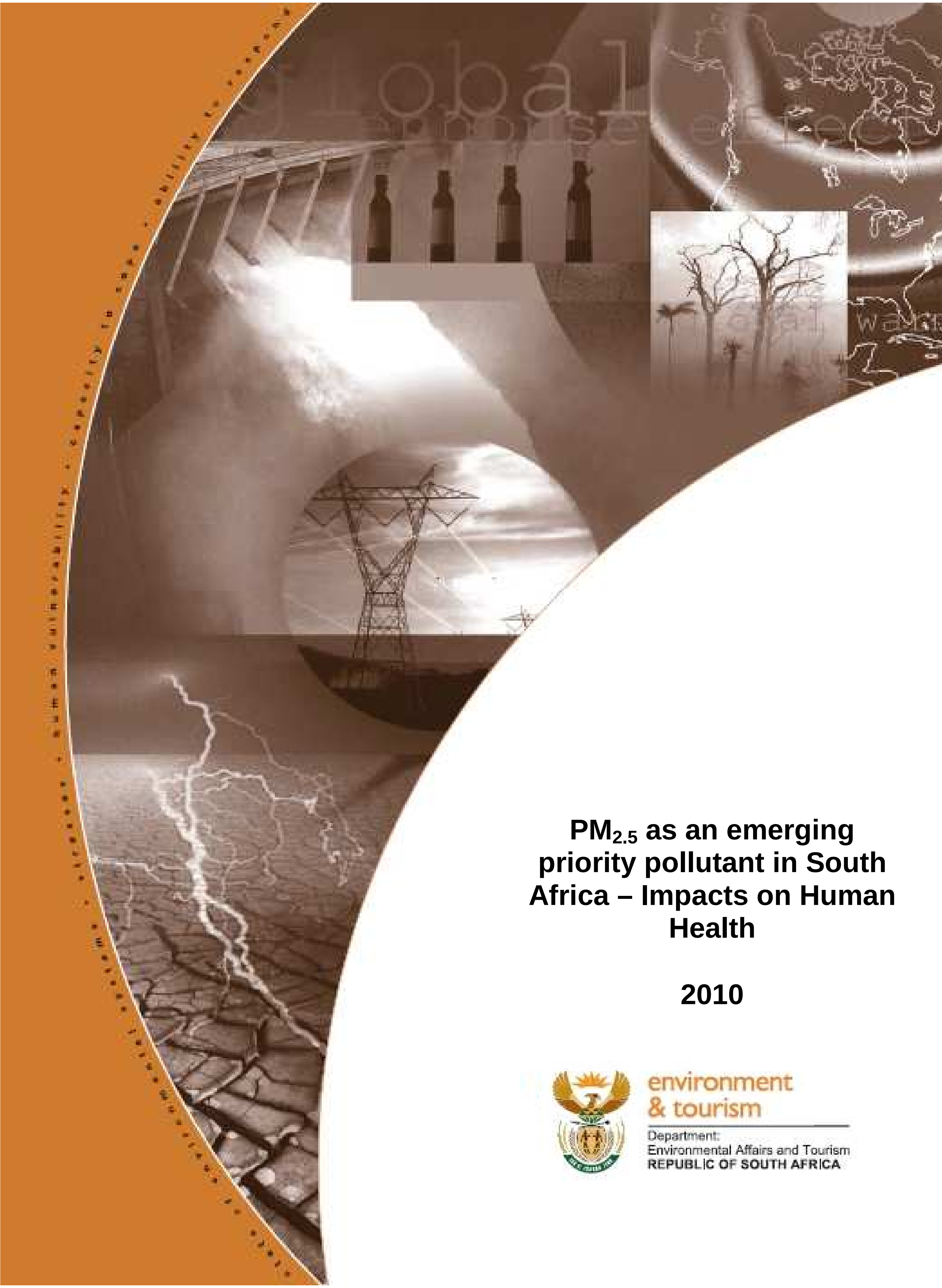

$PM_{2.5}$ as an emerging priority pollutant in South Africa – Impacts on Human Health

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PM2.5 as an emerging priority pollutant in South Africa – Impacts on Human Health

This document contains information on emerging issues that may affect the future state of the environment. The purpose of this paper is to draw attention to issues in preparation for the next state of the environment reporting cycle.

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Introduction

Particle pollution is a combination of microscopic solid particles and liquid droplets in the air. This pollution is known as particulate matter (PM). Fine PM is described as those particles with a diameter of 2.5 micro meters (µm) and less, which is about 1/30th the width of a single strand of human hair. Such small particles pose a great risk to human health as they are able they enter deep into the lungs thereby affecting our respiratory systems. Table 1 provides a definition of important terms.

Table 1. Definition of terms

Term	Definition
Total Suspended Particulate Matter (TSP)	All solid and liquid particles suspended in the air
PM_{10}	Particles with an aerodynamic diameter of less than 10 µm
$PM_{2.5}$	Particles with an aerodynamic diameter of less than 2.5 µm
Nanoparticles	Particles with an aerodynamic diameter of less than 0.1 µm

Epidemiological evidence and refined detection technology have highlighted $PM_{2.5}$ is an air pollutant of concern. In South Africa, much work has been done to address air pollution in recent years. However, few monitoring stations measure ambient $PM_{2.5}$ and little exposure and toxicity (dose-response and health outcomes due to $PM_{2.5}$ exposure) data are available. These shortfalls need to be addressed before a fine particle standard may be issued in South Africa. This, together with other important issues, is discussed below.

Discussion

Sources of PM

In general, most solid particles comprising PM enter the atmosphere directly by emission from natural and anthropogenic sources, i.e. primary sources. Natural sources include wind-blown dust (minerals and organic material), volcanic eruptions, biomass burning, sea spray and biological materials (pollens and spores). Combustion of fossil fuels (especially domestic solid fuel burning in urban and rural areas), agricultural burning and industrial processes are classified as anthropogenic sources. PM composition is extremely transformable and depends on factors such as climate variations, emission sources and geographical position (Polichetti *et al*., 2009).

Some particles are created from gaseous molecules in a process called nucleation. Other particles are formed by chemical reactions, e.g. formation of sulphate aerosols from SO_2 (WHO, 2000a) and are considered secondary particles. They may consist of several elements (e.g. Silica and Iron), transition metals (e.g. Nickel, Zinc), lead, inorganic ions (e.g. NH_4^+, SO_4^{2-}) and volatile organic compounds. Evidence suggests that sulphate particles may be a better indication of possible adverse health effects than $PM_{2.5}$ alone. Relative risk for total mortality was, for example, found to be 1.14 for $PM_{2.5}$ but 1.33 for sulphates (WHO, 2000a). Therefore, the risk of death when exposed to sulphates is greater than when exposed to $PM_{2.5}$.

Possible Human Health Effects from PM exposure

PM has recently been receiving much attention because of its impacts on human health. There is increasing evidence to suggest exposure to PM via inhalation, ingestion or dermal contact causes adverse human health effects. The main health effects of concern are exacerbating existing respiratory diseases, cardiovascular diseases and lung cancer. Individuals suffering from respiratory and cardiovascular illnesses and diseases, children and the elderly are particularly at risk (US EPA, 2009). Physiological systems (especially defence mechanisms) are compromised in people with existing diseases; they are underdeveloped in children and considered to be declining in the elderly.

Particle size is especially important for its impact on human health, particularly the respiratory system (Figure 1). The smaller the particle's size, the greater the particle's potential to cause adverse health effects (Table 2).

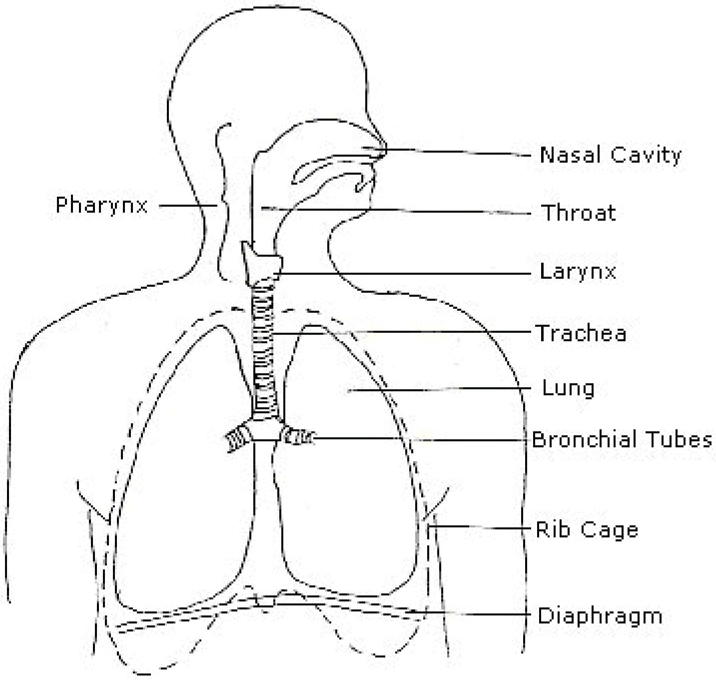

Figure 1. Human respiratory system (Source: Electrical Res Inc)

Table 2. Site and reaction of human respiratory system to particles of various sizes

Site of deposition	Particle or droplet diameter	Inhalable or respirable	How does the body handle this material?
Upper respiratory tract (nasal passages and pharynx)	2.5 - 10 µm* (coarse)#	Inhalable	Sneezing and filtering by nasal hairs
Lower respiratory tract (alveoli – within lungs)	< 2.5 µm (fine) #	Respirable	Uptake by the vascular system with subsequent engulfment by macrophages, which move the material to the terminal bronchi to be cleared by the mucociliary escalator

Note. *Source: (DEA, 2009). Inhalable is defined as 'that which can be inhaled'. Respirable is defined as 'that which can be inhaled deep into the lung'. #Source: (WHO, 2005).

Particles larger that are 2.5 μm and less than 10 μm are known to enter the nose, throat and upper lungs and are, therefore, considered inhalable. Particles smaller than 2.5 μm in diameter are considered respirable since they may potentially enter even deeper into the lungs. This is possibly one of the reasons why $PM_{2.5}$ showed stronger associations with adverse health effects than PM_{10} and much stronger than TSPs (Lippmann, 1998).

The associated range of $PM_{2.5}$ specific adverse acute and chronic health effects include respiratory hospital admissions, bronchodilator use, cough and lower respiratory symptoms, changes in peak expiratory flow, cardiovascular stress and mortality (US EPA, 2009). Adverse health effects in children, such as bronchitis and a reduction in lung function, are associated with long-term (chronic) exposure to $PM_{2.5}$ at concentrations even below 20 μg m^{-3}, hence the World Health Organization (WHO) suggesting that there is no safe limit below which adverse effects are unlikely (WHO, 2000a). These fine particles also stay in the air for longer periods of time than coarser PM_{10} particles (days to weeks versus minutes to hours) and may, therefore, also travel much further (WHO, 2000a), thereby increasing exposure.

Other Effects of PM

PM composition not only impacts upon human health, but also the natural environment. Plants may be even more sensitive than humans to the effects of excess PM in the atmosphere, although whether this is specifically in relation to $PM_{2.5}$ remains relatively unknown. Heavy metals may cause fatal damage to some plant species resulting from phytotoxicity and abrasion during deposition. Deposition loads may also block stomata thus decreasing the rate of transpiration and reduce the amount of light reaching the chloroplasts, thereby decreasing the rate of photosynthesis (Prajapati and Tripathi, 2008). The wet and dry deposition of acidic particles on surface water may cause the water to become more acidic, thereby having a detrimental effect on aquatic systems (Bhattacharjee *et al*., 1999).

Impacts upon soil, and infrastructure, e.g. corrosion of buildings and soot staining of buildings, are also likely. Studies have shown that exposure of materials to particles in the air, may cause soiling, which means that the material degrades to such an extent that it needs to be cleaned or painted more often, thus having an effect on the life expectancy of the material, which has an economic implication. Examples of degradation are metals that corrode faster when exposed to acid forming aerosols and paint that becomes discoloured or loses gloss (Bhattacharjee *et al.,* 1999).

Expanding Epidemiological Evidence

Evidence collected in epidemiology studies has shown that ambient PM is associated with adverse health effects and that increases in concentrations result in increases in morbidity and mortality (Dockery *et al.*, 1993, Pope *et al.*, 1995, Pope *et al*. 2002, Brunekreef and Holgate, 2002, Lippmann, 2003). The WHO's view is that no safe level for PM exists and in 2000 it was reported that, annually, approximately 500 000 individuals die globally from diseases and illnesses associated with exposure to PM and SO_2 (WHO, 2000b).

Not all $PM_{2.5}$ particles are equally toxic, since toxicity depends not only on size and chemical composition but also on other characteristics such as (Fubini and Fenoglio, 2007):

- Form – amorphous silica is less toxic than crystalline silica.
- Surface reactivity – particles' surface sites may react with biological molecules. This reactivity and thus the toxicity, may be enhanced by pollutants such as poly-aromatic hydrocarbons (PAHs), adsorbed to the particle.
- Solubility in biological fluids– the longer the particles stay in the body unchanged, it will cause an effect on cells and tissue in the body.

Epidemiological as well as *in vitro* and *in vivo* studies showed adverse effects due to $PM_{2.5}$ exposure. In an *in vitro* study where alveolar macrophages of rats were exposed to different concentrations of $PM_{2.5}$ particles sampled from normal ambient air and from dust storms at two cities, a decrease in cell viability and an increase in damage to DNA of alveolar macrophages were found (Meng and Zhang, 2007). The same authors used the same particles in an *in vivo* study where rats were instilled using different concentrations. DNA damage to lung cells were the result of this experiment. The effects introduced by the particles from the dust storm were less toxic in both studies, confirming that size is not the only characteristic determining toxicity. The damage to the macrophages (that clear the lungs of PM) indicated that lung clearance could be affected by the toxicological effects that these fine particles may have on macrophages. The effects found in these studies were dose-dependent. *In vitro* studies have found that $PM_{2.5}$ induced dose dependent oxidative stress and inflammation in human lung epithelial cells (Dagher *et al*., 2006).

An epidemiological study conducted on street vendors found statistical significant associations between $PM_{2.5}$ and eye irritation and dizziness (Kongtip *et al.*, 2006). Several other epidemiology studies reported associations between $PM_{2.5}$ and adverse effects such as coronary heart disease, thrombosis, aneurism, vasculitis, lung cancer and premature mortality (Curtis *et al.,* 2006; Dagher *et al.,* 2006; Polichetti *et al.,* 2009). One of these studies, conducted in Chile, demonstrated an association between ambient air levels of $PM_{2.5}$ and visits of children to emergency facilities for respiratory illnesses (Curtis *et al.,* 2006).

In another study, it was established that if chronic exposure to $PM_{2.5}$ could be reduced to a level of 15 μg m^{-3}, there may annually be 11 612 less premature deaths due to cardiopulmonary causes and 1 901 less deaths due to lung cancer in 23 specific European cities (Boldo *et al.,* 2006).

The general increase observed in diseases such as asthma, chronic obstructive pulmonary disease and atherosclerosis over the past 20 years may be as a result of an increase in combustion processes including vehicle emissions (Li *et al.,* 2008). *In vitro* and *in vivo* studies involving ambient PM show toxic effects such as inflammation (Li *et al*., 2008). It has lately been established that ultrafine particulates (<0.1 μm in diameter) have the greatest potential to cause toxicological effects considering, amongst other things, their ability to penetrate deep into the lung and stay there, as well as their large surface area (where reactions may take place) in relation to their size (Li *et al*., 2008). No known ambient air quality standards for these ultrafine particles presently exist.

International actions towards addressing $PM_{2.5}$

Increasing emphasis has been placed on PM_{10} as strong evidence of a dose-response relationship has been supported by the WHO. A dose-response relationship refers to a person's exposure to higher pollution concentrations and therefore, the larger the dose passing into the body, the more severe the health outcome. However, $PM_{2.5}$ as an emerging priority pollutant has also been identified as a global concern. Only recently has technology and instrumentation for monitoring of fine and ultrafine particles become available. Data to describe trends in $PM_{2.5}$ are showing increasing patterns, probably as a result of increased population size, reliance on fossil fuel burning and vehicles as the main transport mode.

Epidemiological studies in Europe and the United States (US) are now being carried out to better understand the association between $PM_{2.5}$ exposure and possible health risks. Furthermore, several countries around the world are presently working towards establishing guidelines and standards for $PM_{2.5}$ emissions and ambient concentrations as new studies show possible human health risks.

The WHO set their first guideline for TSP in 1972 followed by "Air Quality Guidelines for Europe" in 1987 (WHO, 2000a) (Table 3). Revised WHO guidelines followed in 2000 (WHO, 2000b) and again in 2005 (WHO, 2005). Strict limits in support of low concentrations have been enforced by other countries (see Table 3).

Table 3. International Air Quality Standards and Guidelines for $PM_{2.5}$

	US EPA Standards	WHO Guidelines
Annual	15 μg m^{-3}	10 μg m^{-3}
24-hour	35 μg m^{-3}	25 μg m^{-3}

As technology developed globally, smaller particles could be monitored and epidemiology studies were able to determine associations between smaller particles and mortality and morbidity. Initial guidelines developed for TSP could include particles smaller than or equal to 10 μm in diameter (PM_{10}). The ratio of PM_{10} to TSP was found to be between 0.4 and 0.8 for most monitoring sites worldwide (WHO, 2000b).

In China, it was found that during the cold season when heating is necessary, 30 to 50 % of TSP could be classified as $PM_{2.5}$ (WHO, 2000b). In 1997, the Environmental Protection Agency (EPA) in the US approved a guideline for particles smaller than or equal to 2.5 μm in diameter (Sager, 2008) following extensive review of hundreds of health studies. Concurrently, the EPA issued standard methods for monitoring $PM_{2.5}$ in ambient air to determine which places in the country were being subjected to unhealthy levels. More than 1000 monitors were deployed in a nationwide network to collect quality-assured $PM_{2.5}$ data.

South Africa's Response to $PM_{2.5}$

South Africa is an arid country with high naturally-occurring dust levels, compounded by industrial and vehicular pollution emissions. The need to formally address air pollution and appropriate mitigation measures for improved air quality and human health was first recognised in the 1960s. The first attempt to alleviate air pollution was the promulgation of the Atmospheric Pollution Prevention Act No 45 of 1965 (Republic of South Africa, 1965). The first regulations that aimed at regulating fuel-burning apparatus that industries, hotels, dairies and dry cleaners were allowed to use, then followed. Certain residential areas were declared smoke-free zones. The first air pollution monitoring stations measured smoke (the darkening ability on filter paper) and SO_2 (wet chemistry method) (Oosthuizen, 2004).

In 2004, the National Environmental Management: Air Quality Act No 39 of 2004 (Republic of South Africa, 2004) came into effect. This legislation transferred the focus for air quality management from the source to the receiving environment. As part of its implementation, ambient air quality guidelines were drafted, presented for public comment and gazetted on 24 December 2009. These are given in Table 4 below.

Table 4. South African PM Standards

Interim South African PM Standards	**Averaging Period**	**Limit Value**
PM_{10}	24-hour	180 μg m^{-3}
	Annual	60 μg m^{-3}
TSP	24-hour	300 μg m^{-3}
	Annual	100 μg m^{-3}
New South African PM Standards up to 2014		
PM_{10}	24-hour	120 μg m^{-3}
	Annual	50 μg m^{-3}
South African PM Standards after 2014		
PM_{10}	24-hour	75 μg m^{-3}
	Annual	40 μg m^{-3}

No ambient air standards for $PM_{2.5}$ were included. There is growing international evidence (i.e. epidemiological studies linking adverse health effects to $PM_{2.5}$ exposure) to suggest that there is a need in South Africa for:

- a $PM_{2.5}$ ambient air standard,
- continuous monitoring of $PM_{2.5}$, and
- epidemiological studies to better understand the relationship between $PM_{2.5}$ exposure and adverse human health effects specific to South African conditions.

The 2005 State of the Environment Outlook (DEAT, 2005) identified $PM_{2.5}$ as an emerging priority pollutant; however, no $PM_{2.5}$ data were reported. Air quality was described as 'decreasing' in general and SO_2 and PM_{10} levels were deemed high. Health problems due to air pollution are expected to increase by 20% over the next decade, but this is for certain cities and geographical areas in South Africa and not an overall percentage for the country (DEAT, 2005).

An increased need for energy where energy supply tends to rely on combustion of fossil fuels is a likely contributing factor to the declining air quality. Furthermore, as the South African vehicle fleet continues to increase, vehicle exhaust emissions are predicted to continue increasing as much as 44% by 2011 (on levels referred to in 2008) if emission controls are not enforced. Indoor air pollution from domestic solid fuel burning for heating and cooking, mainly SO_2 and PM, was declared the most serious air pollution problem in South Africa (DEAT, 2005).

The South Durban Health Study found that $PM_{2.5}$ concentrations measured at three sites were nearly identical and ranged between 20-22 μg m^{-3} (eThekwini Municipality, 2007). Maximum 24-hr concentrations ranged between 79-131 μg m^{-3}, far exceeding the proposed US EPA annual standard and WHO annual guideline (Table 2). Moderate correlation was found between PM_{10} and $PM_{2.5}$ concentrations; however, the ratio between pollutants (generally constituting less than 50%) was not constant since emission sources present determine percentage contributions of fine and coarse particles (eThekwini Municipality, 2007). Although Durban is a coastal town and sea salt spray is present, this is the only study in South Africa to date that has attempted to consider ambient $PM_{2.5}$ and associated health effects, simultaneously.

PM may also reduce visibility (transparency of the atmosphere) through the scattering of sunlight (WHO, 2000a). Visibility degradation and light extinction by scattering and absorption by particles in large cities may be worsened by meteorological factors, such as humidity (Tao *et al.,* 2009). Fine particles are an order of magnitude more efficient in scattering light than coarse particles (Bhattacharjee *et al*., 1999), in other words fine particles will reduce visibility much more than course particles would. Poor visibility is especially a problem at airports where it may affect operations and it may also have a negative effect on tourism, because individuals will not visit scenic sites where visibility is reduced (Bhattacharjee *et al.,* 1999). In South Africa, Cape Town is synonymous with 'brown haze' during the winter months. 'Brown haze' comprises gases from industrial and vehicle emissions and includes NO_x, O_3, SO_2, PM and volatile organic carbons (VOCs). The brown colouration is caused by NO_2, some of which turns to O_3 during the day. A study in the late 1990s looked at whether $PM_{2.5}$ particles reduce visibility as a component of 'brown haze' in Cape Town by measuring $PM_{2.5}$ at four sites in the metropolitan area (Wicking-Baird *et al*., 1997). Results showed that the US $PM_{2.5}$ daily standard was not exceeded during 'brown haze' episodes measured, but it was likely to be exceeded on the worst 'brown haze' days.

$PM_{2.5}$ Monitoring in South Africa

The first records from monitoring of PM_{10} in ambient air in South Africa were during the Vaal Triangle Air Pollution and Health Study (VAPS) in the early nineties. Prior to this, PM was monitored as TSP (Oosthuizen, 2004). In the VAPS, it was found that concentrations of PM_{10} during summer months were lower than during winter months (Reddy *et al*., 1996). Domestic fuel burning was found to be the biggest contributor to PM_{10} (Scorgie *et al*., 2003).

Some air quality monitoring networks in local municipalities as well as industries also monitor $PM_{2.5}$. However, since the required equipment is relatively expensive, this is largely limited to the metropolitan areas of eThekwini, Cape Town and Johannesburg. Extensive work has been done at the Buccleuch Monitoring Station located in the centre of a large motorway interchange in the City of Johannesburg. Figure 2 presents recently collected $PM_{2.5}$ data at Buccleuch.

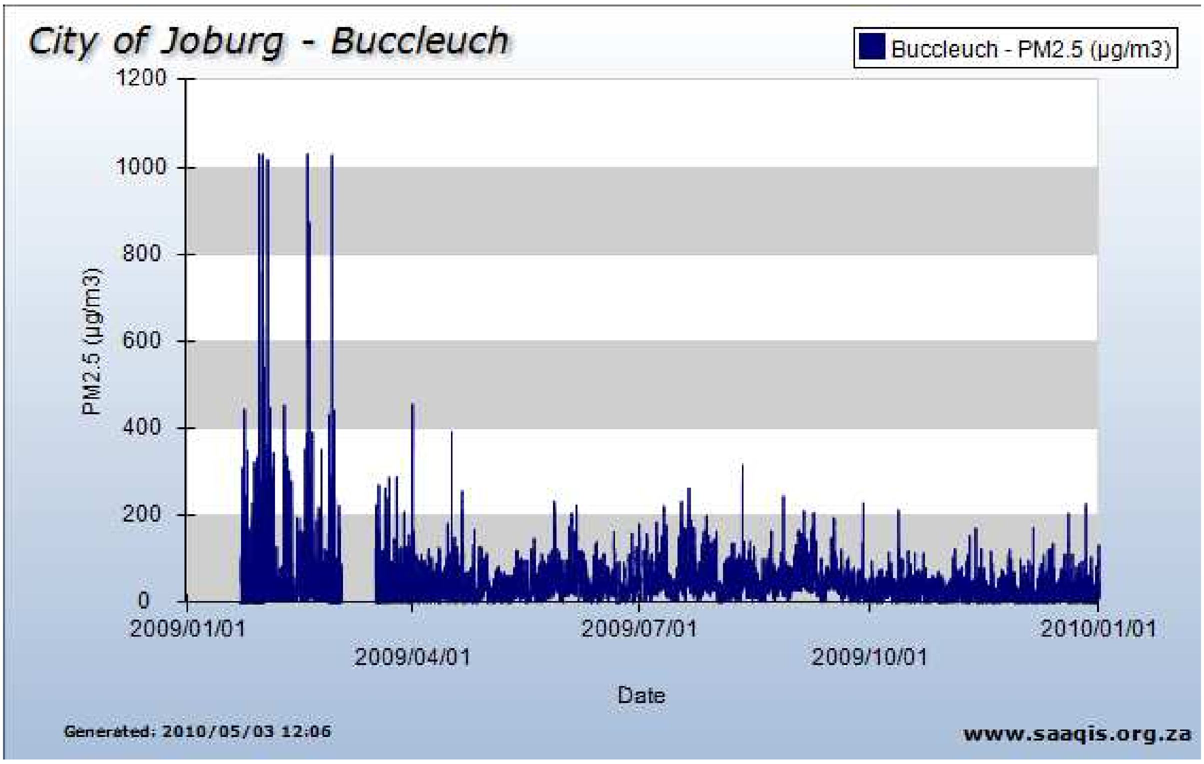

Figure 2. Daily averages of $PM_{2.5}$ at the Buccleuch Monitoring Station in Johannesburg from 1 February 2009 to 31 January 2010 (Source: www.joburgair.org.za)

A guideline of 25 µg m^{-3} was proposed but has not been established thus far. The majority of the daily averages exceed this proposed guideline, indicative of the high pollution levels emitted from vehicles which are the primary pollution source at this site.

Conclusions and Recommendations

Together, epidemiological evidence and advanced detection technology have raised concerns regarding exposure to $PM_{2.5}$ and adverse human health effects. Highly sensitive subpopulations, including asthmatics, the elderly and children, are at increased health risk when exposed to high levels of $PM_{2.5}$.

While there is sufficient international evidence to suggest the development of an ambient standard for $PM_{2.5}$ in South Africa, there is inadequate

South African-specific health evidence to determine the appropriate averaging period at this stage. When formal, continuous monitoring of $PM_{2.5}$ becomes routine across South Africa, and this is slowly taking place, we will better know what current trends are and future trends are likely to be.

It is recommended that South Africa begin to develop an ambient air standard for $PM_{2.5}$, and existing monitoring networks, if they have not done so already, begin monitoring $PM_{2.5}$ as soon as possible so that PM hotspots can be identified and epidemiological studies carried out.

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