperatures were recorded indicating inversion conditions and increased potential for an air pollution event as seen in Figure 46 below. At 20h00, winds backed to a south-westerly direction and increased in speed as the cold front passed over Durban, enhancing horizontal dispersion of air pollutants in the DSB.

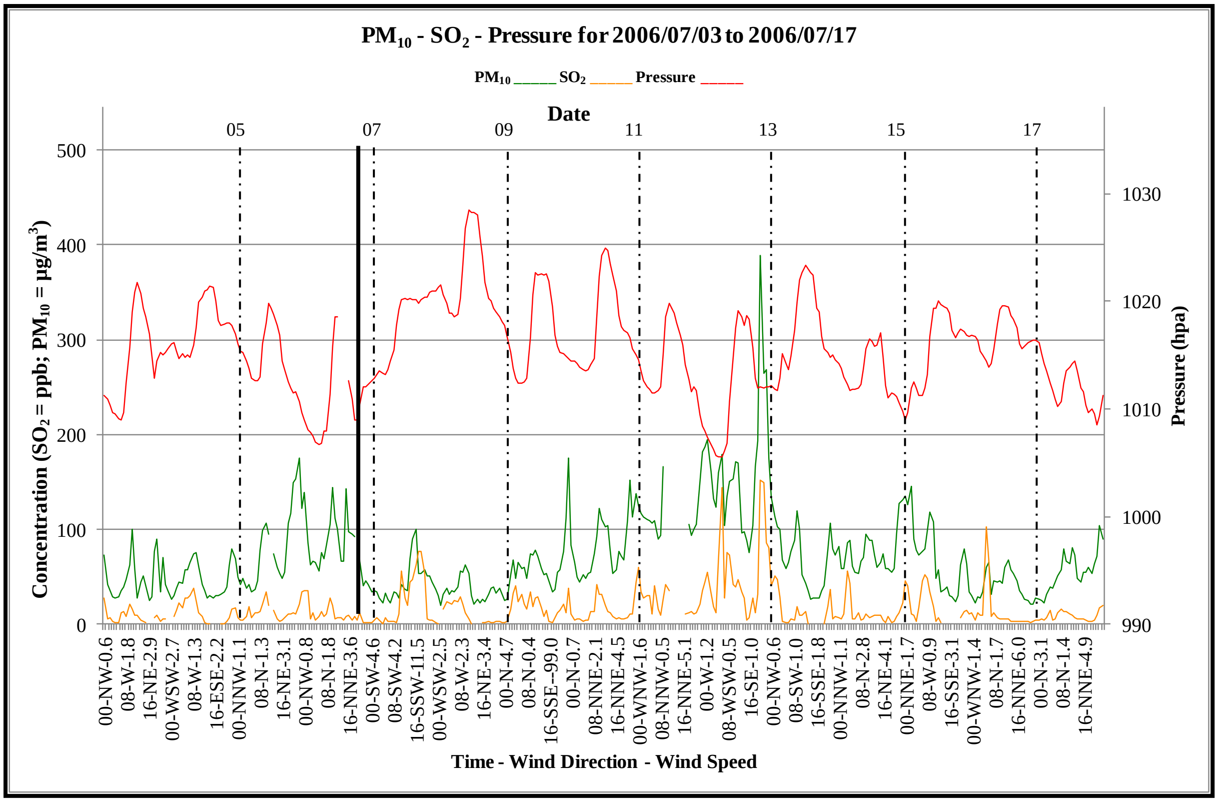

Figure 45: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in pressure for period 03 July 2006 to 17 July 2006. The vertical black line represents the cold front.

As mentioned above, the fifth highest hourly PM_{10} concentration was recorded at 20h00 on 12 July 2006. A review of the synoptic chart for the period before this event shows a cold front approaching Cape Town and a coastal low travelling up the coast towards Durban. Gentle wind speeds and increasing delta temperatures over Durban (Figure 45 and Figure 46) resulted in high air pollution potential. As such, this fifth highest hourly PM_{10} concentration was most likely due to an emission event which coincided with these unfavourable dispersion conditions.

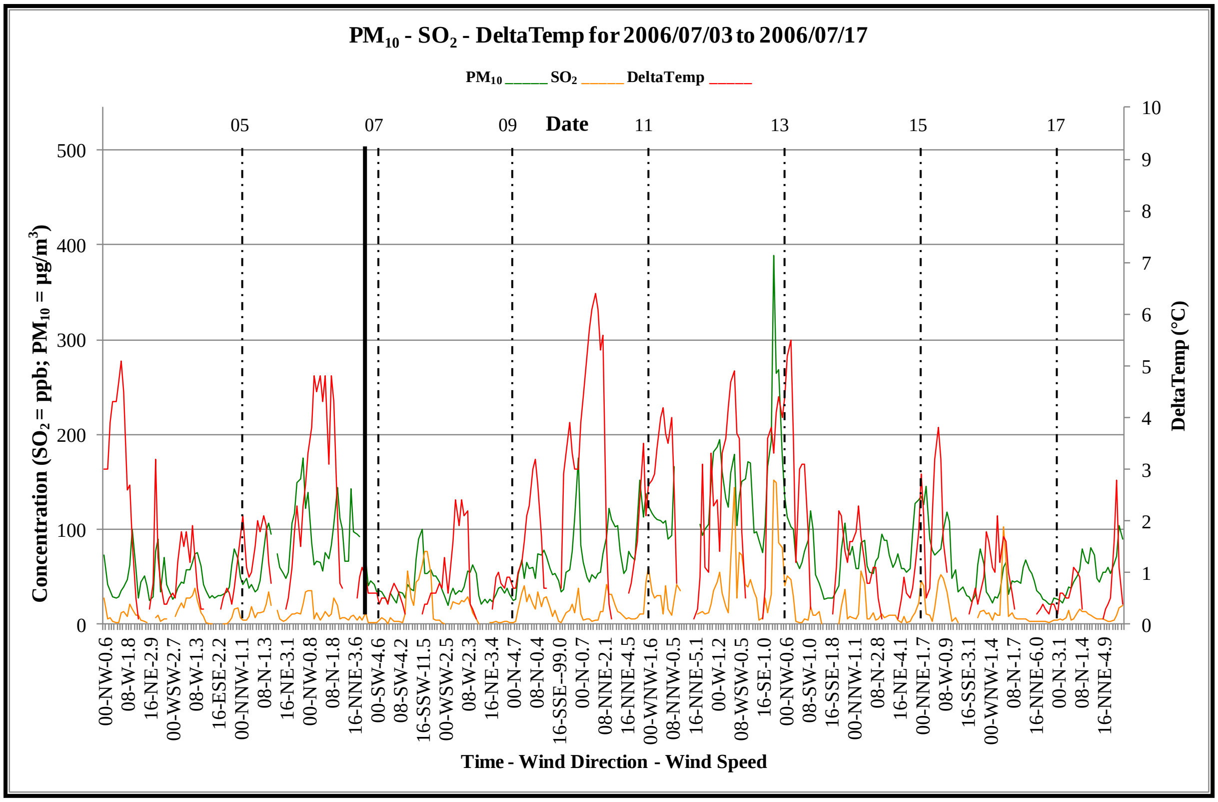

Figure 46: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in delta temperature for the period 03 July 2006 to 17 July 2006. The vertical black line represents the cold front.

5.3.6 AIR POLLUTION EVENT 6 (15 JULY 2008) - WENTWORTH

The sixth highest hourly PM_{10} concentration (380 µg/m^3) was recorded at the Wentworth station at 09h00 on 15 July 2008. This PM_{10} concentration is higher than the hourly threshold defined in this study. Table 14 presents the 24-hour PM_{10} concentrations recorded on each day over the duration of this Event. No exceedences of the 24-hour NAAQS occurred over the duration of this event.

Table 14: Daily averages for the period during which air pollution Event 6 had occurred.

Date	24-hour Average PM_{10} ($\mu g/m^3$)
2008/07/13	29.66
2008/07/14	48.57
2008/07/15	103.59
2008/07/16	62.56
2008/07/17	30.52
2008/07/18	36.40

The highest 24-hour PM_{10} concentrations were recorded on 15 and 16 July 2008. SO_2 concentrations follow a similar trend to the PM_{10} concentration. On 14 July 2008, at 06h00 SO_2 concentrations peaked to 219.5 ppb above the NAAQS.

5.3.6.1 SYNOPTIC SITUATION

The synoptic charts for this period show a cold front approaching Cape Town and a coastal low moving towards Port Elizabeth on 15 July 2008. It is surmised that this air pollution event in the DSB formed as a result of a combination of the strengthening of the subsidence inversion as the front approached, and emissions during the peak morning traffic period. Furthermore by 09h00 erosion of night-time surface inversion from the bottom up due to surface heating may have resulted in a fumigation situation (*cf.* Diab *et al.* 2002). SO_2 and PM_{10} concentrations decrease during the course of that day due to strong north-easterly winds that promote dispersion, but increase again as the front approaches. At 05h00 on 16 July 2008, the wind direction changed to south-westerly, wind speeds increased and air pressure began to increase, indicating that the cold front had passed over Durban. A dip in PM_{10} concentrations was followed by a post-frontal peak, likely due to stack tip downwash. Data showing delta temperature was missing for this event and could not be assessed further.

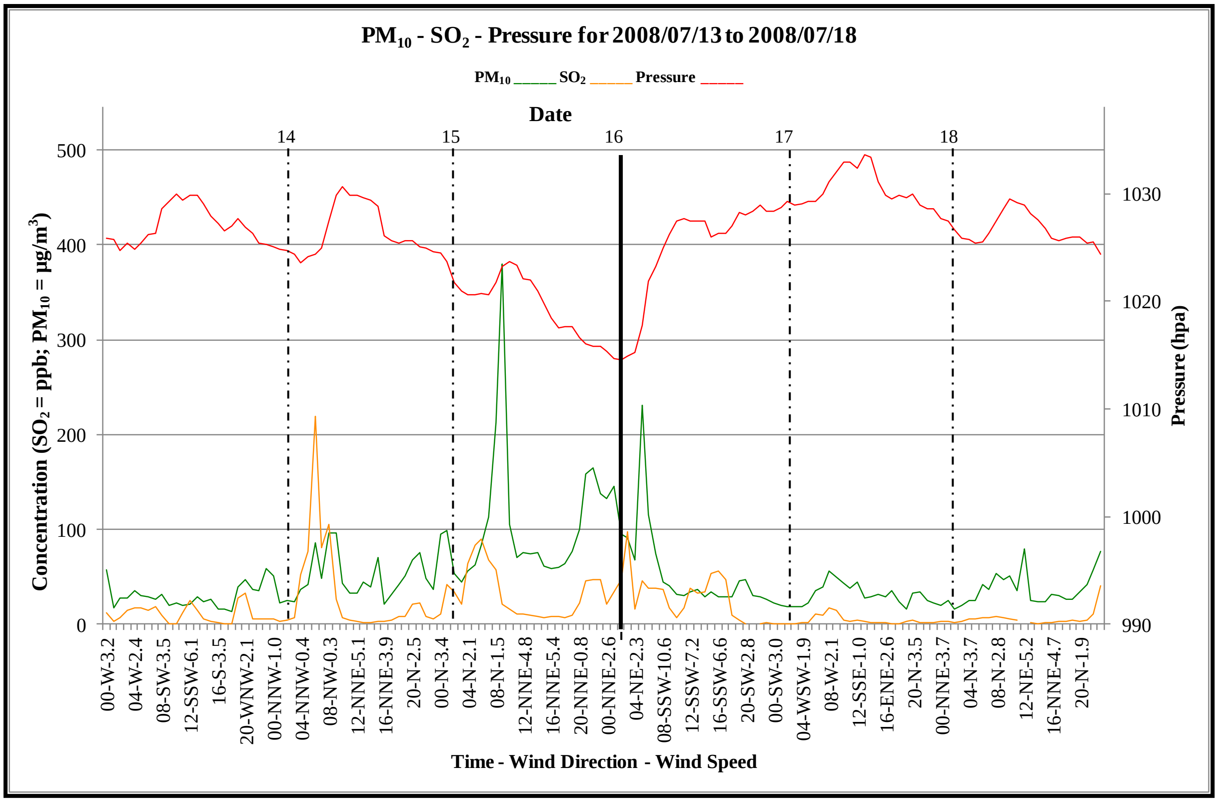

Figure 47: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Wentworth station with changes in pressure for period 13 July 2008 to 18 July 2008. The vertical black line represents the cold front.

5.3.7 AIR POLLUTION EVENT 7 (8 JULY 2008) - GANGES

The seventh highest air pollution value was recorded at 09h00 on 8 July 2008 when hourly PM_{10} concentrations peaked 375.2 µg/m^3. Prior to this peak, numerous other hourly PM_{10} exceedences of the 24-hour NAAQS had occurred on 2, 4 and 7 July 2008. Table 15 below presents the 24-hour average PM_{10} concentrations for the period 30 June 2008 to 10 July 2008. The red value indicates non-compliance against the NAAQS.

Table 15: Daily averages for the period during which air pollution Event 7 had occurred.

Date	24-hour Average PM_{10} ($\mu g/m^3$)
2008/06/30	34.41
2008/07/01	41.03
2008/07/02	86.64
2008/07/03	66.60
2008/07/04	82.67
2008/07/05	47.23
2008/07/06	55.55
2008/07/07	102.83
2008/07/08	**151.57**
2008/07/09	32.16
2008/07/10	34.51

Figure 48 below shows that SO_2 concentrations follow a similar trend to PM_{10} concentrations. The highest hourly average SO_2 concentration over this period was recorded at 09h00 on the 8 July 2008, coinciding with the PM_{10} peak. All hourly averaged SO_2 concentrations over this period were compliant with the hourly SO_2 NAAQS of 134 ppb.

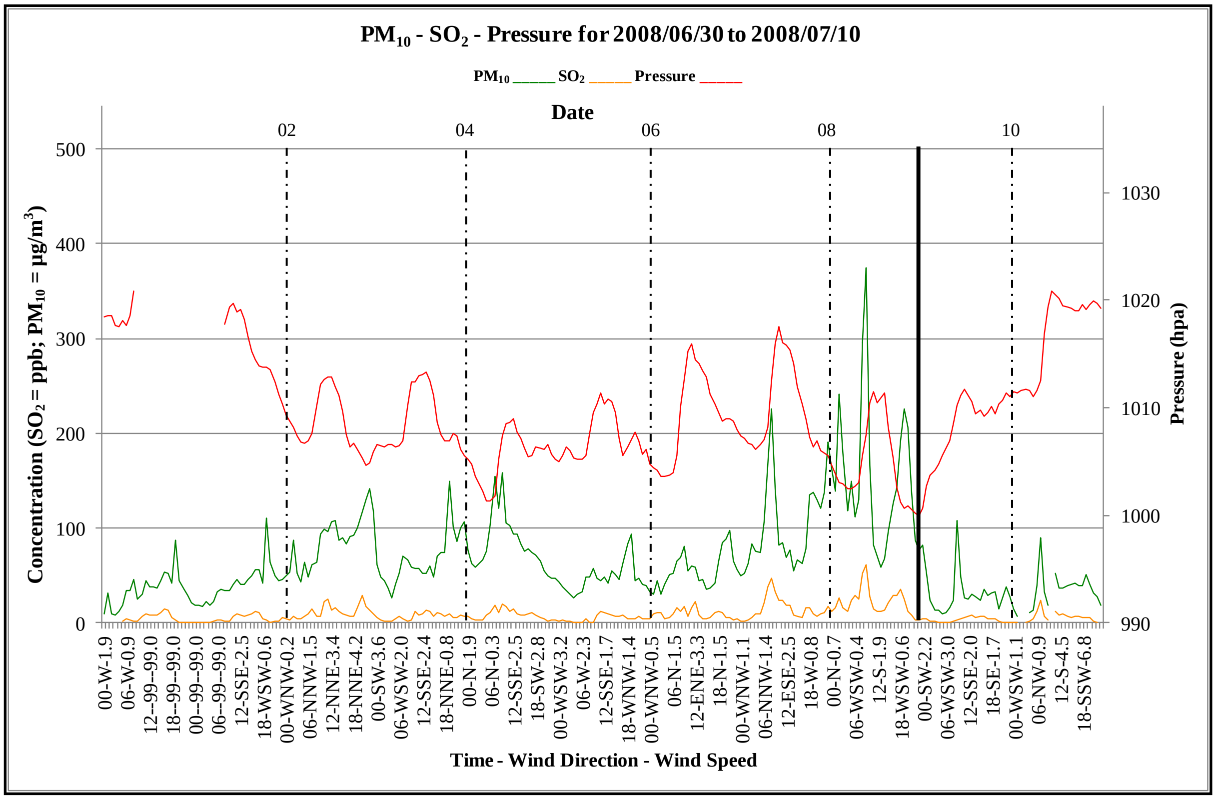

Figure 48: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in pressure for period 30 June 2008 to 10 July 2008. The vertical black lines represent cold fronts.

5.3.7.1 SYNOPTIC SITUATION

The synoptic chart for 2 July 2008 reveals a coastal low approaching Durban with a minimum air pressure of 1008 hPa and a cold front with a steep pressure gradient approaching the west coast of South Africa. At around midnight, the coastal low passes over Durban and winds back from a north-easterly to a south-westerly direction. Air pressure begins to increase and PM_{10} concentrations decrease. By 03 July 2008, the coastal low has shifted away from the east coast of South Africa and air pressure over Durban has increased.

On the morning of 4 of July 2008 a pre-frontal coastal low is seen over Durban and increasing delta temperatures are evident as the front approached Durban. This indicates increased atmospheric stability and thus air pollution potential in the DSB. The cold front passed over

Durban at some point on 5 July 2008 and its exact timing of its passing is not clear from the meteorological data available.

Another cold front travels over the west coast of South Africa and reaches the east coast on 7 July 2008. However, the South Indian High is seen ridging across the east coast and the cold front weakens. The weakened cold front traverses Durban on 8 July 2008.

Figure 49 below shows high delta temperatures prior to the front but with a clear diurnal cycle. The pollution peak at 09h00 on 8 July 2008 is likely the result of the strengthening of the subsidence inversion as the front approached and high emissions during the peak morning traffic period. The passing of the front sees a decrease in air pollution potential due to lower delta temperatures and increased wind speeds.

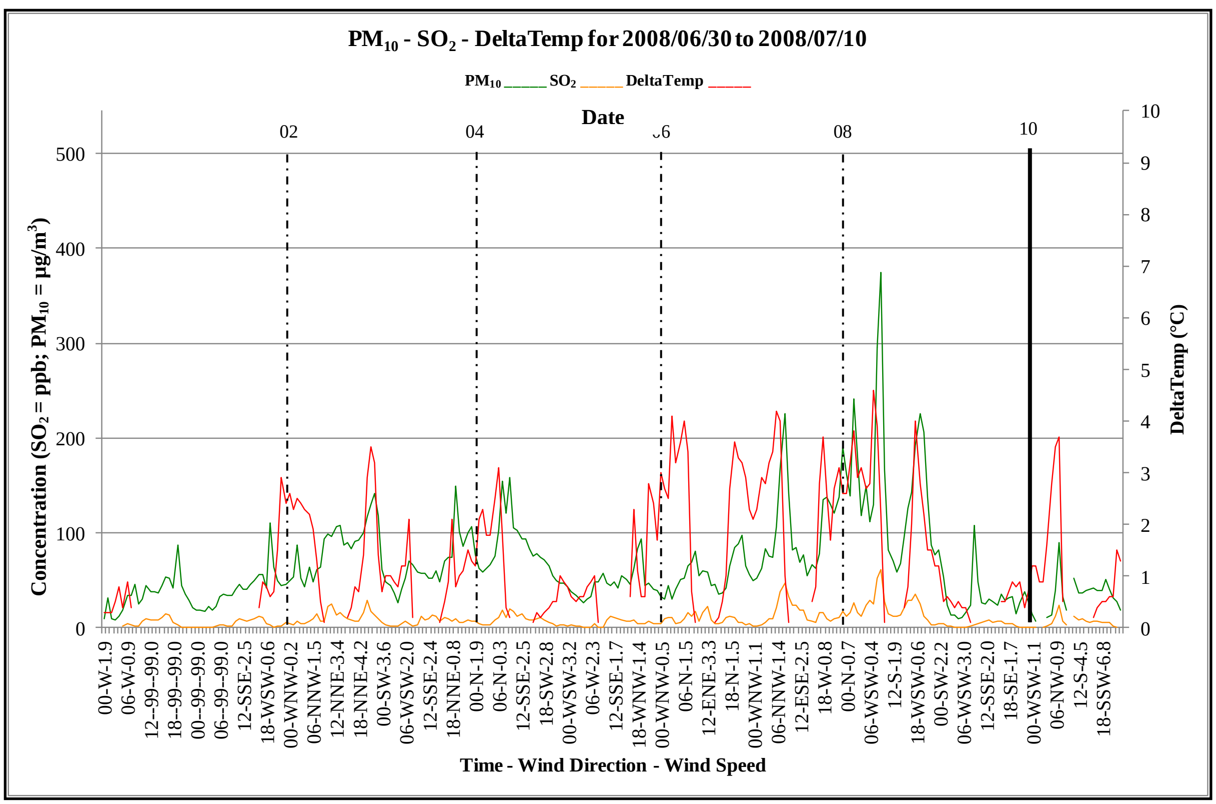

Figure 49: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in delta temperature for the period 30 June 2008 to 10 July 2008. The vertical black lines represent cold fronts.

5.3.8 AIR POLLUTION EVENT 8 (26 JUNE 2007) - GANGES

The eighth highest hourly average air pollution concentration occurred on 26 June 2007 at 08h00 when PM_{10} concentrations peaked at 373.0 µg/m^3. Prior to this peak however, numerous other exceedences of the hourly PM_{10} threshold were detected. The 24-hour average PM_{10} concentrations for the period 15 June 2007 to 28 June 2007 are presented in Table 16 below. Between 23 June 2007 and 26 June 2007, 24-hour PM_{10} concentrations were non-compliant with the 24-hour NAAQS (red values).

Table 16: Daily averages for the period during which air pollution Event 8 had occurred.

Date	24-hour Average PM_{10} (µg/m^3)
2007/06/15	54.22
2007/06/16	53.72
2007/06/17	76.92
2007/06/18	99.92
2007/06/19	52.71
2007/06/20	80.00
2007/06/21	63.37
2007/06/22	79.46
2007/06/23	**158.38**
2007/06/24	**157.11**
2007/06/25	**148.60**
2007/06/26	**131.46**
2007/06/27	4.98
2007/06/28	18.18

All hourly SO_2 concentrations were compliant with the hourly SO_2 NAAQS of 134 ppb. The SO_2 and PM_{10} data together with various meteorological parameters have been graphically presented below in Figure 50. Two distinct periods of elevated PM_{10} concentrations are evident on 18 June 2007 and between 22 and 26 June 2007, with a peak hourly PM_{10} concentration of 373.0 µg/m^3 occurring on 26 June 2007.

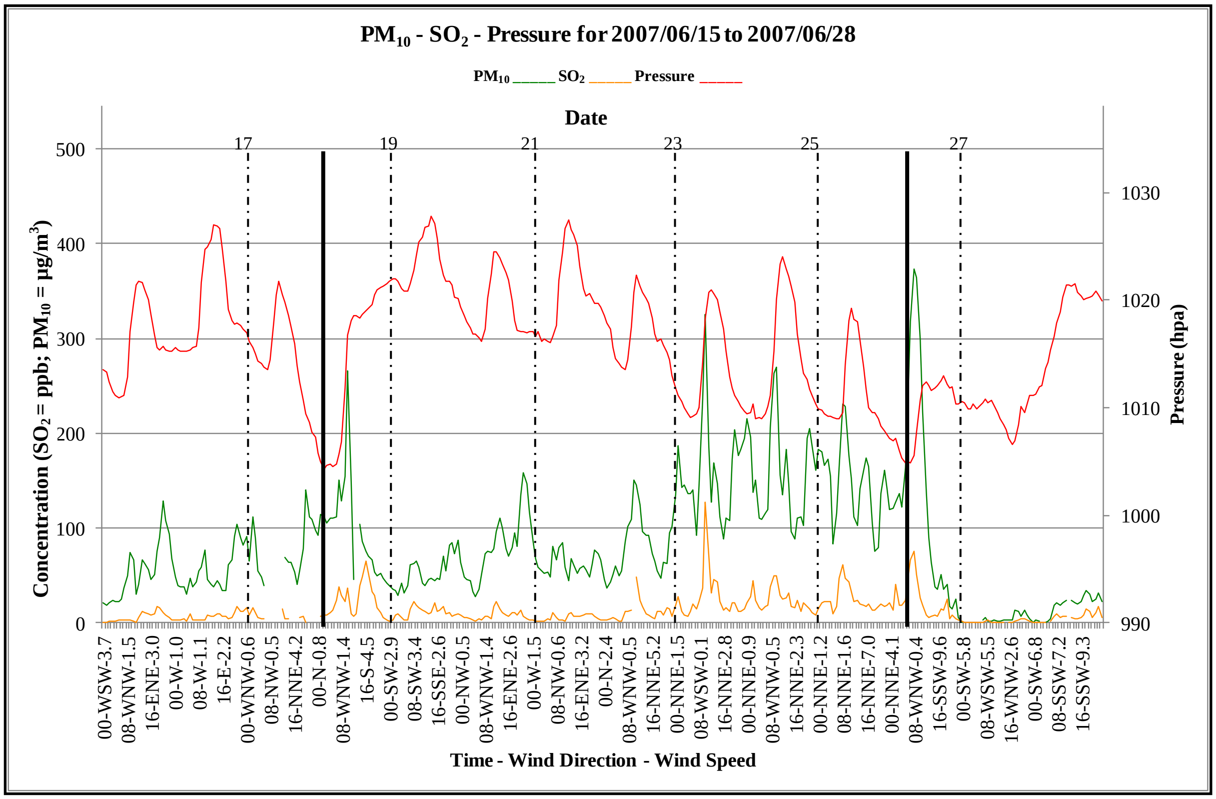

Figure 50: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in pressure for period 15 June 2007 to 28 June 2007. The vertical black lines represent cold fronts.

5.3.8.1 SYNOPTIC SITUATION

The synoptic chart for 17 June 2007 reveals a cold front approaching Cape Town while the South Indian High extends across the east coast of South Africa. The cold front travelled along the South African coastline reaching Durban at approximately 01h00 on 18 June 2007. The approaching cold front caused air pressure to decrease (Figure 50 above) and increased atmospheric stability as indicated by increasing delta temperatures (Figure 51 below). These meteorological conditions resulted in an increase in PM_{10} concentrations as the front approached. Elevated air pollution concentrations were measured prior to passage of the cold front over Durban as well post passage of the cold front. The latter was most likely due to stack tip downwash.

Between 18 and 22 June 2007, the South Atlantic High and South Indian High were the dominant meteorological controls over South Africa. The PM_{10} peak on 20 June 2007 was most likely due to an emission event.

The second cold front passes over on 26 June 2007. Pre-frontal coastal lows, gentle wind speeds and a lowering of the inversion layer resulted in elevated air pollution concentrations prior to the cold front. After passage of the cold front, the eighth highest PM_{10} peak was recorded and was most likely due to stack tip downwash conditions.

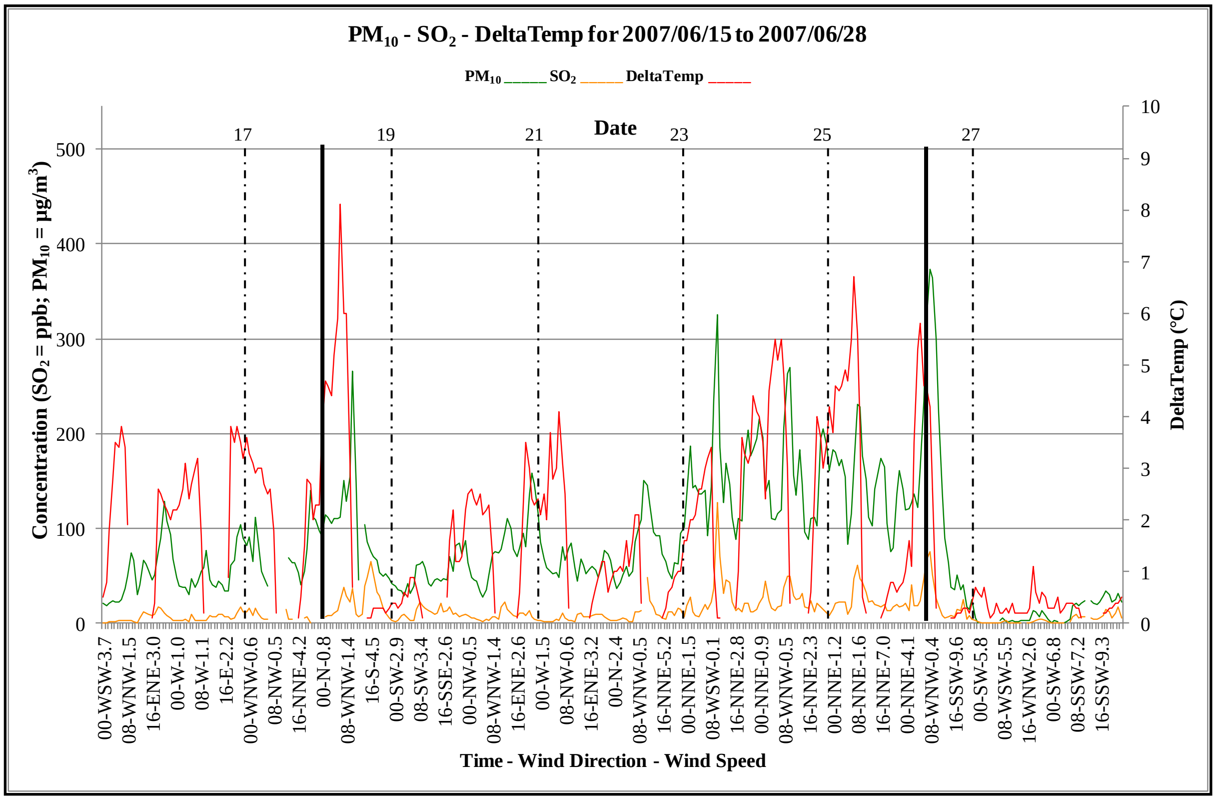

Figure 51: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in delta temperature for the period 15 June 2007to 28 June 2007. The vertical black lines represent cold fronts.

On 23 June 2007 the South Indian High was ridging over the east coast of South Africa while a cold front approached the west coast of South Africa. As the cold front travelled slowly towards Durban (over 24 and 25 June 2007) a pre-frontal coastal low developed. Air pressure is seen to decrease and delta temperature to increase as the front approaches, thereby increasing the potential of an air pollution event to occur. On 26 June 2008 at 08h00 the eighth highest hourly PM_{10} concentration of 373.0 μg/m^3 was recorded by the Ganges monitoring station after the cold front passed over Durban. This event is likely due to stack-tip downwash associated with high wind speeds. An increase in air pressure and a decrease in delta temperature soon after the cold front passed over Durban favoured the dispersion of air pollutants and concentrations promptly decrease.

5.3.9 AIR POLLUTION EVENT 9 (31 JULY 2008) - GANGES

A PM_{10} concentration of 351.5μg/m^3 was recorded at 08h00 on 31 July 2008 at the Ganges station. Table 17 below shows the 24-hour average PM_{10} concentrations measured over the course of this pollution event. Red values indicate non-compliance with the 24-hour NAAQS.

Table 17: Daily averages for the period during which air pollution Event 9 had occurred.

Date	24-hour Average PM_{10} (μg/m^3)
2008/07/13	25.04
2008/07/14	41.93
2008/07/15	87.22
2008/07/16	77.83
2008/07/17	39.72
2008/07/18	41.52
2008/07/19	67.33
2008/07/20	61.68
2008/07/21	60.54
2008/07/22	83.85
2008/07/23	69.33
2008/07/24	53.88
2008/07/25	71.00
2008/07/26	66.65

Date	24-hour Average PM_{10} (µg/m^3)
2008/07/27	84.34
2008/07/28	39.04
2008/07/29	45.20
2008/07/30	**125.03**
2008/07/31	**177.72**
2008/08/01	63.19
2008/08/02	50.18
2008/08/03	21.41

All hourly SO_2 concentrations were compliant with the hourly SO_2 NAAQS. The hourly SO_2 and PM_{10} concentrations are presented below in Figure 52. The two periods of highest PM_{10} concentrations are 15 to 16 July 2012 and 30 July to 01 August 2012.

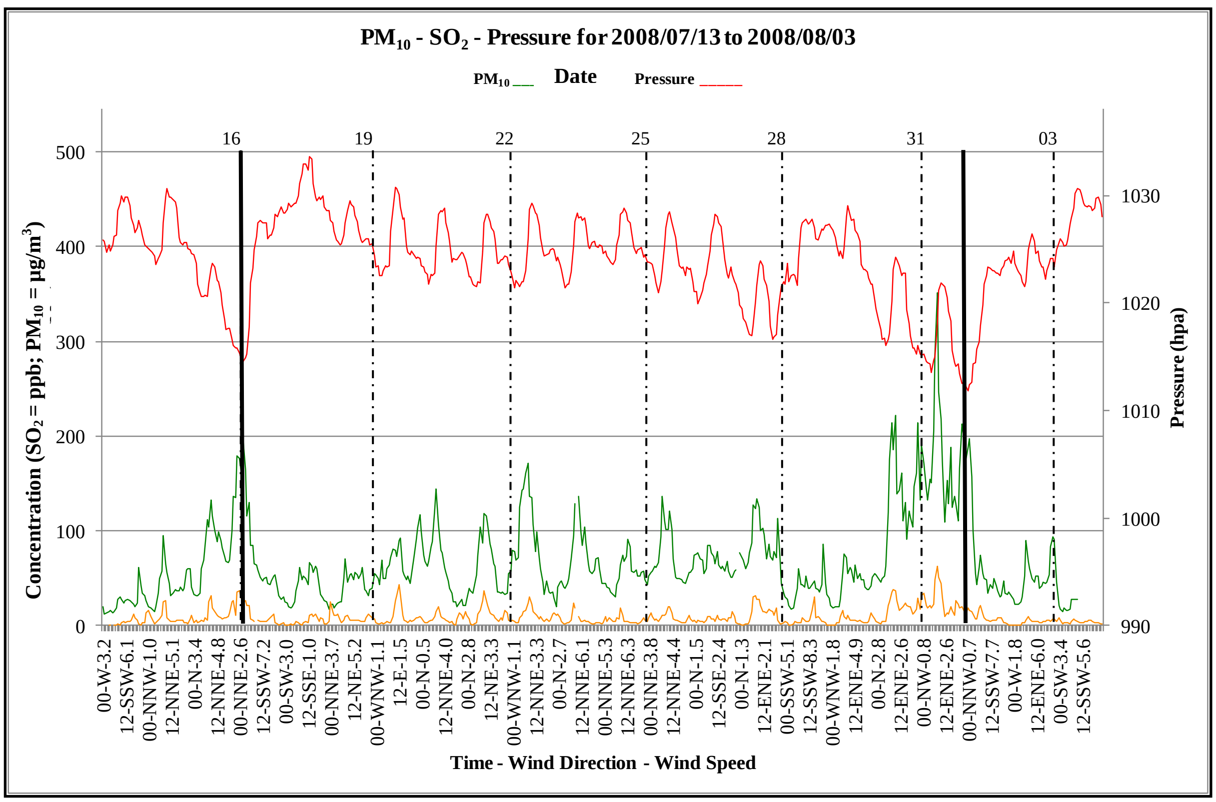

Figure 52: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in pressure for period 13 July 2008 to 03 August 2008. The vertical black lines represent cold fronts.

5.3.9.1 SYNOPTIC SITUATION

On 15 and 16 of July 2012 a cold front approached Durban, resulting in decreasing air pressure and increasing delta temperatures, suggesting increased atmospheric stability. PM_{10} concentrations peaked at 198 µg/m^3 at midnight on 15 of July 2012. This peak would have been enhanced by increased stability associated with weakened convection after sunset. As the cold front passed over Durban, stronger south-westerly winds are evident that promoted pollution dispersion and decreased PM_{10} concentrations.

Between 19 and 30 July 2008, numerous hourly PM_{10} exceedences were detected by the Ganges monitoring station. A closer look at the raw data reveals that these events occurred during the morning traffic rush. The combination of increased vehicular emissions and winter morning inversion conditions are the likely cause of these exceedences.

On 30 July 2008, a cold front passed over Port Elizabeth and pre-frontal coastal low was evident over Durban. As the front travelled towards Durban, air pollution peaked at 351.5µg/m^3 at 08h00 the ninth highest PM_{10} concentration across the monitoring datasets. This value is likely result of a combination of a radiative inversion, which formed at night due to the earth's radiational cooling process, the strengthening of the subsidence inversion as the front approached, and emissions during the peak morning traffic period. by 08h00, the radiative inversion is more likely to have been eroded by surface heading from the bottom up, with the potential for fumigation conditions (*cf.* Diab *et al.* 2002). As the cold front passed over Durban, air pressure increased, delta temperatures decreased (indicating increasing instability) and stronger south-westerly winds promoted horizontal dispersion of air pollutants, thereby decreasing concentrations.

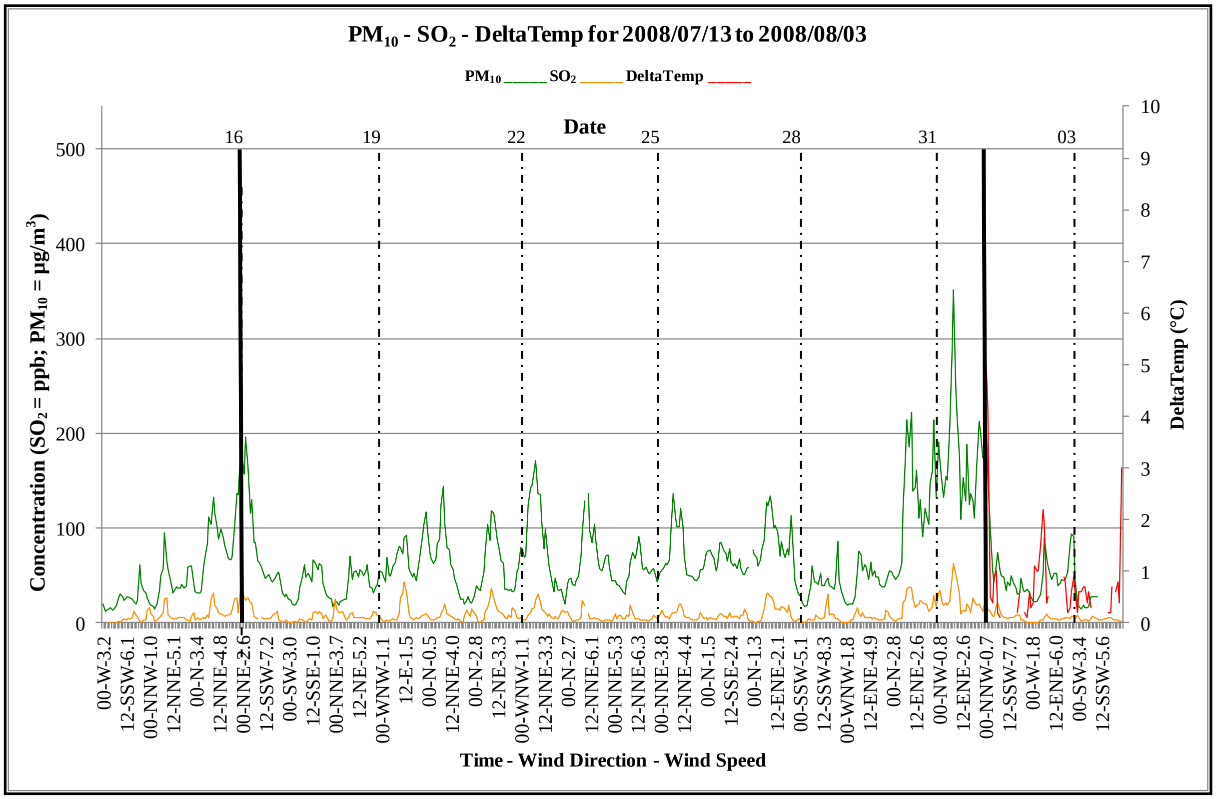

Figure 53: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in delta temperature for the period 13 July 2008 to 03 August 2008. The vertical black lines represent cold fronts.

5.3.10 AIR POLLUTION EVENT 10 (29 MAY 2007) - GANGES

The tenth highest hourly PM_{10} value was 330.4 µg/m^3 recorded at the Ganges monitoring station at 20h00 on 29 May 2007. The pollution event in which this values falls occurred between 26 May 2007 and 7 June 2007. The 24-hour average PM_{10} concentrations for this period are presented in Table 21 below. Values in red (i.e. 29 March 2007 to 31 March 2007) indicate non-compliance with the 24-hour NAAQS.

Table 18: Daily averages for the period during which air pollution Event 10 had occurred.

Date	24-hour Average PM_{10} ($\mu g/m^3$)
2007/05/26	53.60
2007/05/27	63.79
2007/05/28	71.63
2007/05/29	**137.81**
2007/05/30	**164.50**
2007/05/31	**122.93**
2007/06/01	72.06
2007/06/02	32.87
2007/06/03	20.66
2007/06/04	31.72
2007/06/05	81.33
2007/06/06	69.48
2007/06/07	49.86

5.3.10.1 SYNOPTIC SITUATION

On 29 May 2007 a coastal low is evident between Cape Town and Port Elizabeth and the South Indian High persists over the east coast of South Africa. Weak inversion conditions occurred over Durban (Figure 54 and Figure 55 below), which enhanced air pollution potential. The coastal low strengthened as it travelled up the east coast of South Africa. As the low pressure system travelled away from Durban, air pressure is seen to increase and air pollution concentrations decrease.

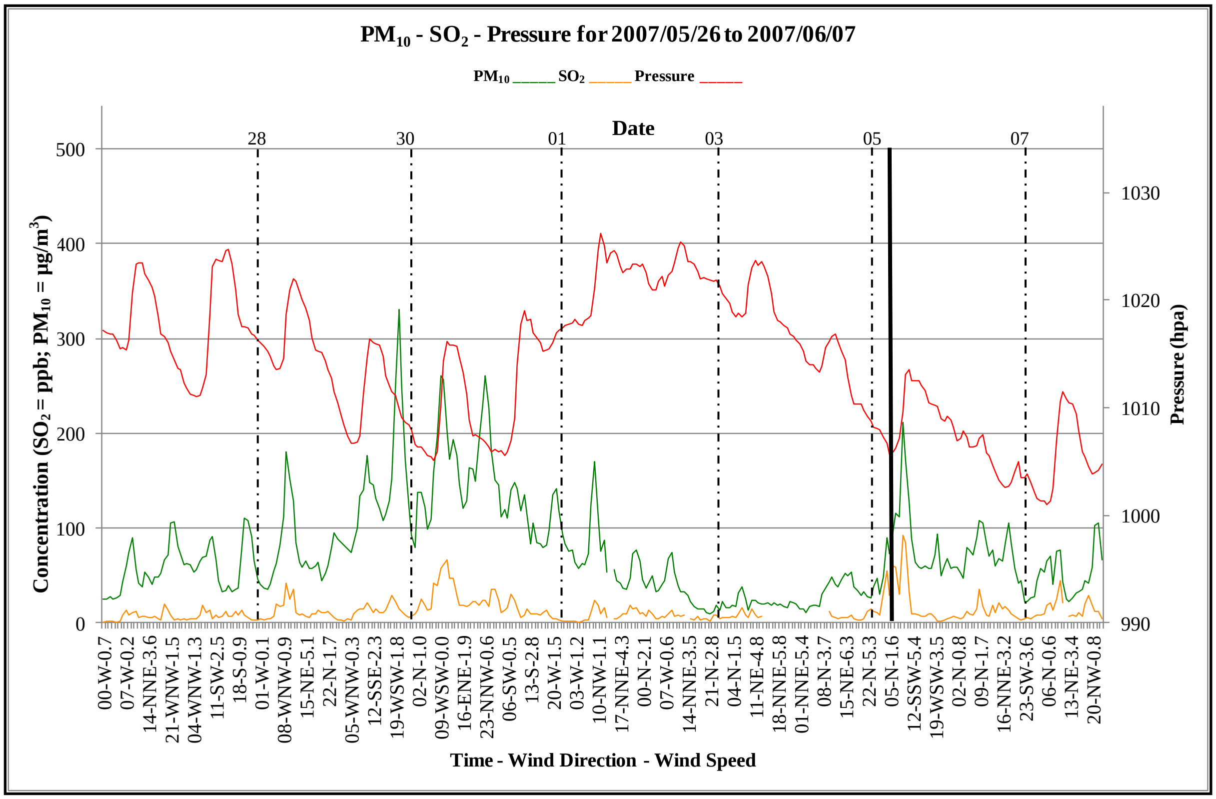

Figure 54: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in pressure for period 26 May 2007 to 07 June 2007. The vertical black line represents the cold front.

On 5 July 2007, a cold front with a pre-frontal coastal low approached Durban. Pressure decreases at these systems apprached. A spike in air pollution concentrations is evident immediately after the front passes Durban. It is assumed that atmospheric stability increased as the low pressures approached but atmospheric instability occurred as the front passed over. Unfortunately stability cannot be assessed further for this event due to a lack of delta temperature data at this time.

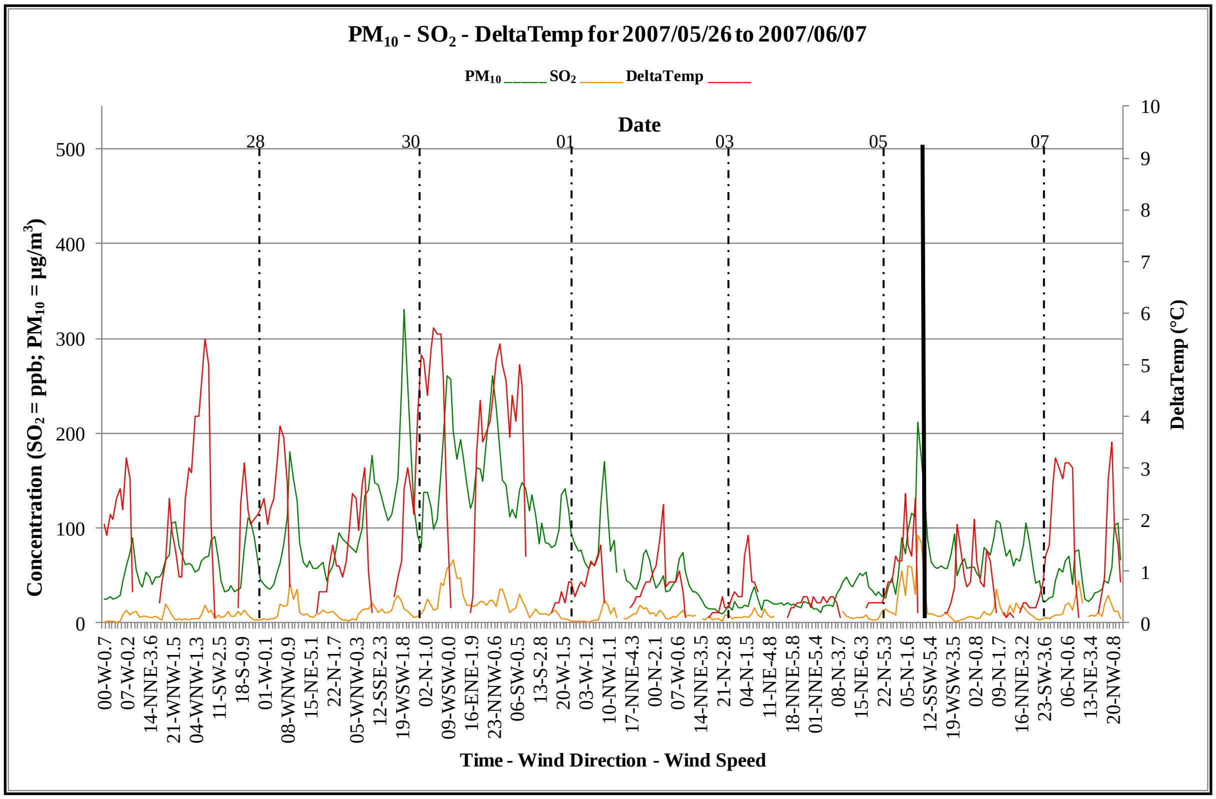

Figure 55: Graph showing relationship of hourly SO_2 and PM_{10} concentrations from Ganges station with changes in delta temperature for the period 26 May 2007 to 07 June 2007. The vertical black line represents the cold fronts.

5.4 FINAL DISCUSSION OF TOP TEN AIR POLLUTION EVENTS IN THE DSB

An analysis of all pollution events (see Appendix B for remainder of events) revealed three distinct meteorological scenarios that are conducive to high pollution values

1. A pre-frontal scenario with strong inversion conditions and generally gentle wind speeds;
2. A scenario without a proximate frontal system, but inversion conditions and generally gentle wind speeds; and
3. A post-frontal scenario with high wind speeds.

The fluctuation of air pollution potential as a low pressure system traverses across Durban is described by Preston-Whyte and Diab (1980) and Preston-Whyte (1991). As shown, the approach of a cold front is accompanied by decreasing atmospheric pressure, gentle to moderate north-easterly winds, and a shallow mixing depth, resulting in a high air pollution potential depending on the intensity of the low pressure system. These conditions give rise to pre-frontal air pollution incidents and are shown in air pollution events 2, 3, 4, 5, 6, 8, 9 and 10.

Upon passing of the cold front over Durban, air pressure rises and strong south-westerly winds prevail decreasing the potential for an air pollution event as described by Preston-Whyte and Diab (1980). However, the relationship between SO_2 concentrations and wind speed was further discussed in a paper by Diab *et al* (2002). Here, high SO_2 concentrations were recorded under low/calm wind conditions. The lowest concentrations were recorded when wind speeds reached approximately 3.5 m/s and then, interestingly, there was a steady rise in air pollution concentrations as wind speeds increased. This could explain Scenario 3 described above. This interesting phenomenon was attributed to stack downwash/down-drafting which gives rise to high air pollution concentrations at ground level. This further suggests that these air pollution concentrations originated from an elevated source such as an industrial stack and resulted in increasing ambient SO_2 concentrations above background levels. This was most evident when wind backed from north-easterly to a south-westerly direction as the cold front or coastal low passed over Durban from north-easterly to a south-westerly direction. Events 2, 4, 6, 8, 9, and 10 show the post-frontal air pollution phenomenon.

As empirically revealed in a paper by Scott and Diab (2000), negative surface pressure remained the key meteorological parameter in identify the commencement of an air pollution event. Although wind direction was the most useful parameter in estimating the end point of an air pollution event, however, as shown here, post-frontal events during south-westerly winds are a possibility, and as the statistics below show, these events generally have the highest PM_{10} concentrations associated with them.

Scenario 2 is associated with gentle inversion conditions and generally low wind speeds, thus limiting vertical and horizontal dispersion. Surface inversions develop at night, particularly during cool, calm winter nights. These tend to be strongest during early mornings before sunrise. After sunrise, the surface temperature inversion is eroded from the bottom up, and may result in fumigation conditions, particularly with increased emissions of pollutants during the peak morning traffic period and boiler start-up conditions in the industrial basin. By late morning, the surface inversion has been totally eroded, or 'popped'. Scenario 2 included Events 2, 3, 5, 7, 9, and 10.

5.5 COMMUNITY COMPLAINTS

All air pollution incidents and events between 2006 and 2010 for each station are presented in Table 19 below. It is also indicated whether the event was recorded in the SDCEA community complaints database. Of the 96 pollution incidents and events shown here, only 18 (18.75%) were recorded by SDCEA, suggesting a discrepancy between community perceptions of air quality and measured air pollutant concentrations. The large difference in reported and recorded emission events could be attributed to one or more the following:

- People's perception that if the air looks clean therefore it must be clean;
- Incidents occur at night when the sky is dark and pollution is not noticeable;
- People living in the DSB have become desensitised to the various toxic odours and have therefore learnt to cope with the negative environmental externality;
- Only major incidents are reported; and
- Community are unaware of the SDCEA to voice their concerns, or have the impression that reporting events will make little difference on the quality of their lives.

These issues are further interrogated in the work of Ramsay (2010).

Table presented overleaf

Table 19: Summary of air pollution events at the Ganges, Wentworth and Southern Works monitoring station against the SDCEA reported pollution events database.

Monitoring Station	Start	End	Reported Pollution Event
Ganges	2006/05/24	2006/06/15	✘
Ganges	2006/06/19	2006/06/24	✘
Ganges	2007/02/18	2007/02/22	✘
Ganges	2007/05/05	2007/05/22	✘
Ganges	2007/05/26	2007/06/07	✘
Ganges	2007/06/09	2007/06/13	✘
Ganges	2007/06/15	2007/06/28	✘
Ganges	2007/07/08	2007/07/26	✘
Ganges	2007/07/30	2007/08/05	✘
Ganges	2007/08/08	2007/08/13	✘
Ganges	2007/08/18	2007/08/23	✘
Ganges	2007/08/29	2007/09/02	✘
Ganges	2008/04/16	2008/04/20	✘
Ganges	2008/05/05	2008/05/17	✘
Ganges	2008/05/20	2008/05/25	✘
Ganges	2008/05/28	2008/06/01	✘
Ganges	2008/06/09	2008/06/18	✘

Monitoring Station	Start	End	Reported Pollution Event
Ganges	2008/06/24	2008/06/28	✘
Ganges	2008/06/30	2008/07/10	✓
Ganges	2008/07/13	2008/08/03	✘
Ganges	2008/08/05	2008/08/17	✘
Ganges	2008/08/31	2008/09/11	✓
Ganges	2008/09/13	2008/09/17	✘
Ganges	2008/10/26	2008/10/30	✓
Ganges	2009/05/13	2009/05/18	✘
Ganges	2009/05/20	2009/05/24	✘
Ganges	2009/06/03	2009/06/27	✓
Ganges	2009/06/30	2009/07/14	✓
Ganges	2009/07/16	2009/07/24	✘
Ganges	2009/07/27	2009/08/07	✓
Ganges	2009/08/09	2009/08/13	✓
Ganges	2009/08/15	2009/08/20	✓
Ganges	2009/08/24	2009/09/02	✘
Ganges	2009/09/04	2009/09/09	✘
Ganges	2009/09/11	2009/09/15	✘
Ganges	2010/01/17	2010/01/21	✘
Ganges	2010/02/08	2010/02/12	✘

Monitoring Station	Start	End	Reported Pollution Event
Ganges	2010/03/23	2010/03/27	✓
Ganges	2010/04/12	2010/04/16	✗
Ganges	2010/04/24	2010/04/30	✗
Ganges	2010/05/07	2010/05/11	✗
Ganges	2010/08/02	2010/08/06	✓
Wentworth	2006/05/04	2006/05/08	✗
Wentworth	2006/05/24	2006/06/02	✗
Wentworth	2006/07/03	2006/07/17	✗
Wentworth	2006/07/19	2006/08/03	✗
Wentworth	2006/08/05	2006/08/14	✗
Wentworth	2006/08/16	2006/08/21	✗
Wentworth	2007/05/05	2007/05/17	✗
Wentworth	2007/05/26	2007/06/03	✗
Wentworth	2007/06/06	2007/06/10	✗
Wentworth	2007/06/13	2007/07/02	✗
Wentworth	2007/07/05	2007/07/26	✗
Wentworth	2007/07/29	2007/08/05	✗
Wentworth	2007/08/08	2007/08/12	✗

Monitoring Station	Start	End	Reported Pollution Event
Wentworth	2007/08/14	2007/08/23	✘
Wentworth	2007/08/29	2007/09/02	✘
Wentworth	2008/04/08	2008/04/12	✘
Wentworth	2008/05/05	2008/05/09	✘
Wentworth	2008/05/20	2008/05/25	✘
Wentworth	2008/05/27	2008/05/31	✘
Wentworth	2008/06/11	2008/06/17	✘
Wentworth	2008/06/24	2008/06/28	✘
Wentworth	2008/07/05	2008/07/10	✓
Wentworth	2008/07/13	2008/07/18	✘
Wentworth	2008/07/20	2008/08/07	✘
Wentworth	2008/08/10	2008/08/17	✘
Wentworth	2008/09/03	2008/09/07	✘
Wentworth	2009/05/13	2009/05/18	✘
Wentworth	2009/06/04	2009/06/08	✘
Wentworth	2009/06/23	2009/06/27	✘
Wentworth	2009/07/07	2009/07/13	✘

Monitoring Station	Start	End	Reported Pollution Event
Wentworth	2009/07/20	2009/07/24	✘
Wentworth	2009/07/27	2009/07/31	✓
Wentworth	2010/05/26	2010/05/30	✘
Wentworth	2010/06/05	2010/06/10	✓
Wentworth	2010/06/23	2010/06/28	✘
Wentworth	2010/07/18	2010/07/22	✓
Wentworth	2010/07/31	2010/08/08	✓
Wentworth	2010/08/11	2010/08/16	✘
Southern Works	2006/07/03	2006/07/17	✘
Southern Works	2006/07/19	2006/08/02	✘
Southern Works	2006/09/21	2006/09/25	✘
Southern Works	2007/05/05	2007/05/17	✘
Southern Works	2007/05/26	2007/06/07	✘
Southern Works	2007/06/09	2007/06/28	✘
Southern Works	2007/07/08	2007/07/26	✘
Southern Works	2007/07/30	2007/08/05	✘
Southern Works	2007/08/08	2007/08/12	✘

Monitoring Station	Start	End	Reported Pollution Event
Southern Works	2007/08/18	2007/08/23	✗
Southern Works	2007/08/29	2007/09/02	✗
Southern Works	2008/07/29	2008/08/03	✗
Southern Works	2009/07/07	2009/07/14	✓
Southern Works	2010/06/24	2010/06/28	✗
Southern Works	2010/07/18	2010/07/23	✓
Southern Works	2010/08/01	2010/08/06	✓

5.6 STATISTICAL ANALYSES

5.6.1 ANANLYSIS OF WENTWORTH AIR POLLUTION INCIDENTS

The data from multiple stations could not be combined for the statistical analysis because some incidents featured at more than one station simultaneously and this would have distorted the results. The Wentworth data was selected for statistical analysis on the basis that four of the top five pollution events occurred at this station. This station is also centrally located within an industrial zone. A pollution incident was defined earlier in this dissertation as occurring when three or more consecutive hours of elevated PM_{10} (above 100 µg/m^3) occur. Between 2006 and 2010, 123 such incidents occurred at Wentworth. Each incident was categorised into one of the following scenarios:

1. A pre-frontal scenario (i.e. occurring within 24 hours subsequent to the passing of a cold front);
2. A scenario without a cold front approaching, but with a temperature inversion occurring (usually a weak inversion) and generally gentle wind conditions;

3. A post-frontal scenario (i.e. occurring within 6 hours of the passing of a cold front);
4. Other, for all other incidents that do not fall into the above three categories. Generally these incidents occurred with the absence of a temperature inversion conditions and are most likely associated with an industrial pollution incident.

The incident start date, start time, end date and end time together with the maximum and average PM_{10} concentrations during the incident are provided in Table 20 below. The scenario in which the incident was categorised into is indicated with an X in the table below. Incidents that correspond to SDCEA complaints database are highlighted in green.

Table 20: Air pollution incidents at the Wentworth monitoring station categorised into each scenario.

Incident Details				**Scenario**			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2006/05/06 11h00	2006/05/06 13h00	113.1	108.9	✘			
2006/05/26 19h00	2006/05/27 00h00	159.9	126.6	✘			
2006/05/30 19h00	2006/05/30 22h00	132.3	121.6		✘		
2006/05/31 19h00	2006/05/31 22h00	124.1	112.8		✘		
2006/07/05 18:00	2006/07/05 20:00	149.9	124.5		✘		
2006/07/06 09h00	2006/07/06 12:00	144.5	115.6	✘			
2006/07/10 10:00	2006/07/10 13:00	122.4	109.8		✘		
2006/07/10 20:00	2006/07/11 06:00	137.3	118.5		✘		
2006/07/11 20:00	2006/07/12 12:00	186.8	115		✘		

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2006/07/12 17h00	2006/07/13 03:00	264.3	182.8		✘		
2006/07/14 22:00	2006/07/15 02:00	145.4	133.1		✘		
2006/07/21 09:00	2006/07/21 14:00	213.3	156.5	✘			
2006/07/26 12:00	2006/07/26 14:00	107	104.9		✘		
2006/07/26 23:00	2006/07/27 02:00	132.6	127.6		✘		
2006/07/27 10h00	2006/07/27 13h00	162.9	145		✘		
2006/07/29 08h00	2006/07/29 11h00	178.6	138.4		✘		
2006/07/30 23h00	2006/07/31 12h00	159.4	128.6		✘		
2006/07/31 21h00	2006/08/01 14h00	166.4	119.7	✘			
2006/08/07 09h00	2006/08/07 11h00	259.5	177.5		✘		
2006/08/07 22h00	2006/08/08 00h00	169.9	135.4		✘		
2006/08/08 08h00	2006/08/08 12h00	137.6	130.2	✘			
2006/08/11 22h00	2006/08/12 01h00	124.7	112.5	✘			
2006/08/18 22h00	2006/08/19 00h00	131.8	120.5		✘		
2007/05/07 20h00	2007/05/08 01h00	175.7	144.1		✘		
2007/05/08 09h00	2007/05/08 11h00	168.5	136.7	✘			

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2007/05/10 09h00	2007/05/10 13h00	238.4	166.6		✘		
2007/05/11 21h00	2007/05/11 23h00	127.4	123.3		✘		
2007/05/12 21h00	2007/05/13 00h00	169.2	140.6		✘		
2007/05/13 19h00	2007/05/14 01h00	151.9	129.5		✘		
2007/05/14 21h00	2007/05/15 01h00	167.5	134.5	✘			
2007/05/28 09h00	2007/05/28 11h00	184.3	140.6		✘		
2007/05/29 12h00	2007/05/30 00h00	214.9	139.5		✘		
2007/05/30 10h00	2007/05/30 16h00	197.7	152.1		✘		
2007/05/30 18h00	2007/05/31 12h00	240.6	147		✘		
2007/05/31 20h00	2007/05/31 22h00	122.6	119.2		✘		
2007/06/01 07h00	2007/06/01 10h00	173.9	130.1		✘		
2007/06/08 20h00	2007/06/08 22h00	128.9	119		✘		
2007/06/15 20h00	2007/06/15 22h00	135.7	114.3	✘			
2007/06/17 21h00	2007/06/17 23h00	141.5	129.2	✘			
2007/06/18 08h00	2007/06/18 11h00	483.7	220.4			✘	
2007/06/20 19h00	2007/06/20 23h00	164.9	152		✘		

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2007/06/22 08h00	2007/06/22 11h00	240.4	173.7		✘		
2007/06/22 22h00	2007/06/23 07h00	143.2	117.2		✘		
2007/06/23 10h00	2007/06/23 15h00	178.4	130.3		✘		
2007/06/23 20h00	2007/06/24 01h00	196.5	164		✘		
2007/06/24 11h00	2007/06/24 14h00	144.4	123.4		✘		
2007/06/24 21h00	2007/06/25 03h00	163.1	138.1		✘		
2007/06/25 09h00	2007/06/25 11h00	128	116.2		✘		
2007/06/25 21h00	2007/06/26 02h00	166.2	137.4		✘		
2007/06/26 03h00	2007/06/26 12h00	417.7	213.5	✘			
2007/06/30 06h00	2007/06/30 08h00	116.3	112.7	✘			
2007/07/07 21h00	2007/07/07 23h00	135.5	114.5	✘			
2007/07/10 21h00	2007/07/11 04h00	137.6	116.6		✘		
2007/07/11 09h00	2007/07/11 14h00	185.7	155.7	✘			
2007/07/11 19h00	2007/07/11 22h00	153	136.5	✘			
2007/07/15 20h00	2007/07/16 01h00	135.9	120.6		✘		
2007/07/16 09h00	2007/07/16 12h00	187.2	127		✘		

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2007/07/16 21h00	2007/07/17 06h00	153.1	125.1		✘		
2007/07/19 07h00	2007/07/19 13h00	184.3	151.5		✘		
2007/07/20 08h00	2007/07/20 10h00	165.9	136.9	✘			
2007/07/20 22h00	2007/07/21 02h00	187.8	133.9	✘			
2007/07/23 22h00	2007/07/24 04h00	136.2	114.2		✘		
2007/07/31 21h00	2007/07/31 23h00	137.6	125.9				✘
2007/08/01 08h00	2007/08/01 13h00	169.6	136.6		✘		
2007/08/01 18h00	2007/08/01 20h00	176.7	147.7		✘		
2007/08/02 08h00	2007/08/02 15h00	173.9	133.2		✘		
2007/08/02 17h00	2007/08/03 04h00	212.6	153.8		✘		
2007/08/10 21h00	2007/08/10 23h00	112.4	108.8	✘			
2007/08/16 09h00	2007/08/16 14h00	544.1	261.5			✘	
2007/08/20 08h00	2007/08/20 11h00	123.9	124.4		✘		
2007/08/21 07h00	2007/08/21 17h00	158.8	131.7		✘		
2007/08/31 08h00	2007/08/31 10h00	128.9	120		✘		
2007/08/31 15h00	2007/08/31 18h00	151.5	130.8		✘		

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2008/04/10 19h00	2008/04/10 22h00	283	194		✘		
2008/05/07 06h00	2008/05/07 10h00	139.1	119.2	✘			
2008/05/22 19h00	2008/05/22 22h00	202.8	133.6		✘		
2008/05/23 17h00	2008/05/23 21h00	152.1	116.7				✘
2008/05/29 10h00	2008/05/29 14h00	113.9	106		✘		
2008/06/13 08h00	2008/06/13 10h00	121.1	109.8				✘
2008/06/14 20h00	2008/06/15 01h00	115.9	110.5		✘		
2008/06/26 19h00	2008/06/26 21h00	130.7	114.2		✘		
2008/07/07 08h00	2008/07/07 10h00	134	113		✘		
2008/07/07 19h00	2008/07/08 02h00	129.5	113.5	✘			
2008/07/08 18h00	2008/07/08 21h00	159.3	136.1	✘			
2008/07/15 07h00	2008/07/15 10h00	380	203	✘			
2008/07/15 20h00	2008/07/16 01h00	165	140.1	✘			
2008/07/22 07h00	2008/07/22 09h00	143.9	127.1				✘
2008/07/25 06h00	2008/07/25 10h00	146.7	128		✘		
2008/07/30 08h00	2008/07/30 12h00	148.8	123.9		✘		

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2008/07/30 17h00	2008/07/30 20h00	151	130.1		✘		
2008/07/31 08h00	2008/07/31 11h00	207.8	157.1	✘			
2008/07/31 16h00	2008/08/01 00h00	172	140.5	✘			
2008/08/01 01h00	2008/08/01 02h00	123.7	115.4			✘	
2008/08/05 17h00	2008/08/05 21h00	226.7	187.3				✘
2008/08/12 10h00	2008/08/12 13h00	141.6	135.9				✘
2008/08/13 07h00	2008/08/13 10h00	177.7	139.9		✘		
2008/08/13 16h00	2008/08/14 03h00	193.7	147		✘		
2008/08/14 20h00	2008/08/15 00h00	142.5	118.6		✘		
2008/09/05 08h00	2008/09/05 13h00	227.6	137.7			✘	
2009/05/15 09h00	2009/05/15 11h00	132.5	120.9		✘		
2009/05/16 09h00	2009/05/16 11h00	113.7	108.9		✘		
2009/06/06 15h00	2009/06/06 17h00	133.9	120	✘			
2009/06/25 18h00	2009/06/25 20h00	288.2	184.5			✘	
2009/07/09 09h00	2009/07/09 11h00	130.2	117.4		✘		
2009/07/09 17h00	2009/07/09 19h00	129.3	123.5		✘		

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2009/07/10 02h00	2009/07/10 12h00	158	121.7		✘		
2009/07/10 19h00	2009/07/11 10h00	242.3	146.2		✘		
2009/07/11 18h00	2009/07/11 23h00	164.7	136.3		✘		
2009/07/22 08h00	2009/07/22 10h00	147.8	128.9	✘			
2009/07/22 18h00	2009/07/22 22h00	139.8	117.8	✘			
2009/07/29 19h00	2009/07/29 21h00	128.6	119.2		✘		
2010/05/28 09h00	2010/05/28 12h00	170.6	155.4			✘	
2010/06/07 22h00	2010/06/08 00h00	110.4	108.7		✘		
2010/06/25 21h00	2010/06/26 01h00	114.4	108.1			✘	
2010/07/20 19h00	2010/07/20 22h00	154.6	128.2		✘		
2010/08/02 07h00	2010/08/02 09h00	127.9	115.4	✘			
2010/08/03 18h00	2010/08/04 04h00	268.5	164		✘		
2010/08/04 07h00	2010/08/04 10h00	247.3	191.6		✘		
2010/08/05 01h00	2010/08/05 03h00	118.9	114.1				✘
2010/08/05 07h00	2010/08/05 09h00	110.4	107.1		✘		
2010/08/05 21h00	2010/08/06 01h00	131	121.6		✘		

Incident Details				Scenario			
Start Date & Time	End Date & Time	Maximum PM_{10} ($\mu g/m^3$)	Average PM_{10} ($\mu g/m^3$)	1	2	3	4
2010/08/13 20h00	2010/08/14 00h00	127.4	110.2		✗		
2010/08/14 20h00	2010/08/14 23h00	113.8	109.8		✗		

From the table above, of the 123 incidents, 30 (24.4%) fell into Scenario 1, 79 (64.2%) into Scenario 2, and seven each (5.7%) for Scenarios 3 and 4. Only four (3.3%) of the 123 incidents (shaded orange in Table 20 above) correlated with community complaints in the SDCEA database.

5.6.2 ANALYSIS OF VARIANCE (ANOVA)

ANOVA was used to determine whether there was a significant difference between categories with respect to the maximum PM_{10} values during each incident, and average PM_{10} values during each incident. Results indicated that there were significant differences (at the 99% confidence level) in the means of both incident maximum and average PM_{10} across scenarios. Descriptive statistics are presented in Table 21 below. As results show, Scenario 3 (post-frontal events) has the highest incident maximum and incident average PM_{10} concentrations.

Table 21: ANOVA between maximum and average PM_{10} concentrations during each air pollution incident at the Wentworth station.

PM_{10}	Scenario	Number	Mean	Standard Deviation	Minimum	Maximum
Maximum	1	30	168.3	67.8	112.4	417.7
	2	79	162.6	41.7	107.0	283.0
	3	7	**278.9**	172.2	114.4	544.1
	4	7	148.8	36.4	118.9	226.7
	Total	123	169.9	66.9	107.0	544.1

Average	1	30	133.0	24.7	108.8	213.5
	2	79	132.0	19.7	104.9	194.0
	3	7	**169.0**	56.5	108.1	261.5
	4	7	131.0	26.4	109.8	187.3
	Total	123	134.3	25.6	104.9	261.5

Finally the timing of each incident was assessed to determine when they are most prevalent. Each hour of each incident was classified as following:

1. Early morning (06h00 - 08h00 inclusive);
2. Late morning (09h00 - 11h00 inclusive);
3. Early afternoon (12h00 - 14h00 inclusive);
4. Late afternoon (15h00 - 17h00 inclusive);
5. Evening (18h00 - 20h00 inclusive); or
6. Overnight (21h00 - 05h00 inclusive).

After each incident was classified (Table 23 above), percentages of each period for each incident could be calculated. Table 22 below shows the results. As results show, the largest proportion of incident hours for Scenarios 1, 2 and 4 occur overnight. This is expected because mixing depth decreases overnight with the cessation of surface heating by the sun and the development of radiative inversions (particularly in winter), and furthermore wind speeds tend to be gentler overnight thus limiting horizontal dispersion. The second largest proportion of incident hours under Scenarios 1 and 3 occur during late morning, and may be enhanced by fumigation with the erosion of the overnight radiative inversions from the bottom up (Diab *et al.* 2002). Scenario 3 (post-frontal) most commonly occurs during the late morning. This scenario has been associated with stack tip downwash with increased wind speeds after the passing of a front. Stack tip downwash would be enhanced during the late morning towards the early afternoon because of increased turbulence during these periods.

Table 22: Percentage number of hours each scenario occurred during each part of the day.

Time of Day	Scenario 1: Pre-frontal (%)	Scenario 2: Non-frontal, inversion, generally calm (%)	Scenario 3: Post-frontal (%)	Scenario 4: Other (%)
Early morning (06h00 - 08h00)	13.2	9.0	6.7	19.2
Late morning (09h00 - 11h00)	22.5	17.8	40.0	11.5
Early afternoon (12h00 - 14h00)	9.3	9.2	20.0	7.7
Late afternoon (15h00 - 17h00)	3.3	4.1	0.0	7.7
Evening (18h00- 20h00)	11.3	14.1	10.0	23.1
Overnight (21h00 - 05h00)	40.4	45.8	23.3	30.8
TOTAL	100.0	100.0	100.0	100.0

5.6.3 CORRELATIONS BETWEEN WENTWORTH AND CAPE TOWN PM_{10}

The purpose of this analysis was to assess whether any relationship existed between PM_{10} values in Cape Town and subsequent PM_{10} values during a pre-frontal pollution incident in Durban. This assessment made use of the data from the Wentworth pre-frontal incidents outlined in Table 20. The varying N-values in Table 23 below are a result of missing meteorological data. Visual inspection of the synoptic charts for the study period revealed that cold fronts take more than 12 hours to reach Durban from Cape Town, but no more than 60 hours. As such maximum hourly

PM_{10} concentrations at the Cape Town stations 12-60 hours prior to the PM_{10} incident in Durban were compared with the Wentworth values. If significant correlations were detected, it would have suggested that frontal pollution maxima in Cape Town could be used as a warning of subsequent peaks in Durban as the front approached, however no significant correlations were detected (Table 23 overleaf).

Table 23: Correlation details for Wentworth pre-frontal pollution incidents (incident maximum hourly value and incident average PM_{10}) and maximum hourly PM_{10} concentrations at Cape Town stations 12-60 hours prior to a PM_{10} incident.

Parameter		Wentworth Maximum	Wentworth Average	Goodwood	Bellville	Khayelitsha
Wentworth Incident Maximum	Pearson Correlation	1	0.969**	-0.123	-0.164	-0.054
	Sigma (2-tailed)	0	0.000	0.568	0.433	0.799
	N	28	28	24	25	25
Wentworth Incident Average	Pearson Correlation	0.969**	1	-0.040	-0.170	-0.052
	Sigma (2-tailed)	0.000	0	0.853	0.416	0.804
	N	28	28	24	25	25
Goodwood	Pearson Correlation	-0.123	-0.040	1	0.498*	0.504*
	Sigma (2-tailed)	0.568	0.853	0	0.016	0.020
	N	24	24	24	23	21
Bellville	Pearson Correlation	-0.164	-0.170	0.498*	1	0.558**
	Sigma (2-tailed)	0.433	0.416	0.016	0	0.007
	N	25	25	23	25	22
Khayelitsha	Pearson Correlation	-0.054	-0.052	0.504*	0.558**	1
	Sigma (2-tailed)	0.799	0.804	0.020	0.007	0
	N	25	25	21	22	25
**. Correlation is significant at the 0.01 level (2-tailed).						
*. Correlation is significant at the 0.05 level (2-tailed).						

5.6.4 REGRESSION ANALYSIS

This analysis was conducted to determine whether the following variables influence PM_{10} concentrations at Wentworth:

1) Traffic levels;
2) Delta temperature, as a proxy for mixing depth; and
3) wind speed.

Initially wind direction was assessed as an explanatory variable since the Wentworth station lies on a south-easterly wind trajectory from Engen, and a south-westerly wind trajectory from Mondi and SAPREF (wind direction was translated to a categorical variable with south westerly winds as category 1, south-easterly as category 2, and all other wind directions as category 3). However, these categorical variables did not contribute significantly to the explanatory power of the model, and surprisingly it was found that on average across the dataset, lower PM_{10} values were measured at Wentworth when the wind was blowing along these key wind trajectories. This suggests that Wentworth station is not particularly representative of industrial emissions (as previously asserted by Ramsay, 2010) and the wind direction variable was dropped from the model below.

The linear regression analysis was conducted in SPSS version 21. Initial collinearity analyses showed variance inflation factor (VIF) values below 2 for all three variables, suggesting collinearity is not an issue in this model. Using the enter method, a significant model emerged ($F_{3,\ 29945} = 1521.511$, $p < 0.0005$). The adjusted R-square value suggests that the model explains 13.2 % of the variance in the dependent variable (hourly PM_{10} concentrations). This is not a large proportion, and it is likely that other variables such as industrial emissions (not included in the model since data is not available) have a significant influence on ambient PM_{10} concentrations. Significant explanatory (sigma <0.05) variables are shown below in Table 24. The model suggests that across the dataset:

- For every degree increase in delta temperature, hourly PM_{10} increases by 9.3 µg/m^3;

- For every one unit increase in the traffic index, hourly PM_{10} increases by 2.0 µg/m^3; and
- For every m/s increase in wind speed, hourly PM_{10} decreases by 1.3 µg/m^3

The standardized coefficients suggest that delta temperature is the most powerful explanatory variable, followed by wind speed and then traffic levels.

Table 24: Regression analysis of PM_{10} concentrations at Wentworth

Model	Unstd. Coeff.		Std. Coeff.	t	Sigma	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
+-Constant	28.009	0.352		79.663	0.000	27.32	28.698		
Wind Speed	-1.344	0.058	-0.132	-23.091	0.000	-1.458	-1.230	0.882	1.133
Delta temperature	9.338	0.175	0.301	53.232	0.000	8.994	9.682	0.906	1.103
Traffic	1.953	0.091	0.118	21.430	0.000	1.774	2.132	0.959	1.042

A second regression model was run, focused specifically on pre-frontal pollution incidents at Wentworth. For this assessment two additional variables were considered:

- The minimum pressure in South Durban when the front passes over (after the incident)
- The minimum pressure in Cape Town when the front passes over (before the incident)

Initial collinearity analyses showed VIF values below 2 for all three variables, suggesting collinearity is not an issue. The linear regression analysis was conducted in SPSS version 21. Using the enter method, a significant model emerged ($F_{5, 74} = 3.476$, $p<0.05$). The adjusted R-square value suggests that the model explains 19.0 % of the variance in the dependent variable (hourly PM_{10} concentrations). This is not a large proportion, and it is likely that other variables such as industrial emissions (not included in the model since data is not available) have a significant influence on ambient PM_{10} concentrations. However, the addition of the Durban pressure variable does increase the explanatory power of the model relative to the first model above. Explanatory variables are shown below in Table 25. The model suggests that:

- For every degree increase in delta temperature, hourly PM_{10} increases by 10.9 µg/m^3;
- For every one unit increase in the traffic index, hourly PM_{10} increases by 13.8 µg/m^3; and
- For every m/s increase in wind speed, hourly PM_{10} increases by 10.5 µg/m^3

Interestingly, the relationship between PM_{10} and wind speed is positive during these events. Initially it was thought that this could be related to stack tip downwash (Diab *et al.*, 2002) due to higher wind speeds associated with the approaching front. However, it was found that during pre-frontal events, wind speeds are lower than the annual average. It is possible that wind speed as the front approaches correlates with the strength of the front and its influence on mixing depth, but then we would have expected multicollinearity between this variable and delta temperature. Thus this relationship becomes difficult to explain and may merely be an artefact of a model with weak explanatory power. While Durban pressure minimum appears to have a negative relationship with PM_{10} concentrations, this relationship was not significant at the 95% confidence level. This tentatively suggests that even when controlling for frontal influences on delta temperature, lower pressure minima (i.e. stronger frontal systems) are associated with higher pollution levels. Further investigation and a larger dataset could enhance our understanding of this relationship. Minimum pressure in Cape Town as the front passed there was not a significant explanatory variable and should be dropped from the model, however these non-significant variables are left here for explanatory purposes. The standardized coefficients suggest that traffic levels are the most powerful explanatory variable in this model, followed by delta temperature, and then wind speed.

Table 25: Regression analysis of pre-frontal pollution incidents at Wentworth.

Model	Unstd. Coeff.		Std. Coeff.	t	Sigma	95% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
+-Constant	1707.144	1340.965		1.273	0.207	-964.788	4379.076		
Delta Temperature	10.919	4.231	0.328	2.581	0.012	2.488	19.35	0.677	1.477
Wind Speed	10.461	4.074	0.301	2.568	0.012	2.344	18.579	0.798	1.253

Model	Unstd. Coeff.		Std. Coeff.	t	Sigma	95% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
Traffic	13.826	4.324	0.425	3.198	0.002	5.210	22.442	0.620	1.612
Durban Pressure	-1.978	1.3	-0.189	-1.522	0.132	-4.568	0.612	0.709	1.41
Cape Town Pressure	0.347	0.823	0.049	0.421	0.675	-1.294	1.987	0.824	1.214

Unfortunately, these model outputs and correlation analysis in Section 5.6.3 above suggest that pollution concentrations and meteorology in Cape Town as a front approaches are not effective predictors of pollution conditions in the DSB when the front approaches there. However, results do show that that higher delta temperature in the DSB are indicative of higher pollution values, and that pollution incidents are more likely during peak traffic periods. Furthermore the data shows that lower wind speeds are generally associated with higher pollution levels, but with an approaching front, it is higher wind speeds are associated with higher pollution levels. Thus, warnings could be given out to the public to be aware of potential pollution incidents when

- Delta temperatures are high or increasing and wind speeds are low, particularly during peak traffic periods; and
- A front is approaching, particularly if the system has a particularly low pressure centre, and wind speeds are high and particularly if its approach or passing coincides with a peak traffic period.

Further consideration is to be given to the possibility of post-frontal stack-down wash events when wind speeds are highest after the passing of a front.

Community strikers protesting the high levels of air pollution in the DSB (SDCEA, 2009b)

6 FINAL COMMENTS AND CONCLUSIONS

This study examined the relationships between a range of meteorological variables in Durban and Cape Town as well as a reported emission events database to air pollution events in the Durban South Basin for the period between 2006 and 2010. This was achieved by acquiring air pollution datasets from the eThekwini Municipality and City of Cape Town monitoring networks as well as meteorological data at hourly resolution and synoptic charts from the South African Weather Services. A community complaints database for the DSB was acquired from the SDCEA for the period 2006 to 2010.

Annual average SO_2 and PM_{10} concentrations measured by the Ganges, Southern Works and Wentworth monitoring stations for the period 2006 to 2010 were analysed in this study. Results confirmed a general increase in PM_{10} and SO_2 concentrations during winter and a decrease in PM_{10} and SO_2 concentrations during summer. While the number of 24-hour average PM_{10} exceedences measured at the Ganges station for the period 2007 to 2009 were above the NAAQS of 4 times per a year, no exceedences were recorded in 2010. These results suggest that objectives of the municipalities AQMP and SDB-MPP are being achieved, but this would need to be validated with more recent data which has not yet been released in the form of annual air quality reports. PM_{10} concentrations measured at the Goodwood and Bellville stations in Cape Town remain fully compliant with the annual NAAQS whilst PM_{10} concentrations measured at Khayelitsha fall marginally below the standard for the period 2007 to 2010. SO_2 concentrations similarly show a decreasing trend with Goodwood and Bellville measuring the highest concentrations in 2006. No SO_2 data was collected in 2009 by either station.

Pollution incidents were defined in the study as three or more consecutive hours when PM_{10} concentrations are above a 100 µg/m^3 threshold. If two such incidents occurred within 24-hours of each other, they were grouped together as a pollution event. Of the 96 events identified across the monitoring stations, only 18 (18.75%) correlated with community complaints in the SDCEA database. The ten events with the highest hourly PM_{10} values were selected for further analysis and description. All ten events occurred between May and August of each year. This was expected as during this time of year, high pressure dominates, resulting in subsidence inversion and a narrowing of the mixing depth. Furthermore, overnight/early morning radiative inversions are more prevalent and tend to be stronger, thus limiting vertical dispersion. The PM_{10} and SO_2

data were plotted against delta temperature (change in temperature with height) to assess the conditions of stability and atmospheric pressure. This analysis revealed three meteorological scenarios associated with high pollution levels in the DSB:

1) **A pre-frontal scenario** where pollution peaks just prior to the front or low passing over, usually with high delta temperatures (usually strong inversion conditions) and gentle winds before the frontal squall;

2) **Still, weak inversion conditions** associated with a front, but generally weak to strong inversion conditions are present and gentle wind speeds;

3) **A post-frontal scenario** with peaks in pollution just subsequent to the passing of a front during the period of strong south-westerly winds. At this point, delta temperatures are decreasing, pressure is increasing and wind speeds are often strong. This scenario is most likely associated with stack-tip downwash. This scenario is important because it was not recognised in the previous study by Scott and Diab (2000) and yet this scenario shows the highest average and peak PM_{10} values.

ANOVA revealed significant differences between peak PM_{10} and average PM_{10} across scenarios, with Scenario 3 showing highest average and peak PM_{10}. At the Wentworth monitoring station, 24.4% of pollution incidents fell under Scenario 1, 64.2% under Scenario 2, and 5.7% under Scenario 3. A further 5.7% of the air pollution incidents did not fall under these three scenarios. The latter were not associated with fronts, and did not show inversion conditions, and are likely to be associated with intermittent industrial pollution events.

A statistical analysis assessed the relationships between various meteorological variables, traffic levels and air pollution concentrations at the Wentworth station. Findings show that delta temperature (change in temperature with height) is the strongest explanatory variable with respect to $PM_{10,}$ wind speed the second strongest, and traffic levels the third strongest. On average:

- For every degree increase in delta temperature, hourly PM_{10} at Wentworth increased by 9.3 µg/m^3;
- For every one unit increase in the traffic index, hourly PM_{10} at Wentworth increases by 2.0 µg/m^3; and
- For every 1 m/s increase in wind speed, hourly PM_{10} decreases by 1.3 µg/m^3

The pressure minimum at Durban associated with an approaching front showed a negative relationship with PM_{10} during pre-frontal events, but this variable was not significant at the 95% confidence level. This tentatively suggests that even when controlling for frontal influences on delta temperature, lower pressure minima (i.e. stronger frontal systems) are associated with higher pollution levels. Pollution maxima at various Cape Town stations and pressure minima in Cape Town prior to the incident in the DSB showed no clear relationships with incident PM_{10} levels at Wentworth.

Unfortunately, these model outputs and the correlation analysis in Section 5.6.3 above suggests that pollution concentrations and meteorology in Cape Town as a front approaches do not appear to be effective predictors of pollution conditions in the DSB when the same front approaches there. However, results do show that that higher delta temperature in the DSB are indicative of higher pollution values, and that pollution incidents are more likely during peak traffic periods. Furthermore the data shows that lower wind speeds are generally associated with higher pollution levels, but with an approaching front, it is higher wind speeds are associated with higher pollution levels. Thus, warnings could be given out to the public to be aware of potential pollution incidents when

- Delta temperatures are high or increasing and wind speeds are low, particularly during peak traffic periods; and
- A front is approaching, particularly if the system has a particularly low pressure centre, and wind speeds are high and particularly if its approach or passing coincides with peak traffic period.

Further consideration should be given to the possibility of post-frontal stack-down wash events when wind speeds are highest after the passing of a front.

South African Petroleum Refinery (SAPREF) in the Durban South Basin

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Pressure gauge at a petrochemical refinery in the DSB

8 APPENDIX A

1.1 GANGES MONITORING STATION

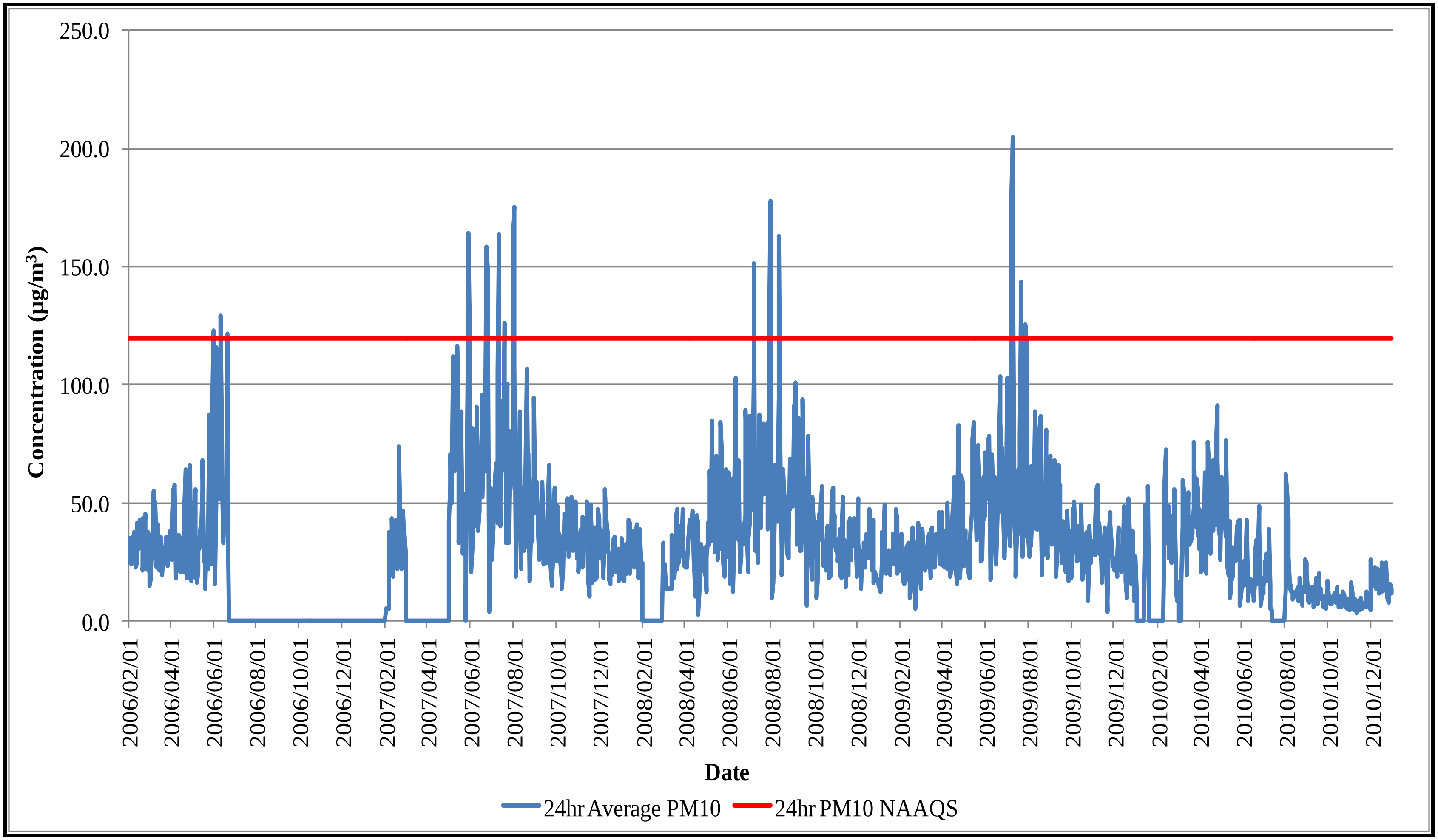

Figure 1: Graph showing 24-hour average PM_{10} concentrations measured by the Ganges station and the 24-hour PM_{10} NAAQS for the period 2006 to 2010.

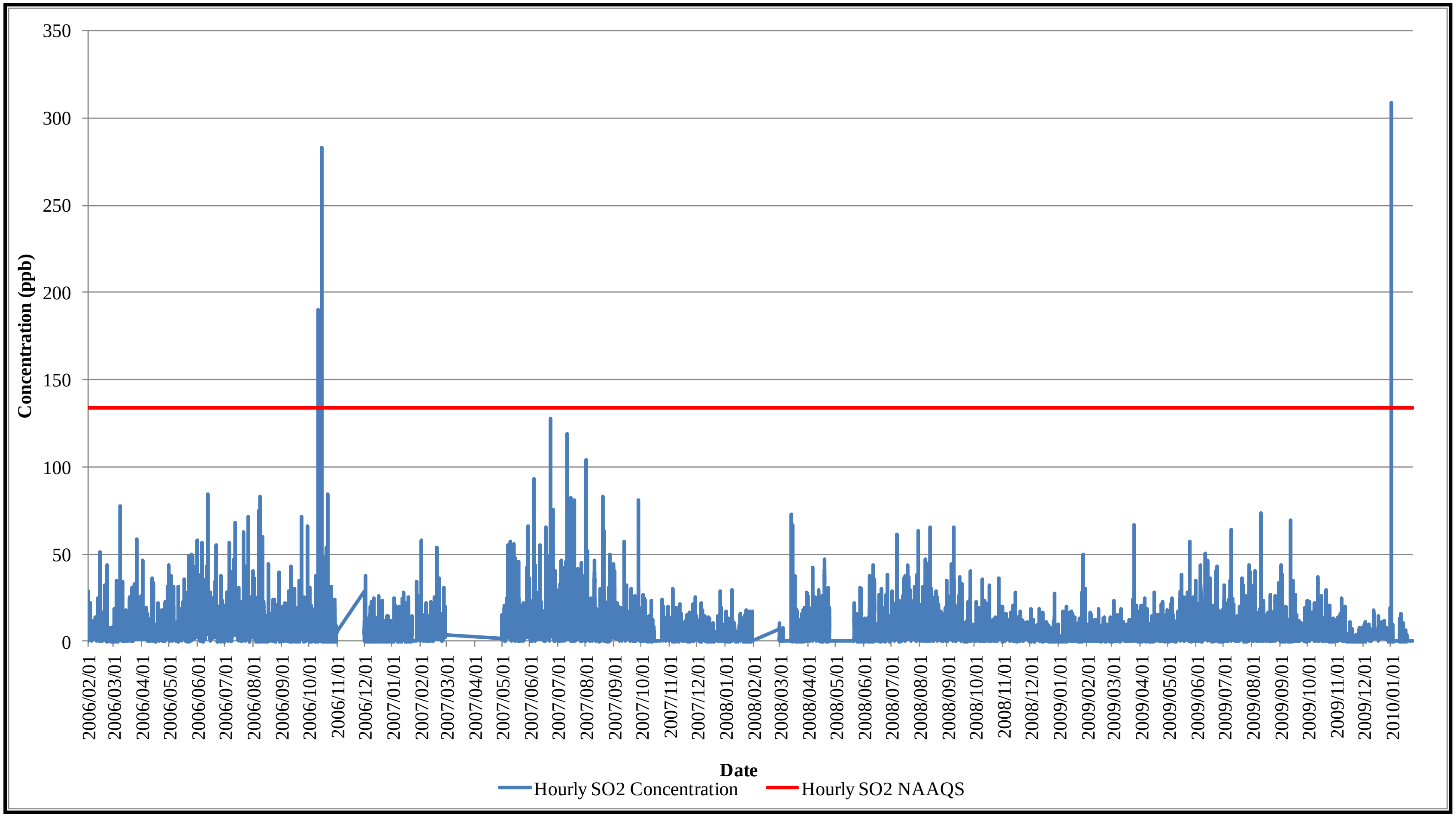

Figure 2: Graph showing hourly average SO_2 concentrations measured at the Ganges station and the hourly SO_2 NAAQS for the period 2006 to 2010.

1.2 WENTWORTH MONITORING STATION

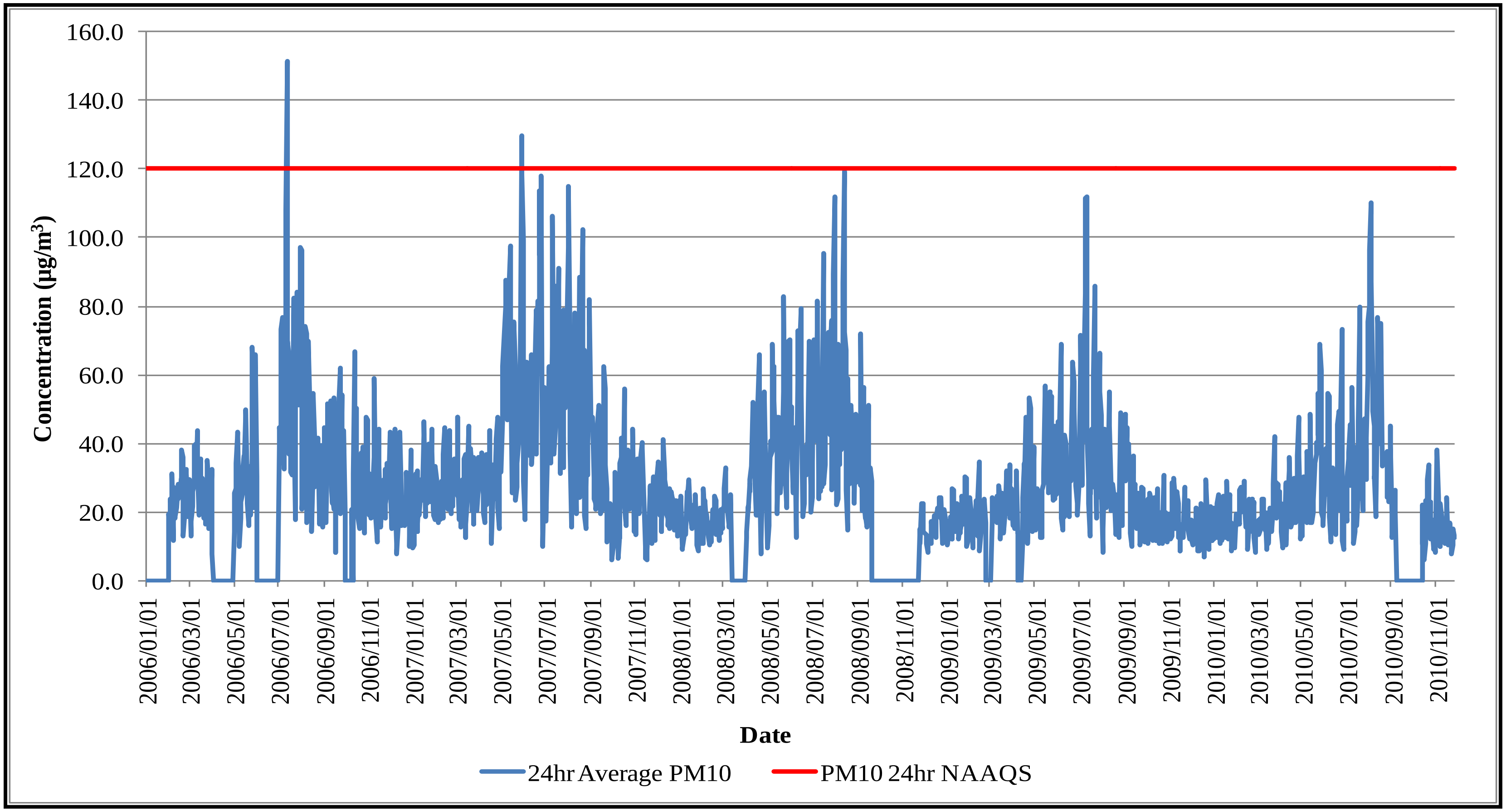

Figure 3: Graph showing 24-hour average PM_{10} concentrations measured by the Wentworth station and the 24-hour PM_{10} NAAQS for the period 2006 to 2010.

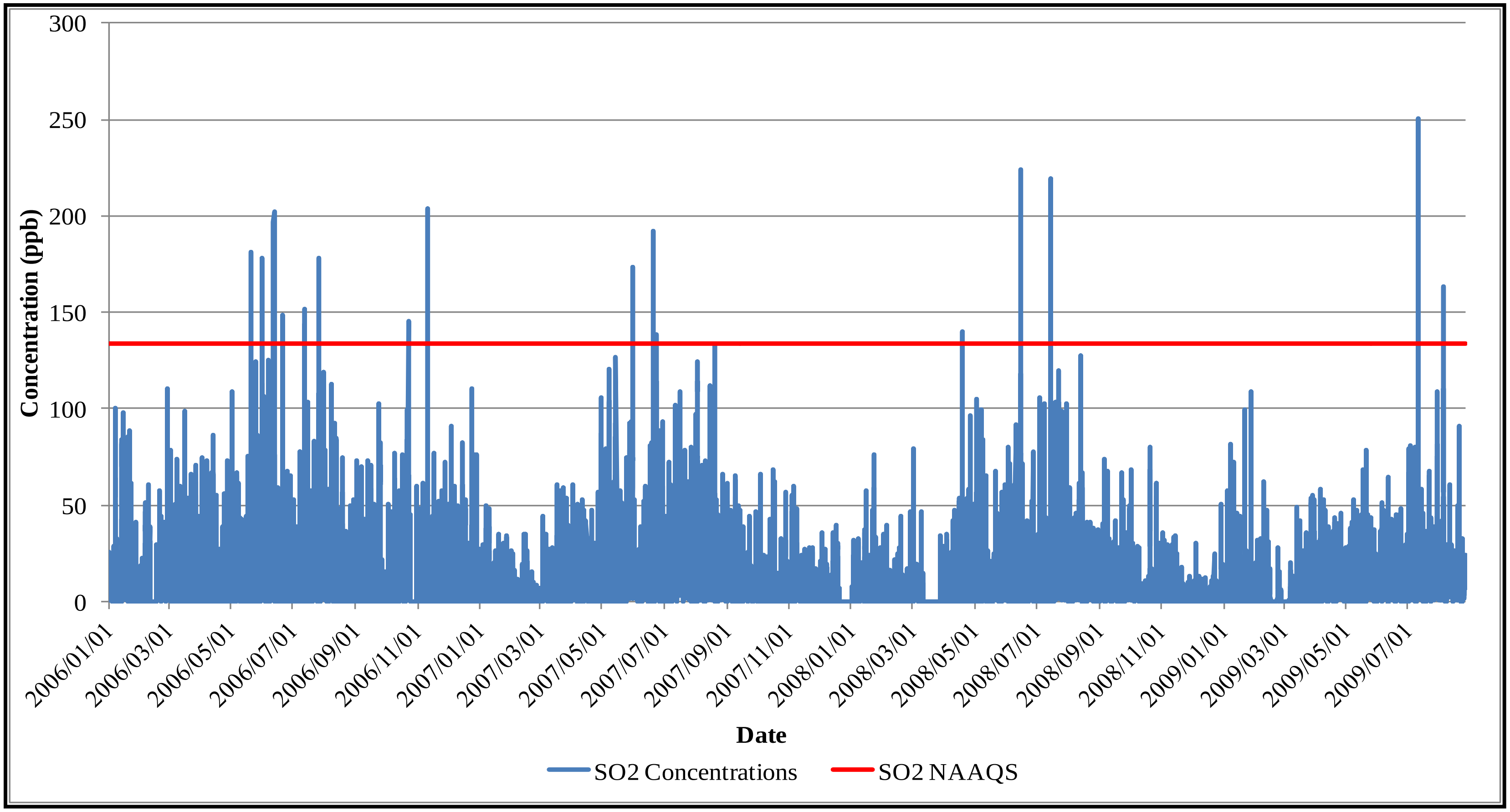

Figure 4: Graph showing hourly average SO_2 concentrations measured at the Wentworth station and the hourly SO_2 NAAQS for the period 2006 to 2010.

1.3 SOUTHERN WORKS MONITORING STATION

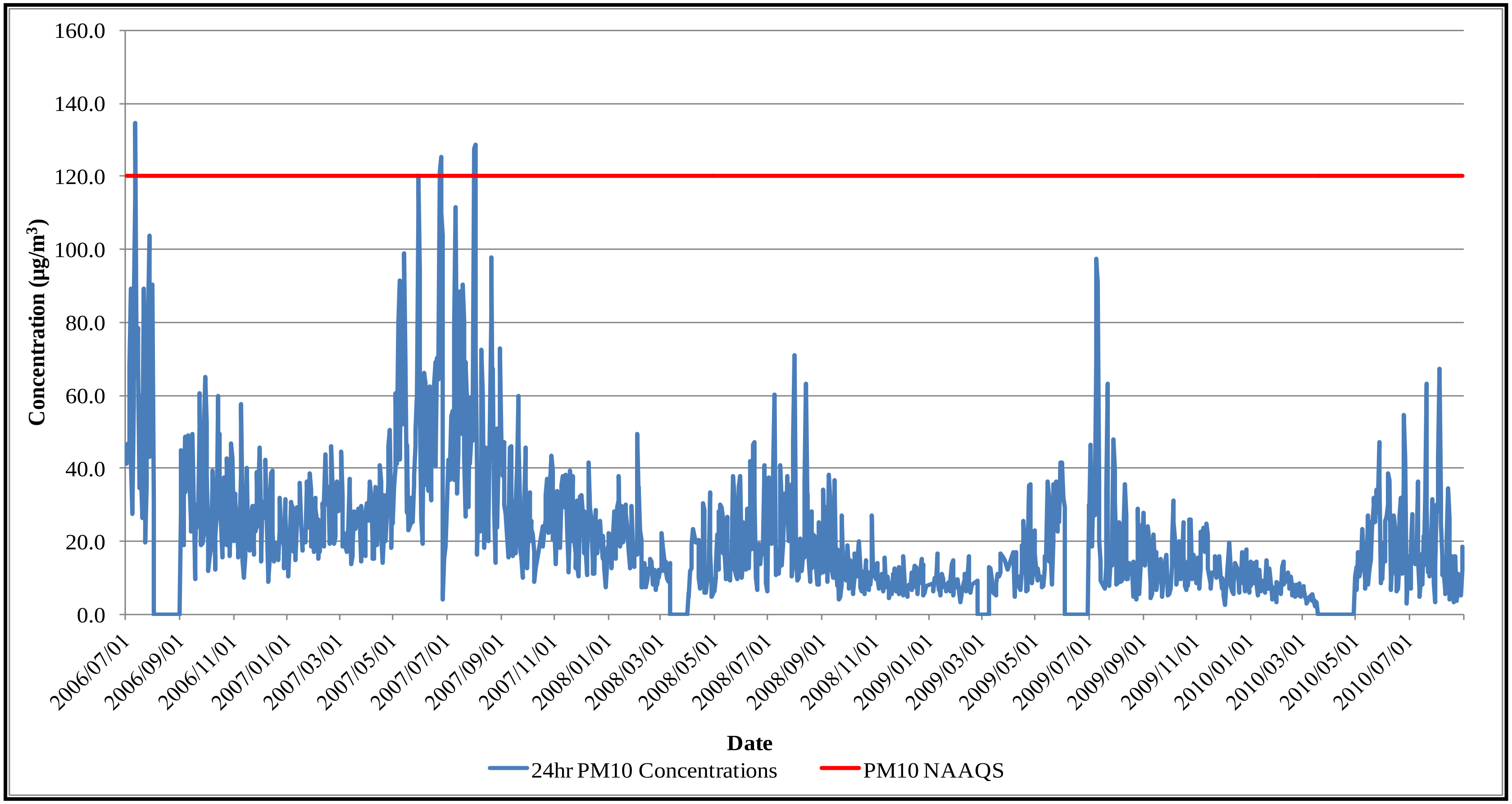

Figure 5: Graph showing 24-hour average PM_{10} concentrations measured by the Southern Works station and the 24-hour PM_{10} NAAQS for the period 2006 to 2010.

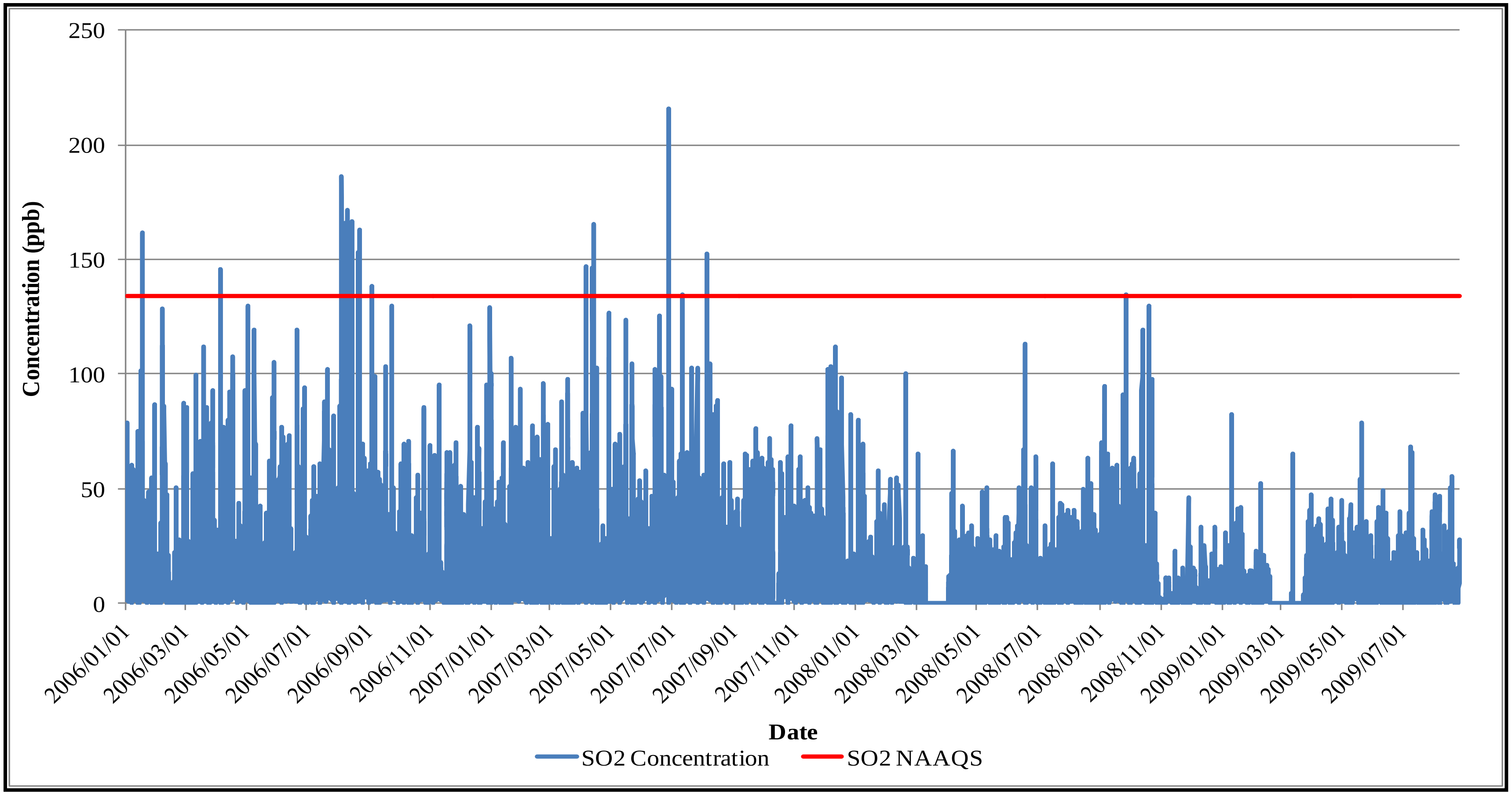

Figure 6: Graph showing hourly average SO_2 concentrations measured at the Southern Works station and the hourly SO_2 NAAQS for the period 2006 to 2010.

1.4 BELLVILLE MONITORING STATION

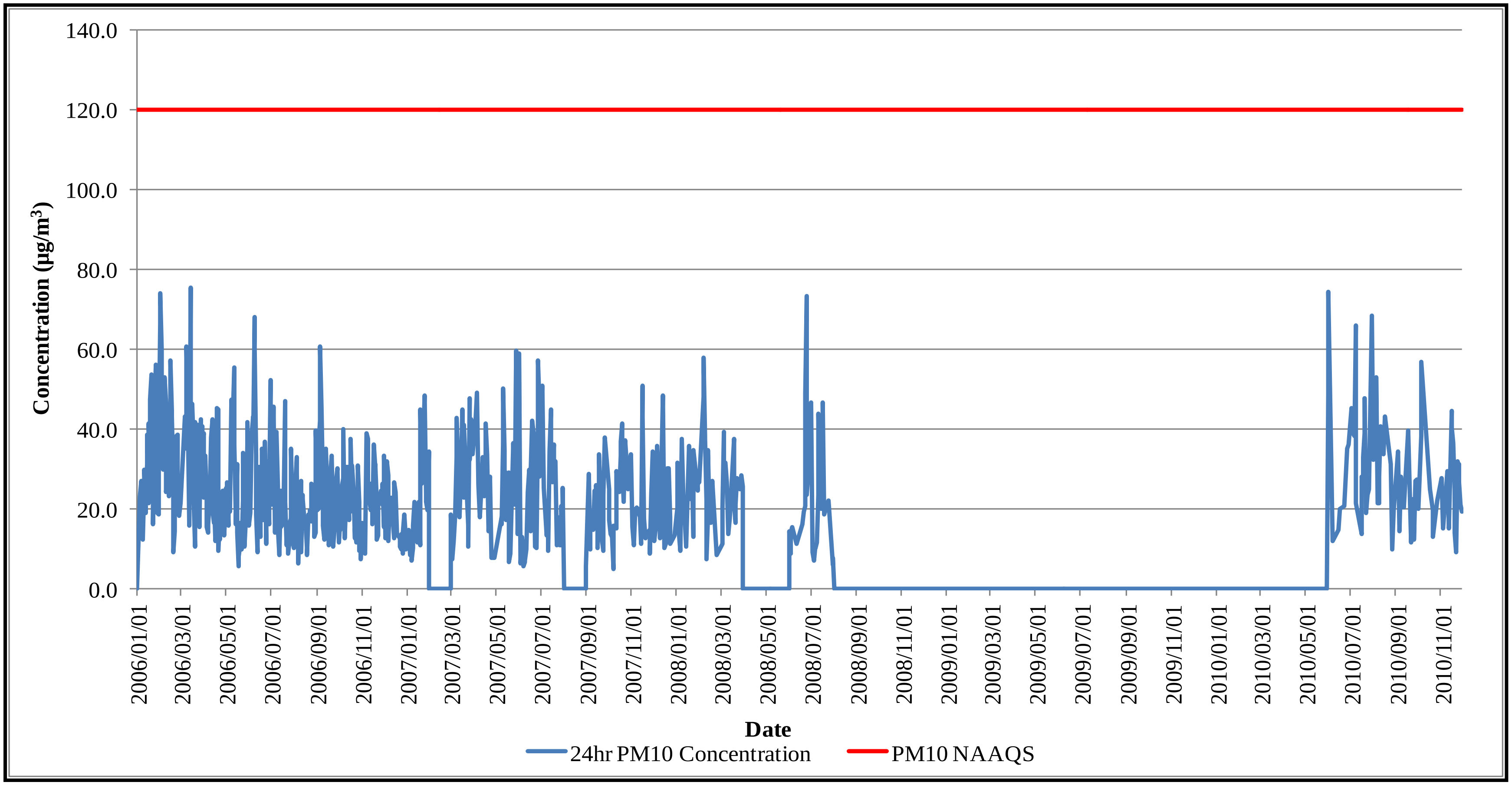

Figure 7: Graph showing 24-hour average PM_{10} concentrations measured by the Bellville station and the 24-hour PM_{10} NAAQS for the period 2006 to 2010.

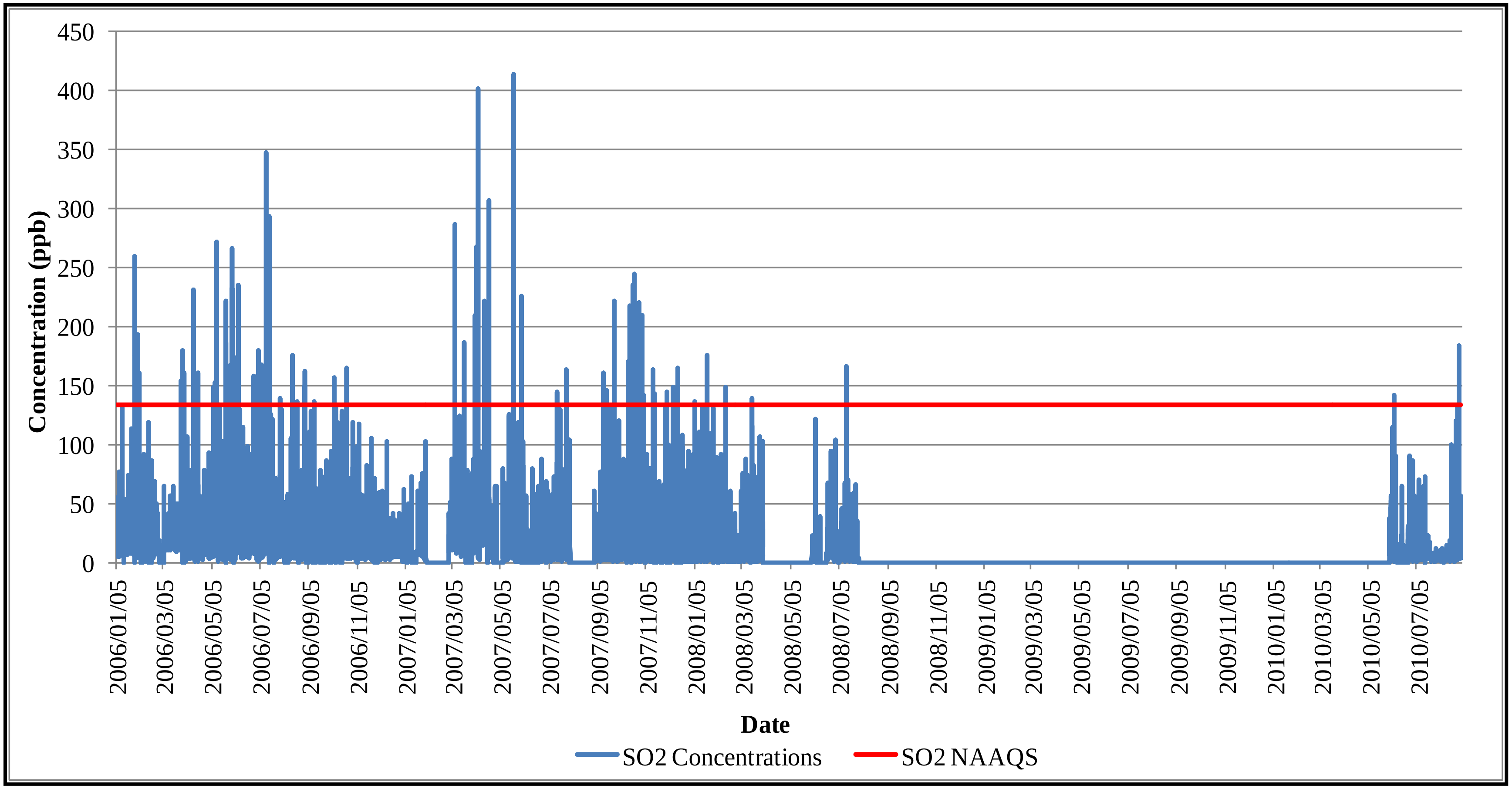

Figure 8: Graph showing hourly average SO_2 concentrations measured at the Bellville monitoring station and the hourly SO_2 NAAQS for the period 2006 to 2010.

1.5 KHAYELITSHA MONITORING STATION

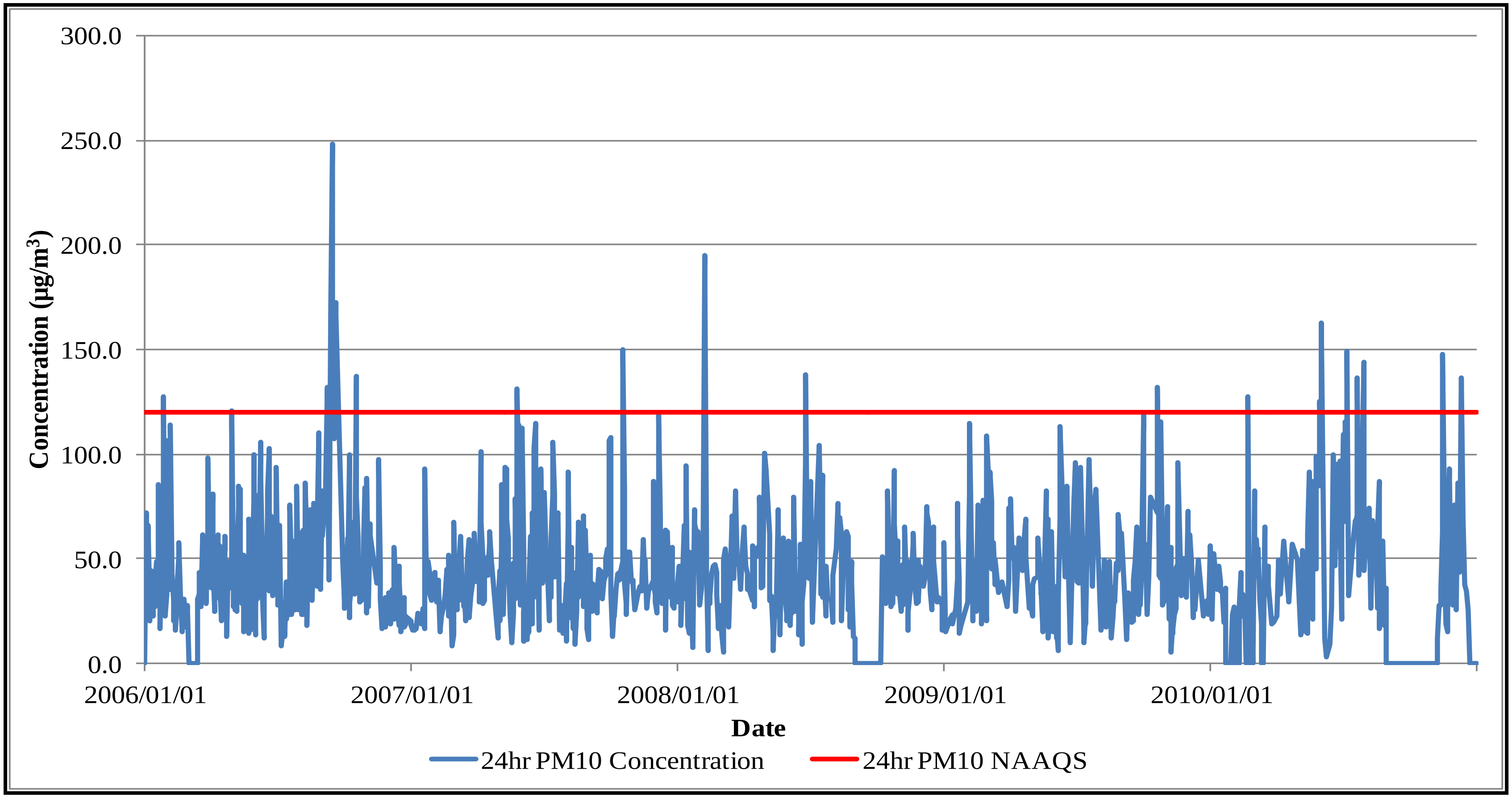

Figure 9: Graph showing 24-hour average PM_{10} concentrations measured by the Khayelitsha monitoring station and the 24-hour PM_{10} NAAQS for the period 2006 to 2010.

1.6 GOODWOOD MONITORING STATION

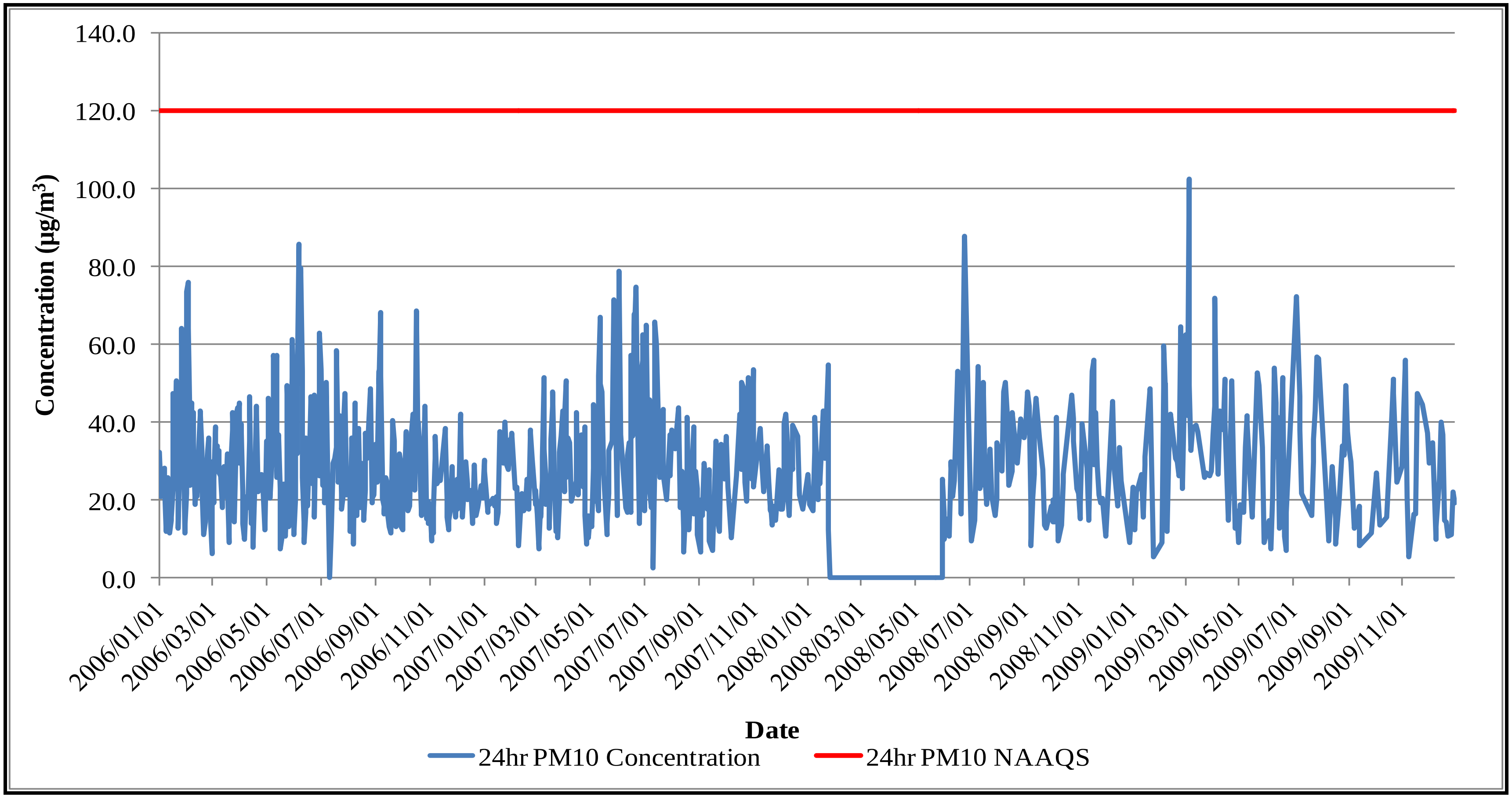

Figure 10: Graph showing 24-hour average PM_{10} concentrations measured by the Goodwood monitoring station and the 24-hour PM_{10} NAAQS for the period 2006 to 2010.

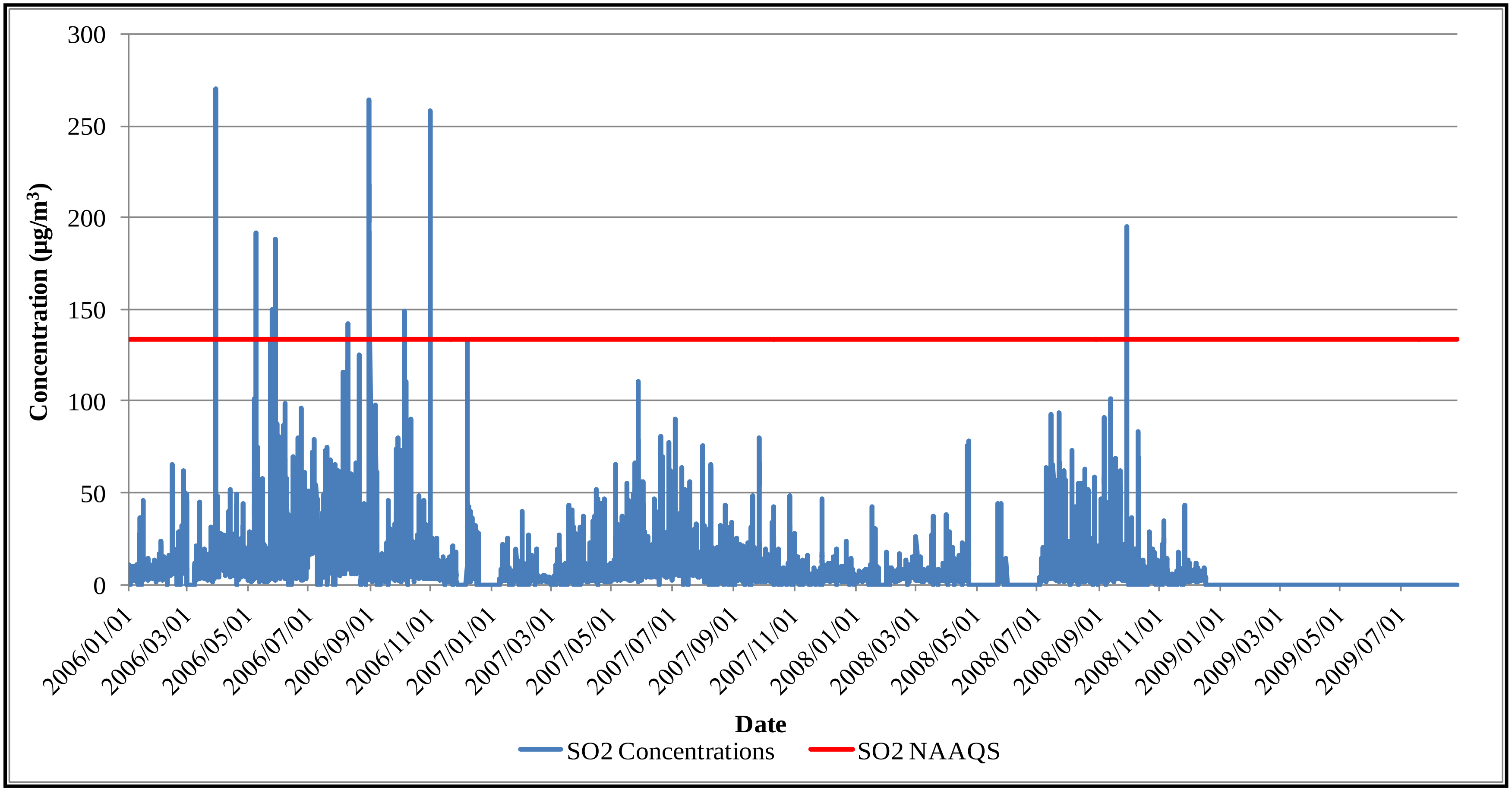

Figure 11: Graph showing hourly average SO_2 concentrations measured at the Goodwood monitoring station and the hourly SO_2 NAAQS for the period 2006 to 2010.