THE CONTRIBUTION OF LONG-RANGE TRANSPORT OF AIR POLLUTION TO THE SULPHUR BUDGET OF THE UNITED ARAB EMIRATES

Mary Yvonne Evans

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ABSTRACT

An air chemistry study over the United Arab Emirates revealed a high concentration of sulphur dioxide. SO_2 and its resultant aerosols can have a significant effect on the atmospheric processes. These aerosols could both directly and indirectly affect the climate by scattering solar radiation and increasing the albedo of the atmosphere or by altering the cloud formation processes and characteristics. Sulphur dioxide and the resultant aerosols also have a damaging effect on the environment and on human health. Previous studies reviewed suggest that pollution can be transported for hundreds of kilometres from the source of the emission and affect the air chemistry of the receptor regions. The possibility that long-range transport of pollution to the UAE may have contributed to these high concentrations was also investigated. The possibility that the UAE is a receptor region of pollution transported over long distances is investigated with the intention of identifying the possible source regions of this pollution. In order to examine the import of pollution to the UAE it was important to analyse the background sulphur concentrations of the atmosphere over the UAE.

DECLARATION

I declare that, apart from the assistance acknowledge, this research report is my own unaided work. It is being submitted in partial fulfilment of the requirements for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg, South Africa. It has not been submitted before for any degree or examination in any other University.

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Mary Yvonne Evans

_____ day of _____ 2004

To my parents,

Gerald and Johanna Lepan

for the gift of learning,

and to my husband Graeme and

daughter Ffion for your love and inspiration

PREFACE

Air quality and air pollution control have become an international concern, as air pollutants are not confined to their emission sites but are transported across international boundaries; and the sources of air pollutants such as industrial plants and motor vehicles are in widespread use today (Baumbach, 1996; Schultz and Bey, 2004). Pollution characterised by high aerosol concentrations is of particular concern as aerosols may exert a climate forcing comparable in magnitude, but opposite in sign to that of greenhouse gases. Where the pollution contains sulphur-based gases and aerosols, the characteristics of sulphates and their trace gas precursors sulphur dioxide reveal a significant effect not only on the atmosphere and climate change but also on the environment and on human health.

In 2001-2002 a rainfall enhancement and air chemistry study was conducted in the UAE. A series of trace gases and aerosol concentrations were measured during the campaign to determine the characteristics of the air chemistry of the region. The focus of this report is on the sulphur budget of the region referring particularly to the SO_2 and aerosol concentrations measured. As sulphates where not measured separately in the campaign, the total aerosol concentrations are used as surrogate indicators of sulphate concentrations.

Objectives

The concentration of local industries especially oil refineries can be assumed to be a significant source of SO_2 and sulphates in the atmosphere over the UAE. It is also possible that SO_2 can be released by through the production of dimethylsulphide in the marine environment, which when released into the atmosphere will react to form a sulphate and methane sulphate aerosol (Yoon and Brimblecombe, 2001). Another significant source of SO_2 and sulphates could be through the transport of pollution from industrialised countries in Europe and Asia. The purpose of the report is to determine the horizontal and vertical distribution of SO_2 and aerosols across the UAE as well as the possible source regions and pathways along which pollution is transported into the region.

Recent studies have shown that air pollution from Europe and Asia are transported by the prevailing winds across the Mediterranean and the Negev regions. The aim of this study is to determine the possibility that the UAE may be affected by these "cross-roads" of air pollution. The objectives of this research are to:

- Review the SO_2 and sulphate distribution across the UAE
- Ascertain whether the differences in vertical concentrations of SO_2 are associated with local or remote sources;

- Determine the possible sources of long-range transport of pollution to the UAE,

Organisation of the Report

This research report is divided into five chapters. **Chapter 1** provides an introduction to the research study and an overview of the research site. The necessary background information related to the characteristics and effects of the sulphate aerosols and the gaseous precursor, sulphur dioxide is reviewed. An overview of the current studies pertaining to long-range transport of air pollution in the Middle East and Mediterranean region is also presented. **Chapter 2** comprises a description of the data collection and analysis methodologies. The horizontal and vertical distribution of SO_2 is discussed in Chapter **3.** The contribution of pollution transported to the UAE to the air chemistry of the region is explained in **Chapter 4.** A summary of the key results and suggestions for possible future research concludes **Chapter 5**.

Acknowledgements

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CHAPTER 1

OVERVIEW

A brief description of the United Arab Emirates (UAE) as the research site is presented with a focus on the climate and synoptic features that affect the region. The literature review focuses on the characteristics of sulphate aerosols and their gaseous precursors with a brief outline of the effects of SO_2 and sulphates on human health and climate change. Previous studies of long-range transport of pollution are reviewed in relation to their significance to the United Arab Emirates.

Introduction

In response to the increased demand for water in the arid regions of the United Arab Emirates (UAE), a rainfall enhancement and air chemistry study was conducted over the region in 2001-2002. Part of the feasibility study for the augmentation of rain in the UAE included a series of trace gas and aerosol characteristics measurements to determine the nature of the atmospheric constituents over the UAE. The study revealed high concentrations of sulphur dioxide (SO_2) in the atmosphere. This measurement is significant in that SO_2 in high concentrations constitutes a serious health hazard (Baumbach, 1996), it may form acid rain which damages ecosystems and it also converts to sulphates aerosols which are hygroscopic in nature and which may affect the albedo and cloud condensation nuclei (CCN) concentrations in the atmosphere (Pham *et al*., 1995; Ichoku *et al*., 1999).

Gases such as SO_2, H_2S, NO, NO_2 and NH_3 vary rapidly in time and space due to their reactive nature. These gases all have sources and sinks that determine their local and regional concentrations in the atmosphere (Pruppacher and Klett, 1980; Warneck, 1983). Emissions of sulphur gases from both natural and anthropogenic sources have a significant effect on the chemistry of the atmosphere (McEwan and Phillips, 1975; Bates *et al*, 1992). The cycling of sulphur through the troposphere plays an important role in the acid-base chemistry of the atmosphere as well as in the formation of aerosol particles. Over time the natural sulphur cycle has been perturbed over many areas of the globe, resulting in highly acidic precipitation and an increase in the concentrations of fine hygroscopic particles (Bates *et al*, 1992; Muller and Brasseur, 1995).

Atmospheric aerosols play an important role in regulating the amount of solar radiation absorbed by the Earth-atmosphere system. They are significant in the direct aerosol effect in that they reflect part of the incident solar radiation back to space and absorb part of the solar radiation thereby affecting the distribution of solar radiation through the atmosphere. Some atmospheric aerosols also serve as CCN affecting the formation of clouds, their optical properties and precipitation processes. This is referred to as the indirect effect of aerosols (Charlson *et al*., 1987). The concentration of atmospheric aerosols is both temporally and spatially variable (Chylek *et al*., 1995; Pilinis *et al*., 1995).

Local industries in the UAE, especially oil refineries, emit high concentrations of SO_2. These high concentrations may have a negative effect on the health of the population and on the environment. But as the SO_2 converts to sulphates in the atmosphere it may also affect the cloud microphysical processes and therefore the rainfall potential of the region. As sulphates can be transported over long distances it is possible that the high aerosol concentrations measured could reflect the import of pollution across international boundaries. Where aerosol concentrations do not correspond with the trace-gas concentrations it is assumed that pollution is transported into the region and the pathways and possible sources for this will be determined in this study.

Background to the United Arab Emirates

The United Arab Emirates (UAE) is a federation of seven emirates with an area of 77,700 km^2 and a population of 3,4 million (estimates for 2002) (www.uae.org.ae). The emirates is located at 22°-25,5° N and 51° - 56,5° E. It overlooks the Gulf of Oman to the east and the Arabian Gulf to the north. To the south of it lies the Sultanate of Oman and to the west Qatar. It also shares a south and west border with Saudi Arabia (Figure 1.1).

Figure 1.1. Map of the United Arab Emirates and neighbouring regions (www.uae.org.ae).

Climate of the United Arab Emirates

The unique location of the UAE, with characteristic land-sea distribution, the Tropic of Cancer passing through it and the subtropical anticyclone above it, provides this region with a tropical desert climate and several typical climatic features. Although a semi-permanent trough of low pressure exists over the Arabian Gulf, the sub-tropical anticyclone cell above it, in the middle and upper troposphere, inhibits cloud formation and growth. As a result, the Arabian Peninsula has very little or no rainfall for a large part of the year. Although the Intertropical Convergence Zone (ITCZ) passes through the UAE during the summer months (June to September), there is

still little or no rain for the reason stated above (Ministry of Communications, 1996).

Average summer conditions

During the summer months, the Hadley cell reverses over the Asiatic monsoon region and the monsoon circulation dominates over the region. The circulation forms with a rising column of air over the Assam region and the subsiding column over the Arabian Gulf region. This enhances subsidence and prolongs the hot summer season. These features together with the sub-tropical anticyclone make the climate generally arid with little or no rainfall and very high temperature during summer (Ministry of Communications, 1996). The months of July and August are very hot and oppressive due to excessive subsidence of air in this region. Summer precipitation is mostly confined to the mountainous regions in the east and over Oman (NCAR, 2002).

Average winter conditions

During the winter months (December to April) the surface flow over the UAE and Arabian Gulf becomes easterly under the influence of the intense Siberian anticyclone, which occasionally extends to Pakistan and

Iran. The anticyclone in the middle and upper troposphere shift southwards giving way to the passage of westerly waves through this area. Winter is the primary rainfall season in the UAE; a result of the influence of upper level westerly flow and rainfall is associated with a westerly trough and frontal systems passing through the region (NCAR, 2002). Rainfall can be experienced throughout the region but reaches its peak over mountainous areas as a result of the orographic uplift. The rainfall belt during a particular rain spell generally moves west to east over the area (Ministry of Communications, 1996).

Synoptic Circulation over the UAE

The synoptic circulation over the UAE is complex and frequently the result of a combination of different pressure systems. The pressure systems, which appear to affect the UAE, are: the Siberian High, the Easterly trough, the Red Sea trough, the Indian Ocean High and the Thermal low (Mandoos, 2004).

The Siberian High (Figure1.2a) dominates over the region during winter from early November to April. This high is usually associated with cold and dry northwesterly to northerly winds. This system may cause extreme minimum temperatures of 0 °C over the Emirates.

The Easterly trough (Figure 1.2b) persists over the region throughout the year. This feature results from the extension of the depression from the east and depends on the weakening of the Siberian High at the end of the winter season and a slowing down of the thermal depression at the end of summer. It is associated with warm, moist air and may bring rain to the UAE. The winds associated with these depressions are generally easterly but could become south-easterly or north-easterly depending on the location of the depression in relation to the UAE.

The Thermal Low (Figure 1.2c) develops due to the high insolation over the interior of the Arabian Peninsula. The thermal depression is usually centred over the Arabian Peninsula and is a common feature during the summer months from June to September. The hot and dry southerly wind associated with this system can raise the temperature significantly.

The Red Sea Trough (Figure 1.2d) is an extension of the tropical Sudan Monsoon low over the Red Sea that affects the Arabian Gulf Regions. The effect of this system is noticeable in the winter season. Unstable weather conditions usually associated with these depressions bring warm and moist air from the south or southwest to the UAE.

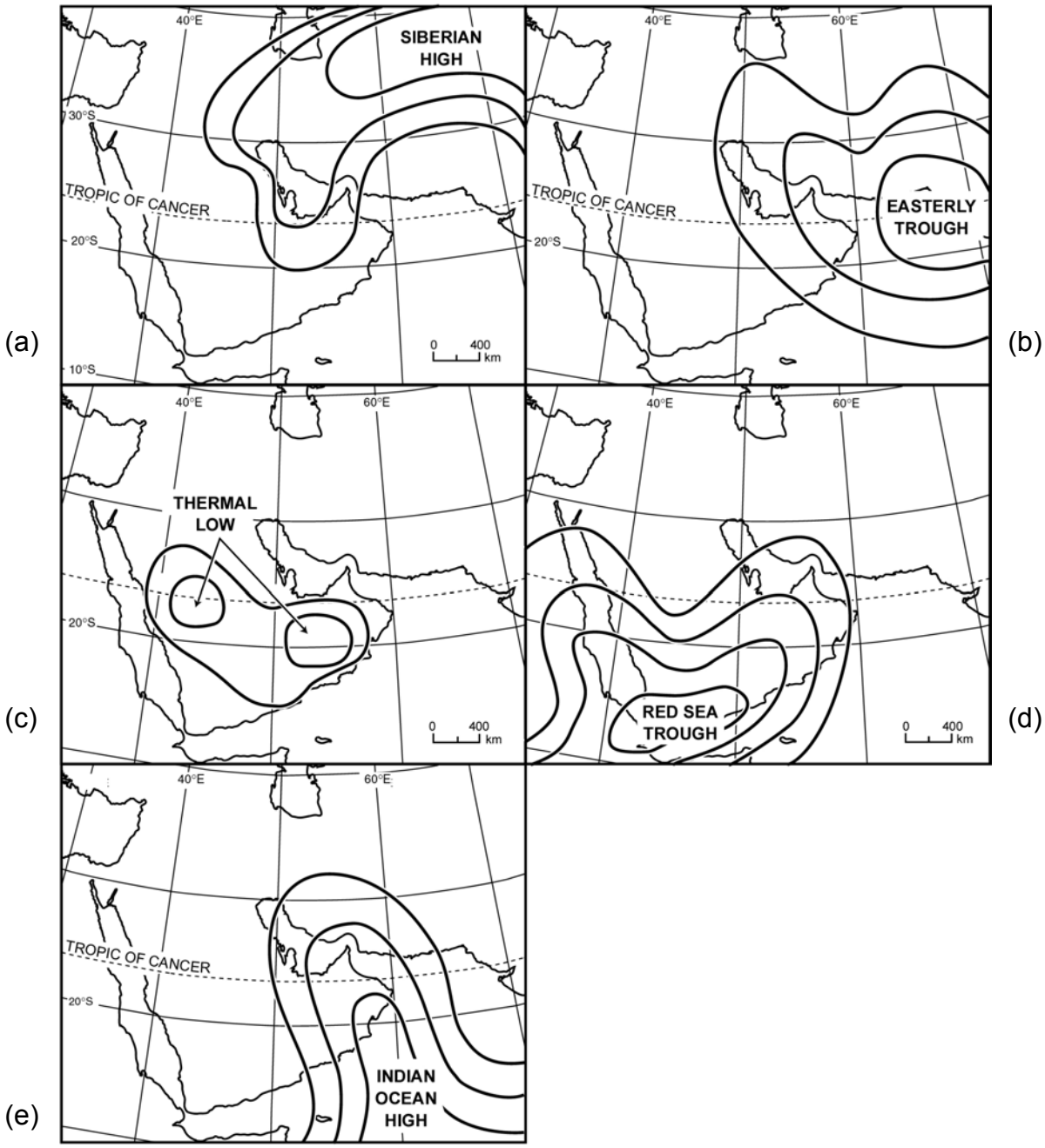

Figure 1.2. The surface pressure systems that affect the UAE (after Mandoos, 2004)

The Indian Ocean High (Figure 1.2e) dominates over the Indian Ocean throughout the year but the effect of its extension to the UAE is prominent during summer. The system usually brings moist air from the Indian Ocean to the UAE. The winds associated with the Indian Ocean high are mostly south or south westerly.

Literature Review

Little information exists in the scientific literature on the characteristics of the atmospheric composition of the Middle East and specifically of the UAE. The most extensive studies conducted in the Middle East concentrated on the Kuwait oil-well fires that occurred after the Gulf War in 1992 (Hobbs and Radke, 1992; Herring and Hobbs, 1994; Cahill *et al*, 1996). However, several studies have been conducted in the Negev desert and at Sde Boker in Israel (Maenhaut *et al*, 1997; Formenti *et al*, 2001) as well as over the Mediterranean region (Lelieveld *et al*., 2002). These studies showed that much of the anthropogenic material measured over the Mediterranean and Negev regions was transported from parts of highly industrialised Europe and the Asian continent. Until recently North America and Europe dominated the use of fossil fuels, resulting in strong pollution emissions. However, as Asia's population increases, it's potential for higher pollutant emissions is growing to levels to rival North America and Europe (Lelieveld *et al*., 2001; Phadnis *et*

al, 2002). The Middle East and North Africa may be possible receptor regions for this pollution (Lelieveld *et al.*, 2001, 2002). The pollution transported to the UAE may contain many different aerosols and their trace-gas precursors. However, significant to this report are the sulphates and their gaseous precursors, SO_2.

Sulphur based gases and aerosols in the atmosphere

Sulphur dioxide (SO_2) is a non-stable gas in the atmosphere and its concentration is greatest at the source of emission and decreases steadily downwind of that source. SO_2 has a relatively short lifetime in the atmosphere: less than one day (Pruppacher and Klett, 1980). In remote marine environments SO_2 concentrations are mostly below 1 ppb, whereas in areas of the world where large scale burning of fossil fuels occurs for the generation of electricity, or in the petrochemical industry (such as the UAE), levels of SO_2 range from 2 to 20 ppb (NCAR, 2002).

After being emitted sulphur dioxide may be converted to a sulphate through the process of oxidation (Table 1.1) (Wilson, 1978; Hopke *et al*., 1995; Pham *et al*., 1995; Stockwell and Calvert, 1983; Sorokin *et al*, 2004). It has been well established that the oxides of sulphur (SO_2 and SO_3) are oxidised to sulphuric acid and other compounds like ammonia bisulphate(NH_4SO_4) with

an average oxidation yield of about $8X10^{11}$ in an atmosphere with a temperature of 25°C at 1 atmosphere (Breytenbach *et al*, 1994).

Table 1.1 Mechanisms by which sulphur dioxide is converted to sulphates (Wilson, 1978, 538)

Mechanism	Overall Reaction	Factors on which sulfate formation primarily depends
1. Direct photooxidation	$SO_2 \xrightarrow[water]{light\ oxygen} H_2SO_4$	Sulphur dioxide concentration, sunlight intensity
2. Indirect photo-oxidation	$SO_2 \xrightarrow[\substack{organic\ oxidants\\ hydroxyl\ radical\ (OH)\\ HO_2\ \ RO_2\ radicals}]{smog\ water\ NO_2} H_2SO_4$	Sulphur dioxide concentration, organic oxidant concentration OH, NOx, HO_2, RO_2.
3. Air oxidation in liquid droplets	$SO_2 \xrightarrow{liquid\ water} H_2SO_3$ $NH_3 + H_2SO_3 \xrightarrow{oxygen} NH_4^+ + SO_4^{2-}$	Ammonia concentration
4. Catalysed oxidation in liquid droplets	$SO_2 \xrightarrow[heavy\ metal\ ions]{oxygen\ liquid\ water} SO_4^{2-}$	Concentration of heavy metal (Fe, V, Mn) ions
5. Catalysed oxidation on dry surfaces	$SO_2 \xrightarrow[carbon\ particle]{oxygen\ water} H_2SO_4$	Carbon-particle concentration (surface area).

The mechanisms by which SO_2 is oxidised to sulphate are important because they determine the rate of formation of the sulphate, the influence of the concentration of SO_2 on the reaction rate and the final form of the sulphate (Wilson, 1978).

Dry aerosol particles can be classified into 3 categories: nucleation or Aitken mode particles (radii < 0,1µm), large or accumulation mode particles

(0,1<radii<1,0 μm) and giant particles (radii>1,0 μm) (Pruppacher and Klett, 1980). Sulphate and its associated cations occur in the atmosphere in the accumulation mode with a peak frequency of occurrence between 0.2 and 0.4μm aerodynamic diameter (Wilson, 1978; Warneck, 1988; Jaenicke, 1998). Sulphates have the greatest potential to contribute to global aerosol forcing, due to the fact that sulphate aerosols are smaller than dust and sea aerosols and thus have a longer lifetime in the atmosphere (tens of days) (Pruppacher and Klett, 1980). Sulphates are hygroscopic and therefore have twice the optical scattering per unit mass concentration as dry particles (White, 1990; Charlson *et al*, 1992). Both sulphuric acid and ammonium sulphate are highly efficient cloud condensation nuclei (Bari *et al*, 2003). Sulphur dioxide and the resultant sulphates have a significant effect on both human health and on climate change.

The effects of sulphur gases and aerosols on human health

Sulphur dioxide is a colourless gas but has a characteristic sour taste in pure air from 0,6 mg/m^3 (Baumbach, 1996). SO_2 is an irritant gas in the respiratory system, and because of its good solubility it is easily absorbed in the upper respiratory passage. Sensitivity varies among people, however, short exposure to low concentrations may produce a reversible decrease in lung function. A 10-30 minute exposure to concentrations as low as 5 ppm

produces constriction of the bronchiole tubes and mild throat and nose irritation. In case of very high concentrations, SO_2 can cause severe airway obstruction, hypoxemia (insufficient oxygenation of the blood), pulmonary oedema (accumulation of fluid in the lungs) and death (Cheminfo, 1999). When SO_2 is combined with fine particulate matter, it increases the toxic SO_2 effect (Baumbach, 1996).

Several human studies have shown that repeated exposure to low levels of SO_2 (below 5 ppm) causes permanent pulmonary impairment. This effect is probably due to repeated episodes of bronchio-constriction. The gas will also react with moisture on the skin and cause irritation or burning and lachrymation (tears) if it comes into contact with the eyes (Cheminfo, 1999).

Epidemiological studies indicate that sulphate may be more toxic than SO_2 (Wilson, 1978). As the acidic aerosols penetrate the inner respiratory organs, H_2SO_4 is formed. There is an increased susceptibility to chronic bronchitis, high risk of acute diseases of the respiratory system and an increased frequency of broncho-pathic symptoms (Baumbach, 1996). Reported cases of lung disease, asthma and cardio-pulmonary disease are strongly associated with fine particulates such as sulphates (Bari *et al*, 2003).

The effects of sulphur gases and aerosols on climate change

Aerosols affect climate in two ways: directly through the scattering of incoming solar radiation and indirectly through changes to cloud microphysical processes. According to the International Panel on Climate Change (1995) aerosols derived from fossil fuel and biomass burning can reflect solar radiation, which leads to a cooling tendency in the climate system, whereas carbonaceous aerosols can absorb solar radiation and tends to warm the climate system. The direct radiative forcing for sulphates is estimated to be -0.4Wm^{-2} (a cooling effect) as opposed to +0.2 Wm^{-2} for fossil fuel black carbon aerosols (a warming effect) (IPCC, 1995).

The indirect forcing of climate through cloud processes is complex. An increase in the total number concentration of particles in the accumulation mode at a given liquid content, results in a decrease in the mean droplet radius in the cloud, and a corresponding increase in the cloud albedo (Charlson *et al*, 1992). It was calculated that a 30 % increase in the cloud droplet number would result in a 0.02 increase in the planetary albedo and a subsequent decrease in the mean surface temperature of approximately 1.3 °C (Charlson *et al*, 1992).

Aerosols decrease precipitation efficiency of clouds by inhibiting the mechanisms for warm-cloud coalescence, thus increasing the cloud liquid-water content and fractional cloud cover (Albrecht, 1989). This effect influences mainly low-level cloud where scattering of incoming solar radiation is expected to dominate over the potential of absorbing long wave radiation from the ground, resulting in a net cooling. Albrecht (1989) found that an increase of 4% low cloud cover would increase the global albedo by 0.02.

The impacts of industrial aerosols, and indirectly their trace gas precursors (e.g. SO_2) are known to be highly hygroscopic and therefore important to any cloud microphysical processes in the region in which they occur. Particulate sulphur is an accumulation mode aerosol and because of its relatively small size has the potential to create highly continental clouds with low rainfall potential. This mechanism in the atmosphere not only impacts on rainfall but also indirectly on the radiative budget and therefore on climate changes (Charlson *et al*, 1992). As sulphate aerosols have a longer lifetime in the atmosphere than its precursor SO_2, it is possible for these aerosols to be transported over long distances.

Long-range transport of air pollution

Several aircraft field campaigns, with detailed measurements of the atmospheric chemical composition, have been conducted over the last decade to sample the outflow of pollution from various regions of the world. These measurements have documented the occurrence of intercontinental pollution transport events (Schultz and Bey, 2004). Pertinent to this study are the ARACHNE, MINOS and INDOEX campaigns, as they detail the transport of pollution across areas that may impact on the UAE.

Air pollution over the Negev Desert (Israel)

The Aerosol, Radiation and Chemistry Experiment (ARACHNE), focussed in 1996, on the role of anthropogenic pollution from distant (Europe and Asia) and local sources within Israel and their respective efficiencies in affecting regional air quality and atmospheric optical properties (Formenti *et al*, 2001). Chemistry transport models suggest that aerosol loading over the eastern Mediterranean and the Negev Desert is significantly affected by anthropogenic and natural sources. The anthropogenic component consists of sulphates and carbonaceous particles transported primarily from Europe, whereas the natural component is dominated by sea-salt and dust particles,

which are either locally produced or generated in the Saharan and/or Arabian Deserts and advected towards the Negev Desert (Formenti *et al*, 2001).

At low altitudes (below 800 hPa) the Negev Desert was generally impacted by polluted air masses travelling over the Balkan regions, Turkey and Greece (Figure 1.3). Additional pollution was often added to these air masses along the Israeli-Mediterranean coast where population and industrial centres are concentrated. At high altitudes, air masses came either from Eastern Europe or from North Africa (Algerian or Egyptian Deserts) (Formenti *et al*, 2001). Sulphate aerosols were either produced from SO_2 emitted by the power plants located along the Israeli-Mediterranean coast or advected by long-range transport from southern and Eastern Europe with production of SO_2 also taking place along the path. The average direct forcing for sulphate aerosols in the region has been estimated to be in the order of 5 Wm^{-2}. This constitutes a regional maximum in the global aerosol forcing distribution (Formenti *et al*, 2001).

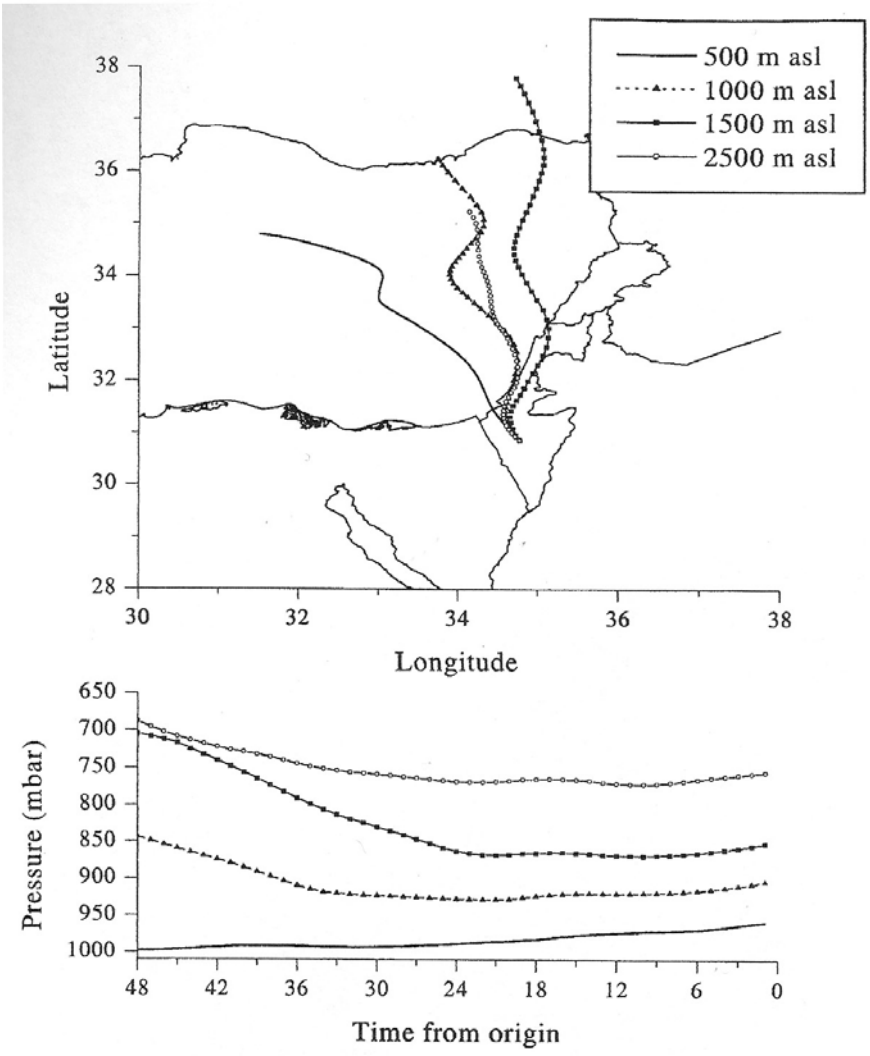

Figure 1.3. Three-dimensional 2-day back trajectories for 26 June 1996 (top) and the air mass pressure (bottom) (Formenti *et al*., 2001)

Air pollution over the Mediterranean

The Mediterranean Intensive Oxidant Study (MINOS) conducted in 2001 found that air pollution from Europe, Asia and North America crosses

the Mediterranean tropopause and pollutes the lower stratosphere in the middle latitudes, affecting mostly North Africa and the Middle East (Lelieveld *et al.,* 2002). The chemical composition and energy budget of the Mediterranean troposphere were measured. The aim was to study the long-range transport of air pollution and its effects on air quality and climate. Although measurements revealed a high level of air pollution from the surface to the top of the troposphere at 11-15 km, the greatest amount of pollution was observed in the lower 4 km, originating from both western and eastern Europe (Lelieveld *et al.*, 2002).

At altitudes above 4 km, long-range pollution, transported from both North America and Asia, was a major contributor to pollution over the Mediterranean. The pollution transport followed the prevailing westerly winds (Lelieveld *et al.*, 2002). Another pollution layer was discovered in the upper troposphere (8 km) over the Mediterranean Sea, which originated from South Asia. This pollution is lifted to the upper troposphere by thunderstorms in the Indian Monsoon (Figure 1.4). It then follows the easterly tropical jet stream and turns north over the eastern Mediterranean (Lelieveld *et al*, 2002).

An analysis from the MINOS study shows that the largest contribution over the Mediterranean is from Asia (40-50%) in an extensive subtropical CO plume that combines with North American emissions (30-40%) before it crosses the Atlantic Ocean.

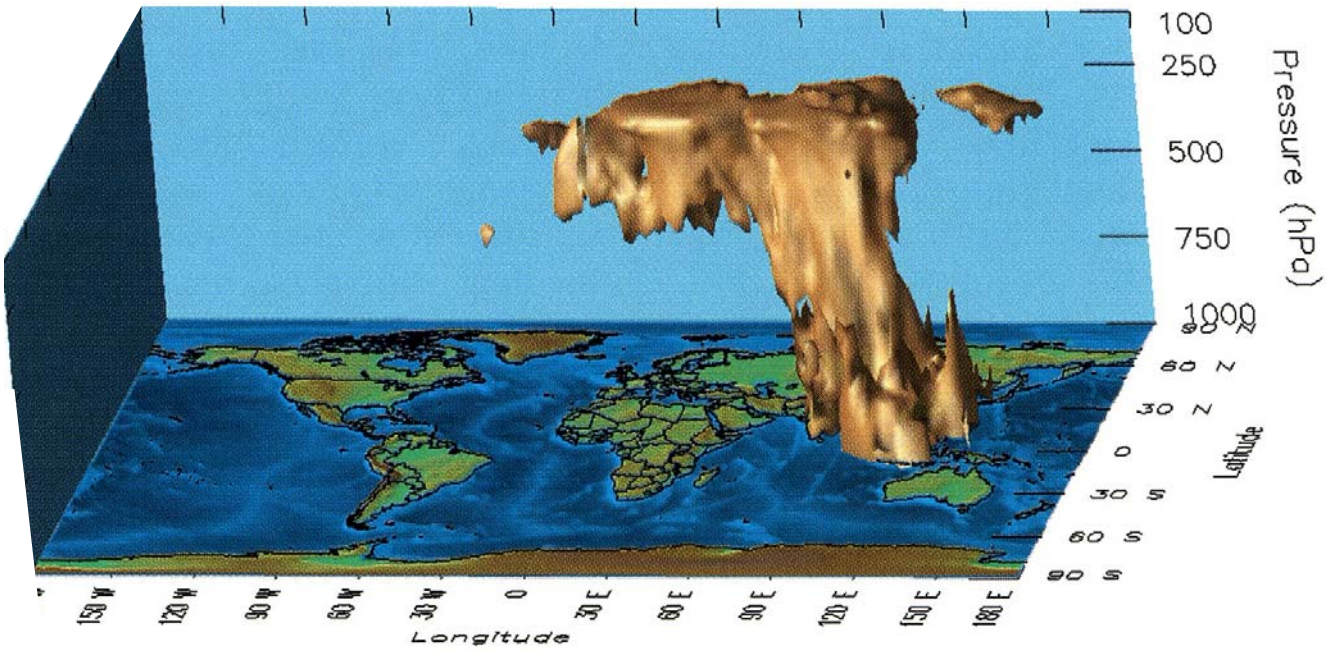

Figure 1.4. Model calculation of pollution transport from South Asia. Thunderstorms in the summer monsoon carry pollution to the Mediterranean at altitudes above 8-10 km (the upper troposphere). Part of this pollution can subsequently be transported into the stratosphere (Lawrence, 2004).

The Indian Ocean Experiment (INDOEX) field campaign measured the long-range transport of air pollution from south and Southeast Asia towards the Indian Ocean during the dry monsoon season (January to March 1999) (Lelieveld *et al*, 2001). The samples collected in the clean marine boundary layer south of the ITCZ reveal a fine aerosol sulphate concentration of about 0,5 $\mu g/m^3$ probably from the oxidation of naturally emitted dimethylsulphide (DMS). The sulphate concentration over the northern Indian Ocean was

close to 7μg/m^3 and the anthropogenic contribution could be inferred at 90 % (Lelieveld *et al.*, 2001). Because precipitation is scarce during the winter monsoon, the aerosols can be spread over the entire northern Indian Ocean, before entering the ITCZ (Lelieveld *et al*, 2001). The equatorward monsoonal flow over the north Indian Ocean into the convectively active ITCZ provides an efficient mechanism for transporting surface pollution from South Asia into the tropical upper troposphere / lower stratosphere, where, because of stronger winds and longer lifetimes, rapid long-range transport can occur (Phadnis *et al*., 2002).

The strong influence of Asian pollution at the eastern Mediterranean tropopause is associated with Asian monsoon convection and the extended high-pressure trough in the upper atmosphere. Anticyclonic flow transports the pollution northwards over Africa following the upper troposphere trajectories (Lelieveld *et al*., 2001; 2002).

The Mediterranean is mostly cloudless during summer and sunlight levels are high, hence pollutants are transformed into photochemical smog, which is harmful to human health and damages the ecosystem. European polluting of the Mediterranean lower troposphere reduces air quality, particularly during summer. Lelieveld *et al*, (2002) found that the effects of the pollution near the surface are:

- The European Union's eight-hourly air quality standard for ozone (110 mg/m^3) is exceeded throughout summer in the Mediterranean regions;
- High ozone concentrations are harmful to ecosystems and to human health;
- Aerosols affect the Mediterranean atmospheric energy budget by scattering and absorbing solar radiation. The sulphate and aerosol particles reduce solar radiation absorption by the sea by approximately 10% and change the heating profile of the lower troposphere. As a result, evaporation and moisture transport to North Africa and the Middle East are suppressed.

Pollution is largely determined by intercontinental transport in a free troposphere, whereas upper tropospheric pollution from Asia can reach the stratosphere. These "crossroads" carry large pollution loads over the Mediterranean and the effects extend far beyond the region.

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The study of sulphates and its gaseous precursor SO_2 is significant because of the effect they have not only on human health and the environment but also on the cloud microphysical processes and climate change. The MINOS, INDOEX and ARACHNE studies have highlighted the contributions made by long-range transport of air pollution to local concentration levels by determining the source and receptor regions of long-range transport of air pollution. The MINOS study suggests that North Africa and the Middle East could be receptor regions for the pollution crossing the Mediterranean Sea. The possibility that

the UAE could be impacted on is part of this investigation. Further studies are needed to determine the exact effect of the pollution on the local climates, environments and health conditions of the affected areas.

CHAPTER 2

DATA ACQUISITION AND RESEARCH METHODOLOGY

The data used for this research was collected during the rainfall enhancement and air chemistry studies of the United Arab Emirates in 2001-2002. Intensive studies were conducted during winter 2001/ 2002 and summer 2001/ 2002 over the UAE. The air chemistry study, which can be divided into two parts *viz*. trace gas data (all measured on the airborne platform) and aerosols is the focus of this research. Trajectory analysis using the HYSPLIT model was computed to determine possible sources of the long-range transport of pollution to the UAE.

The Rainfall Enhancement and Air Chemistry Study

Aircraft campaigns are usually conducted over a limited period of time and a limited region. However, they provide a comprehensive set of measurements and fine-scale resolution (Schultz and Bey, 2004). The strategy for data collection was to fly over the entire UAE region to obtain spatial and vertical distributions of measured trace gases and aerosols. Flight patterns were either in a spiral to measure vertical distribution or flying vertical profiles along a flight transect (Figure 2.1). Attempts were also made to map plumes from significant sources over the UAE by transecting the plume with "long legs" as the aircraft moved downstream from the source (Figure. 2.2). Wherever possible, a pass directly down the centre was also taken.

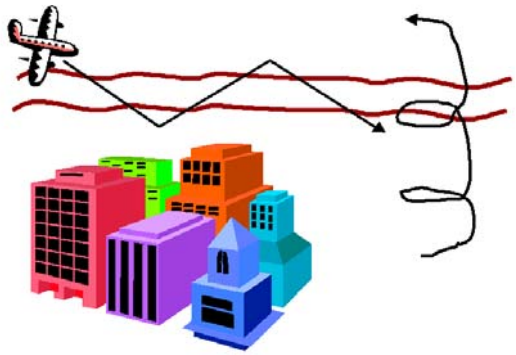

Figure 2.1. Schematic diagram showing the general flight strategy for investigating the spatial distribution of trace gases and aerosols over the UAE during winter and summer 2001.

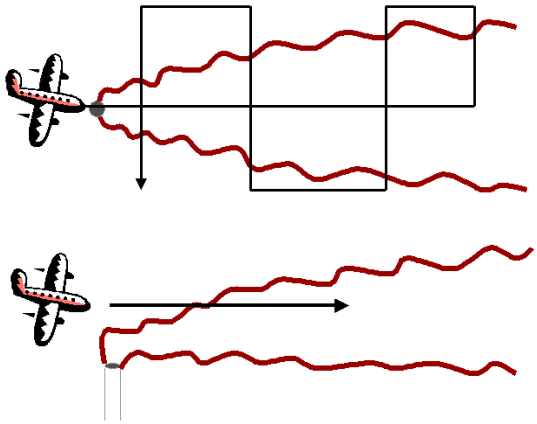

Figure 2.2. Schematic diagram showing the general flight strategy for investigating the spatial distribution individual plumes at identified sources of trace gases and aerosols over the UAE during winter and summer 2001.

During the campaign a Piper Cheyenne II (used in 2001) and a Beechcraft King Air 2000 (used in 2002) aircraft were instrumented with trace gas and

aerosol equipment. Atmospheric ambient air was drawn into the pressurised aircraft through a branch manifold in which the temperature, pressure and flow were constantly monitored. The inlet was mass flow controlled with a separate pump, which ensured that a steady flow to all the trace gas instruments was maintained. The Breechcraft replaced the Piper as the need for more load and electrical capabilities became evident. This craft performed all the same sampling functions as the Piper, but allowed for more instruments to be carried at one time. Problems occured at 14 000 ft as pressure and air flow problems affect the quality of trace gas data (NCAR, 2002).

Air chemistry data was collected on all 200 flights conducted during the 4 seasons (Figures 2.3 and 2.4). However, where the aircraft flew into the cloud, the data was excluded, as the impact of precipitable water on individual trace gases and aerosol measurements is not well understood.

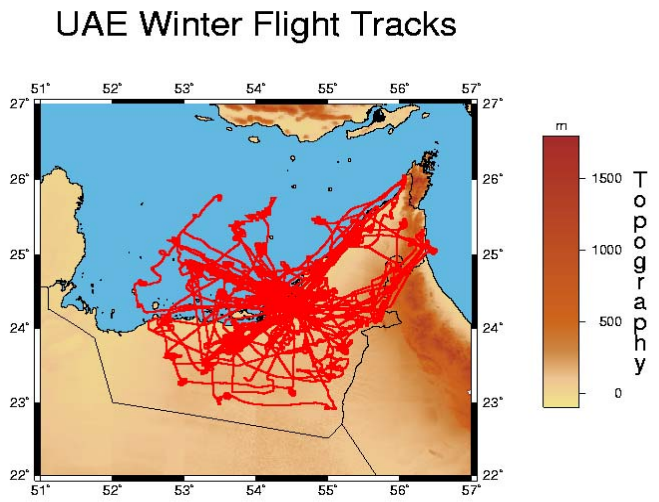

Figure 2.3. Flights conducted over the UAE during winter 2001

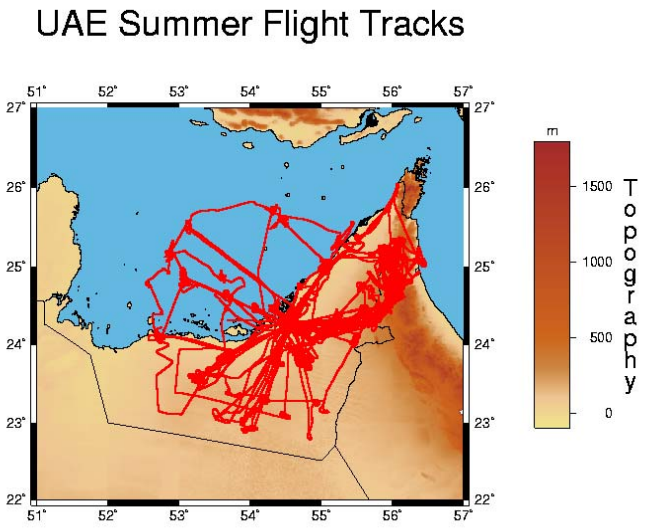

Figure 2.4. Flights conducted over the UAE during summer 2001

The data collected were summarised according to nine regions delimited around the UAE (Figure. 2.5). The type of source found there determined each region. The latitude and longitude boundaries of the nine regions are given in Table 2.1.

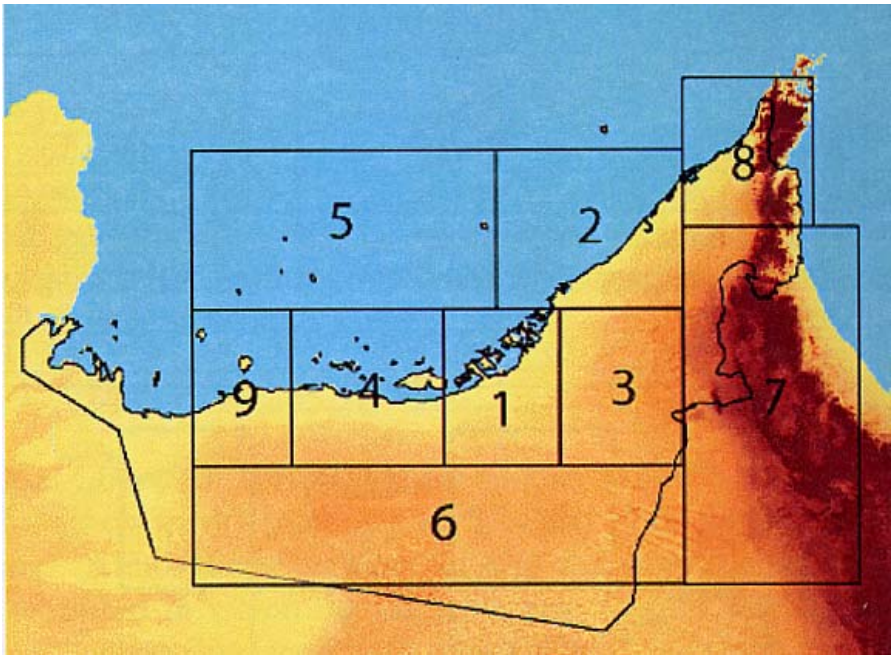

Figure 2.5. A map of the UAE depicting the boundaries of each of the defined areas

Table 2.1. Details of areas identified over the UAE for summarising aerosol and trace gas data

Area	Name	Lat min	Lat max	Long min	Long max
Zone 1	Abu Dhabi	23.50	24.75	54.00	54.75
Zone 2	Dubai/ Jebel Ali	24.75	25.75	54.50	55.75
Area 3	Desert	23.52	24.75	54.75	55.75
Area 4	Habshan / Bu Hasa	23.50	24.75	53.00	54.00
Area 5	Das / Zirku Island	24.75	25.75	52.75	54.50
Area 6	Liwa	22.75	23.50	52.50	55.25
Area 7	Oman Mountains	22.75	25.25	55.75	57.00
Area 8	Rams / Fujairah	25.25	26.25	55.75	56.65
Area 9	Jebel Dana	23.50	24.75	52.70	53.00

Instrumentation

The Passive Cavity Aerosol Spectrometer Probe (PCASP)

The PCASP was used to measure concentrations and sizes of aerosol particles between 0.1 and 0.3 μm in diameter. It detects single particles and sizes them by measuring the intensity of light that the particle scatters when passing through a light beam (Strapp *et al*., 1992; Liu and Daum, 2000). The size that is determined by the PCASP assumes that the scattered light

detected is from a spherical particle of a given refractive index and diameter (Wendisch *et al*., 1996). The size distribution produced from these measurements must be viewed with great caution when in mixed composition aerosols. Particles will not be correctly sized due to their different refractive index and non-spherical shapes (Liu and Daum, 2000).

The probability of more than a single particle coinciding in the beam or being missed during the electronic reset time increases with concentration. Corrections are applied to account for these losses, but still leads to concentration uncertainties.

The PCASP is a single particle sizing instrument and not a particle surface area or volume probe. Since the surface area and volumes are derived by integrating the size distribution, uncertainties in the size measurements lead to root sum squared inaccuracies in surface area and volume, a factor of two and three higher, respectively. Liu and Daum (2000) also found that the use of uncorrected PCASP-measured size distributions causes calculated light scattering coefficients to be significantly underestimated. PCASP-measured size distributions need to be corrected for the difference between the refractive index of calibration and ambient aerosol yield light scattering coefficients. The under-sizing of particles by the PCASP can lead to significant negative errors in the calculation of ambient light scattering

because optical counters undersize aerosol particles mostly in the range where particles are most efficient at scattering solar radiation (Liu and Daum, 2000).

Sulphur Dioxide Analyser

The Model 43C Sulphur Dioxide Analyzer is based on the principle that SO_2 molecules absorb ultraviolet (UV) light and become excited at one wavelength, then decay to a lower energy state emitting UV light at a different wavelength (Thermo Environmental Instruments, 2000). The sample is drawn into the Model 43C through the sample bulkhead (Figure 2.6). The sample flows through a hydrocarbon "kicker," which removes hydrocarbons from the sample by forcing the hydrocarbon molecules to permeate through the tube wall. The SO_2 molecules pass through the hydrocarbon "kicker" unaffected. The sample flows into the fluorescence chamber, where pulsating UV light excites the SO_2 molecules. The condensing lens focuses the pulsating UV light into the mirror assembly. The mirror assembly contains four selective mirrors that reflect only the wavelengths that excite SO_2 molecules. As the excited SO_2 molecules decay to lower energy states they emit UV light that is proportional to the SO_2 concentration. The bandpass filter allows only the wavelengths emitted by the excited SO_2 molecules to reach the photo-multiplier tube (PMT). The PMT detects the UV light emission from the decaying SO_2 molecules. The photo-detector, located at

the back of the fluorescence chamber, continuously monitors the pulsating UV light source and is connected to a circuit that compensates for fluctuations in the UV light. The sample then flows through a flow sensor, a capillary, and the shell side of the hydrocarbon "kicker." The Model 43C outputs the SO_2 concentration to the front panel display and the analog outputs (Thermo Environmental Instruments, 2000).

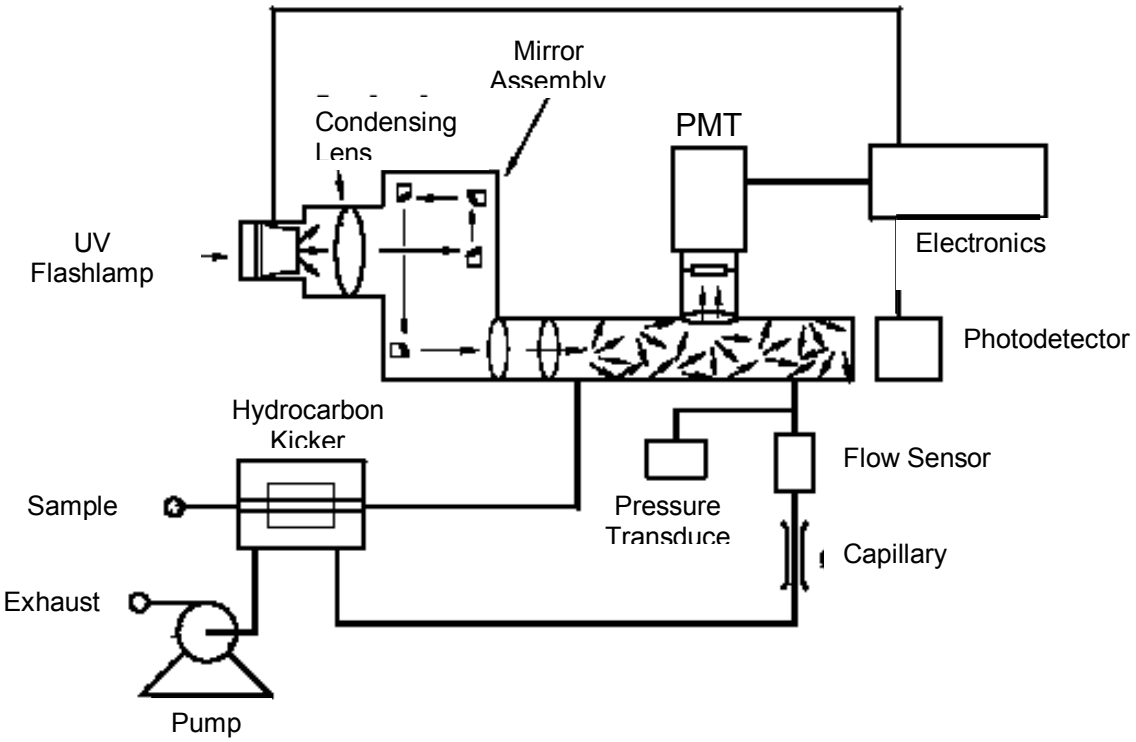

Figure 2.6. A schematic diagram of the SO_2 analyser (Thermo Environmental Instruments, 2000).

The HYSPLIT Model Analysis

The air chemistry data provides an overview of the SO_2 concentrations and distribution in the UAE. Three-day backward trajectories were calculated to determine the possible source regions and pathways for long-range transport of pollution into the UAE. Accumulation mode ($N_{0,12}$) particles have a lifetime of the order of a week (in the absence of precipitation) and can therefore be used to trace air masses with aged pollution. (Formenti *et al*, 2001).

The trajectory analysis was done using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to determine the possible external source of pollution in the UAE. The HYSPLIT model is available online through the National Oceanic and Atmospheric Administration (NOAA) and is a system for computing simple air parcel trajectories to complex dispersion simulations (Draxler and Hess, 1997, 1998). In the particle model, a fixed number of initial particles are advected about the model domain by the mean wind field and a turbulent component (Draxler and Rolph, 2003). The model's default configuration assumes a puff distribution in the horizontal and particle dispersion in the vertical direction. In this way, the greater accuracy of the vertical dispersion parameterisation of the particle model is combined with the advantage of having an ever-expanding number of particles

represent the pollution distribution (Draxler and Rolph, 2003). For this analysis the default setting was used to compute the trajectories.

Trajectories are calculated to determine the paths followed by air parcels with time. They provide a useful tool for understanding the 3-dimensional transport of airborne material in the atmosphere (D'Abreton and Tyson, 1996). The backward trajectories are useful in tracing aerosols back in time and space to determine their possible source regions.

Trajectories were calculated for summer (July) and winter (January) for 2001 and 2002. Four regions were selected as the end points of the trajectory pathways viz.: Al Ain, Ras-Al-Khaima, Zirku Island and Abu-Dhabi. The trajectories were also calculated for three different height levels, 1000 hPa, 700 hPa and 500 hPa. A total of 496 trajectories were downloaded. The trajectory plots were analysed to determine the major sources of air pollution to these 4 end points and to plot the pathways along which this pollution may travel.

There appeared to be no great differences in the trajectory pathways patterns for the 4 regions. Therefore, the most significant pathways were taken as an average of the 4 regions for each season. These averages were then calculated as a percentage of the month, to create maps showing the

most to least significant transport pathways. It is important to note that these percentages are not statistically significant but provide a representation of the most important source regions of long-range transported pollution to the UAE.

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The rainfall enhancement and air chemistry study conducted in 2001-2002 provided the data for the analysis of the SO_2 concentrations over the 4 selected regions in the UAE. The contribution of long-range transport of air pollution to the air chemistry was determined by the trajectory analysis, using the HYSPLIT model. The trajectories were analysed to determine the most significant sources and pathways of pollution to the UAE.

CHAPTER 3

DISTRIBUTION OF SULPHUR DIOXIDE OVER THE UAE

The background chemistry of the UAE with respect to the SO_2 and sulphate concentrations is presented. The horizontal and vertical distributions of the aerosols and its gaseous pre-cursor are discussed. The seasonal variations in concentrations are also highlighted.

Horizontal distribution of SO_2

Pollutants appear to be concentrated around specific sources located around the UAE. Sulphur dioxide concentrations are highest at all points in the region at which combustion of fossil fuels is conducted. Elevated SO_2 concentrations are associated with oil-related activities in the UAE. Refineries at Habshan, Zirku Island and Das Island and another unknown source in the Arabian Gulf, northeast of Das Island are the major sources of sulphur dioxide in the UAE. These elevated levels have been recorded in a north-south band across the UAE and the Arabian Gulf, which incorporates the major refineries (Figure 3.1). Concentrations over the UAE range over 2 orders of magnitude and spatial gradients arise because SO_2 has a relatively short lifetime in the atmosphere (less than 1 day) (NCAR, 2002). Average concentrations were generally higher during the summer months.

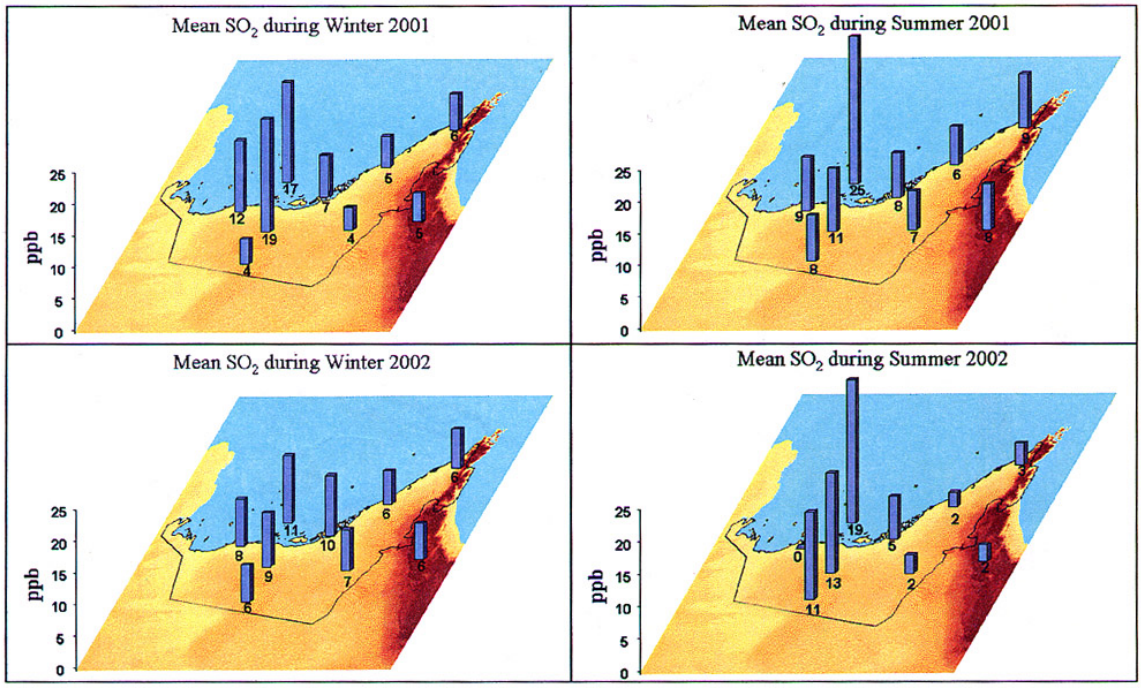

Figure 3.1. Average concentrations of SO_2 over the UAE during the winter and summer. Numbers under columns specify the concentration each column represents.

Vertical distribution of SO_2

A regional rather than an overall analysis of the vertical concentrations of SO_2 and aerosols is presented as SO_2 has a relatively short residence time in the atmosphere and its conversion to sulphates occurs quite rapidly as the ambient air mixes with the plume (Wilson, 1978). The highest concentrations tend to occur close to the source of the emissions. As sulphate concentrations were not measured during the data collection process, the total aerosol concentrations are used as surrogate indicators of sulphates in

the atmosphere. The size distribution for sulphates occurs in the atmosphere in the accumulation mode as measured by the PCASP. It is obvious from the distribution (Figure 3.2) that aerosol enhancement in the range 0,1<radii<1,0 µm falls within the size fraction expected for sulphates. The aerosol size distribution graph (Figure 3.2) shows the combined data of the PCASP (Passive Cavity Aerosol Spectrometer Probe) and the FSSP (Forward Scattering Spectrometer Probe). The FSSP data is however not considered for this report.

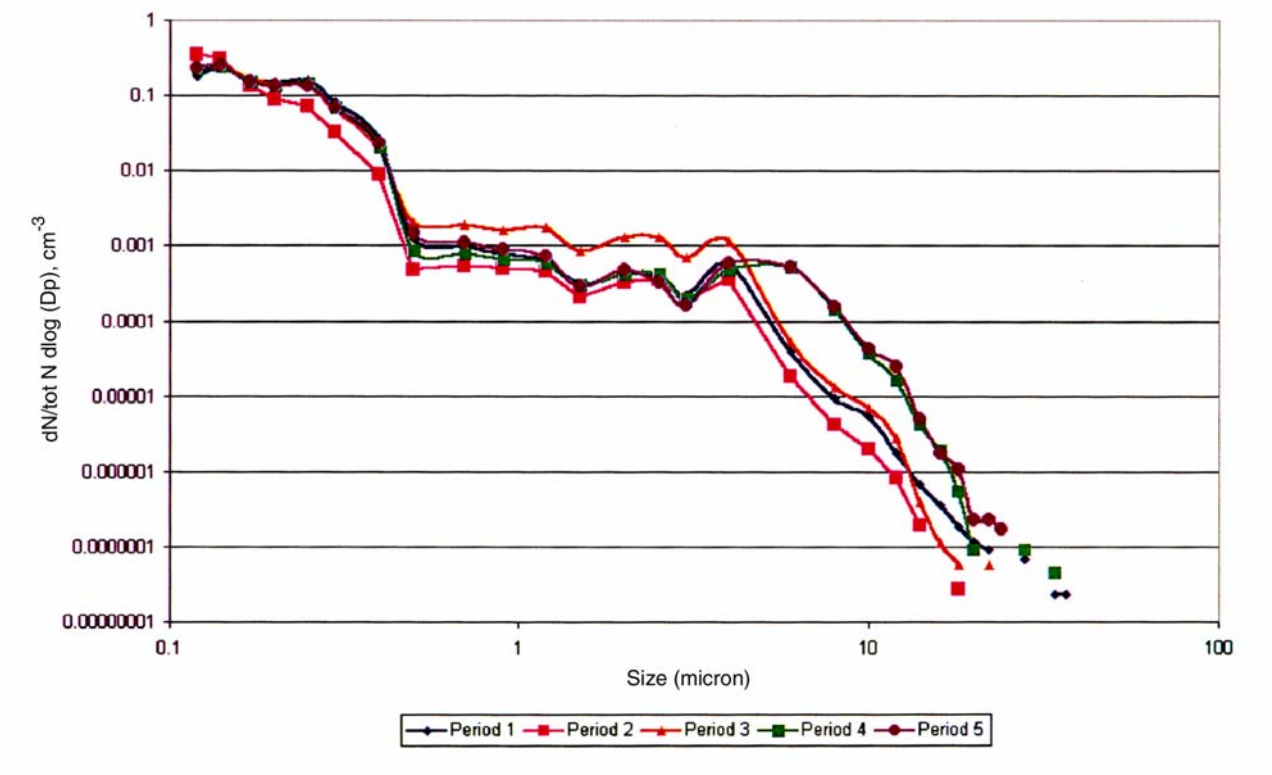

Figure 3.2. Aerosol size distribution of fine and coarse mode particles as measured by the PCASP and the FSSP probes.

The most pronounced SO_2 concentrations occur over Zirku Island. High sulphur dioxide concentrations were recorded over the Island below 1000m, with average values of ~80ppb (Figure 3.3). Above 2000m the concentration levels dropped off in both summer and winter. Significantly, high aerosol concentrations of between 2000-3000 cm^{-3} were measured near the surface.

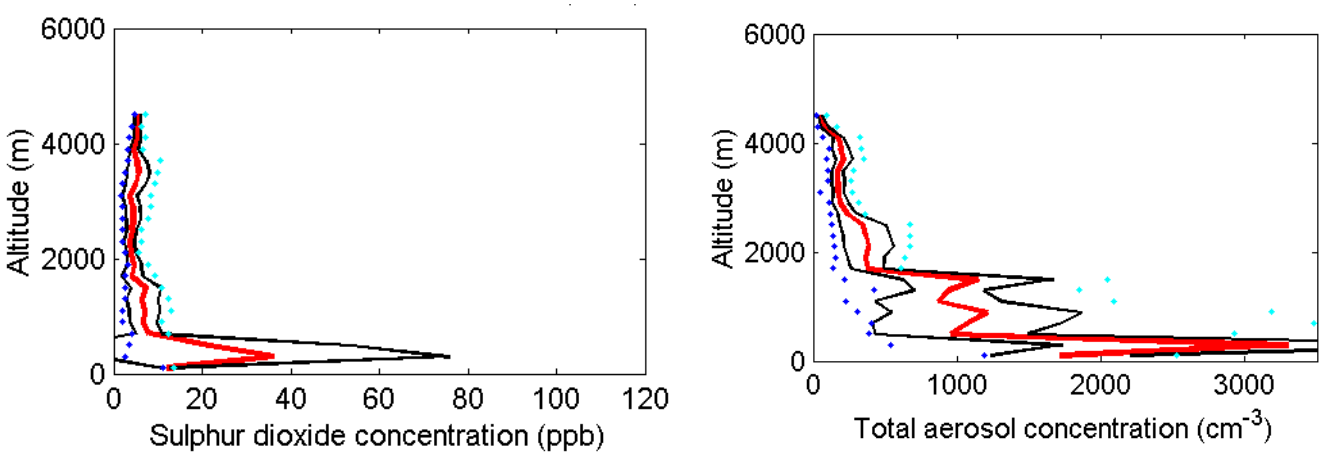

Figure 3.3. Vertical distribution of SO_2 and the total aerosol concentrations over Zirku Island. The mean is indicated by the red line, the standard deviation by the black line, the minimum values by the dark blue dots and the light blue dots show the maximum values.

The main anthropogenic source of airborne sulphur compounds is the sulphur content of fossils fuels released into the atmosphere by combustion. For petroleum products virtually all the sulphur content of the fuel is emitted (Semb, 1978). The presence of and activities associated with the oil field and outgassing flame may therefore account for the high levels of SO_2 measured near the surface at Zirku Island.

The stability of the atmosphere over the island during the sampling period may also account for the high concentration. Smith and Hunt (1978) noted that the dispersion of pollutants such as SO_2 is strongly influenced by the time- dependent depth of the layer over which it is dispersed. During the winter of 2001, temperature inversions were evident at five levels: 800m, 1400m, 1800m, 2800m and 3700m, possibly the effect of the Siberian High present over the region during winter. Most emissions may be trapped below the 800m inversions, and then dispersed up to the 1400m inversion as the one at 800m weakened (NCAR, 2001). The conversion of SO_2 to sulphate is slow in the early part of the plume close to the source of the emission; however, the aerosol concentrations close to the surface were very high at above 3000 cm^{-3}.

Sulphur dioxide concentrations in Abu Dhabi are very low below 1000 m with values of less than 10ppb in summer (Figure 3.4). At about 1500 m there is an increase in concentration to about 20 ppb. SO_2 is not produced in large quantities over Abu Dhabi, but the high concentrations recorded above 1600m probably has its source in the oil related activities in the Arabian Gulf as several pollution sources were detected in the Gulf oilfields.

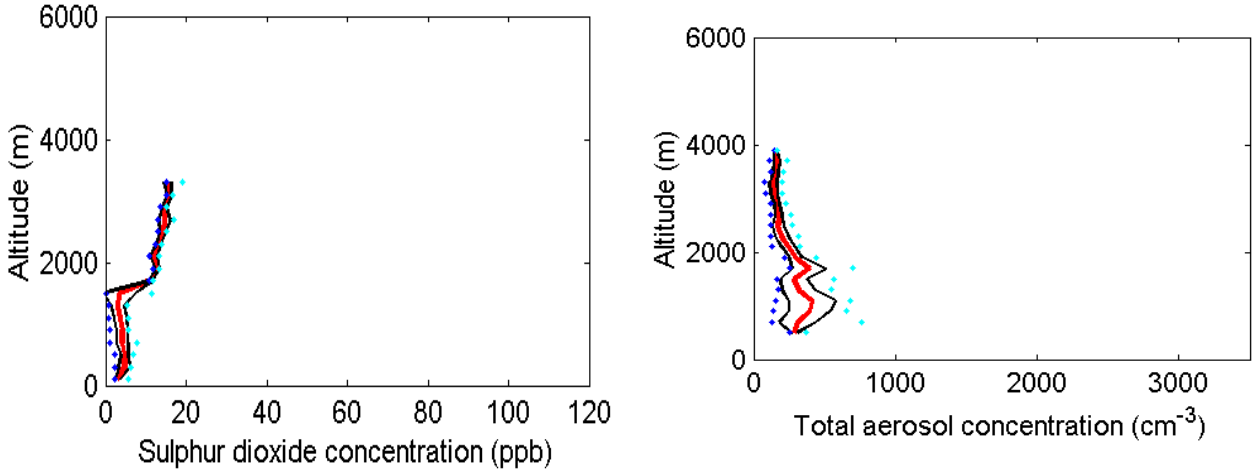

Figure 3.4. Vertical distribution of SO_2 and the total aerosol concentrations over Abu Dhabi. (The mean is indicated by the red line, the standard deviation by the black line, the minimum values by the dark blue dots and the light blue dots show the maximum values).

Pollution is transported onshore by the sea breezes which develop almost everyday. During winter these concentrations drop even lower throughout the vertical profile to less than 10ppb (Figure 3.3). Again the aerosol concentrations are higher than the SO_2 measured.

The industries at Ra's-al-Khaima and Al Ain are smaller sources of pollution. No measurements of SO_2 were available for the first 500 m for both summer and winter over Al Ain. From approximately 1000 m to 5000 m the concentrations fluctuate between 5 to 20 ppb for summer. In winter the vertical concentrations are consistent at about 10ppb to a height of 4000m (Figure 3.5).

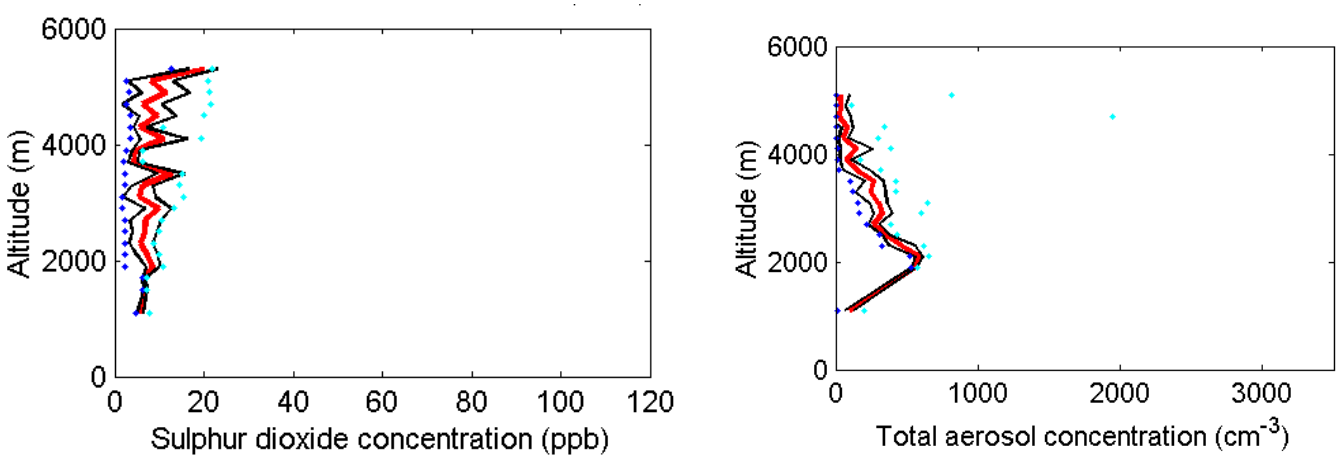

Figure 3.5. Vertical distribution of SO_2 and the total aerosol concentration over Al Ain. (The mean is indicated by the red line, the standard deviation by the black line, the minimum values by the dark blue dots and the light blue dots show the maximum values).

The vertical profile of SO_2 over Ras-Al-Khaima shows a significant change from the surface to the upper atmosphere during summer. The average concentrations are about 30 ppb (peaking at 70ppb), but steadily decrease to less than 10ppb with an increase in altitude. The measurements available for winter do not adequately reflect the vertical changes in SO_2 concentrations over Ras-Al-Khaima (Figure 3.6).

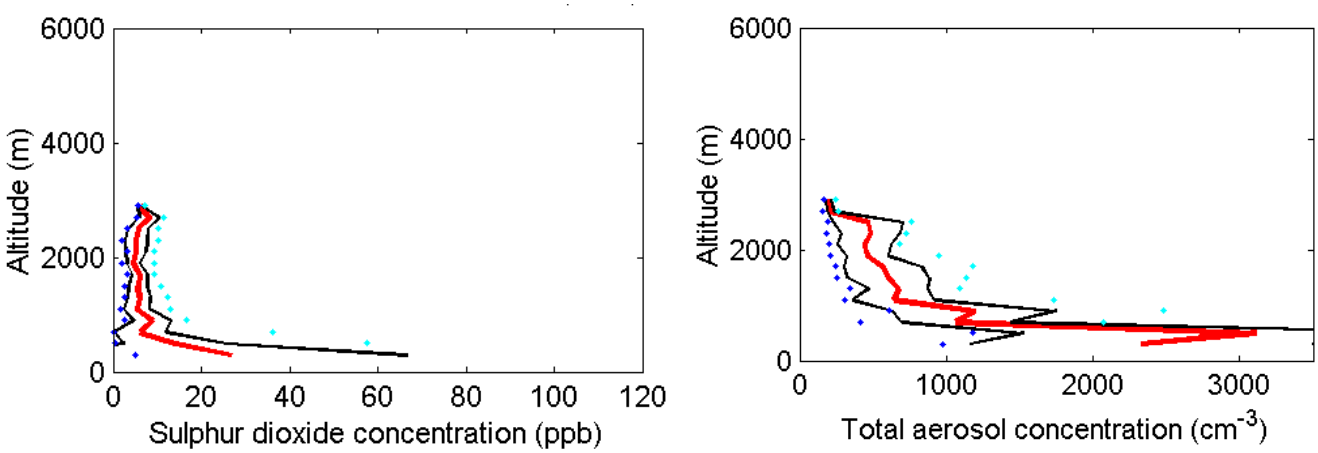

Figure 3.6. Vertical distribution of SO_2 and the total aerosol concentration over Ras-Al-Khaima. (The mean is indicated by the red line, the standard deviation by the black line, the minimum values by the dark blue dots and the light blue dots show the maximum values).

Although the aerosol concentrations shown here are the sum total of all the aerosols measured during the campaign, they are used as an indicator of the conversion from the trace gas precursor to the resultant aerosol. Where large aerosol concentrations are found in a region where the SO_2 is low, it is assumed that some of the aerosols may have been imported from external sources. The trajectories were computed to determine whether these sources might have impacted on the aerosol concentrations over the region.

Seasonal variations in SO_2 concentrations

There is no seasonal pattern in SO_2 levels (Figure 3.7). The anthropogenic input is expected to be fairly constant throughout the year. Average SO_2 concentrations vary over an order of magnitude across the country (from ~5ppb over Abu Dhabi, Al Ain, Fujairah and Dubai / Jebel Ali to ~ 50 ppb over the Arabian Gulf near Das and Zirku Islands). Maximum SO_2 concentrations were recorded in the plume over Zirku Island and Habshan. The afternoon and evening sea breeze could bring many of the pollutants onshore from the oil production facilities in the Gulf. The average SO_2 concentrations were not consistent for each season. In Abu Dhabi (zone 1) for example, the average concentration was highest in winter 2002, where the maximum level reached over 400ppb. These differences can probably be attributed to the changing atmospheric circulation patterns.

Zirku Island (zone 5) had high average concentrations for all four seasons with the maximum reaching 500ppb in both winter 2001 and summer 2001. Industries at Ruwais emit low levels of SO_2 and levels are also low over the rest of the country.

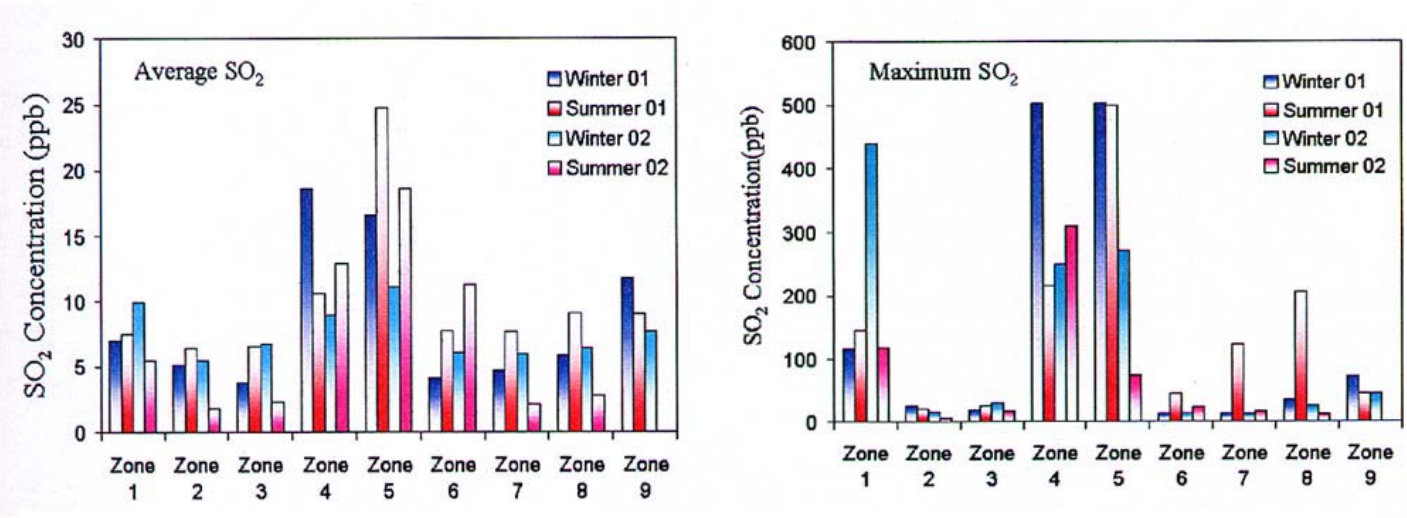

Figure 3.7. Seasonal differences in average and maximum sulphur dioxide concentrations. The zones are defined as:

Zone	Region
Zone 1	Abu Dhabi
Zone 2	Dubai/ Jebel Ali
Zone 3	Desert
Zone 4	Habshan / Bu Hasa
Zone 5	Das / Zirku Island
Zone 6	Liwa
Zone 7	Oman Mountains
Zone 8	Rams / Fujairah
Zone 9	Jebel Dana

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The average horizontal and vertical distributions of sulphur dioxide over the UAE showed that SO_2 is concentrated around specific sites where the burning of fossil fuels dominates. Zirku Island has the highest concentration of SO_2 emissions as a result of the industries and oil refineries located there. There are no significant seasonal variations in SO_2 concentrations.

CHAPTER 4

CONTRIBUTION OF LONG-RANGE TRANSPORT OF AIR POLLUTION

The combined trajectory analysis for the four regions Zirku Island, Abu Dhabi, Al Ain and Ras-Al-Khaima are presented, with the focus on the different levels of 1000hPa, 700hPa and 500hPa. These trajectories reveal the possible sources and pathways of pollution transported over the United Arab Emirates The trajectory analysis highlighted 3 main source regions for airflow into the UAE. The main source regions are firstly, the local circulation of air around the Gulf Regions, secondly, air transported from Asia and finally air transported across North Africa and the Mediterranean Sea.

Transport pathways of pollution to the UAE

It is important to identify the source regions of the airflow into the UAE, as this may determine the nature and effects of the pollutants transported in on the air chemistry of the UAE. A location map (Figure 4.1) showing the source regions of pollution to the UAE is provided. The problem with defining these regions as the actual sites of emission is that aerosols can travel hundreds of kilometres over short time periods. For this study, backward trajectories were calculated for three day periods and the emissions could have been transported into the areas defined as 'source regions'. Therefore, the pathways along which the pollution travels also needs to be considered.

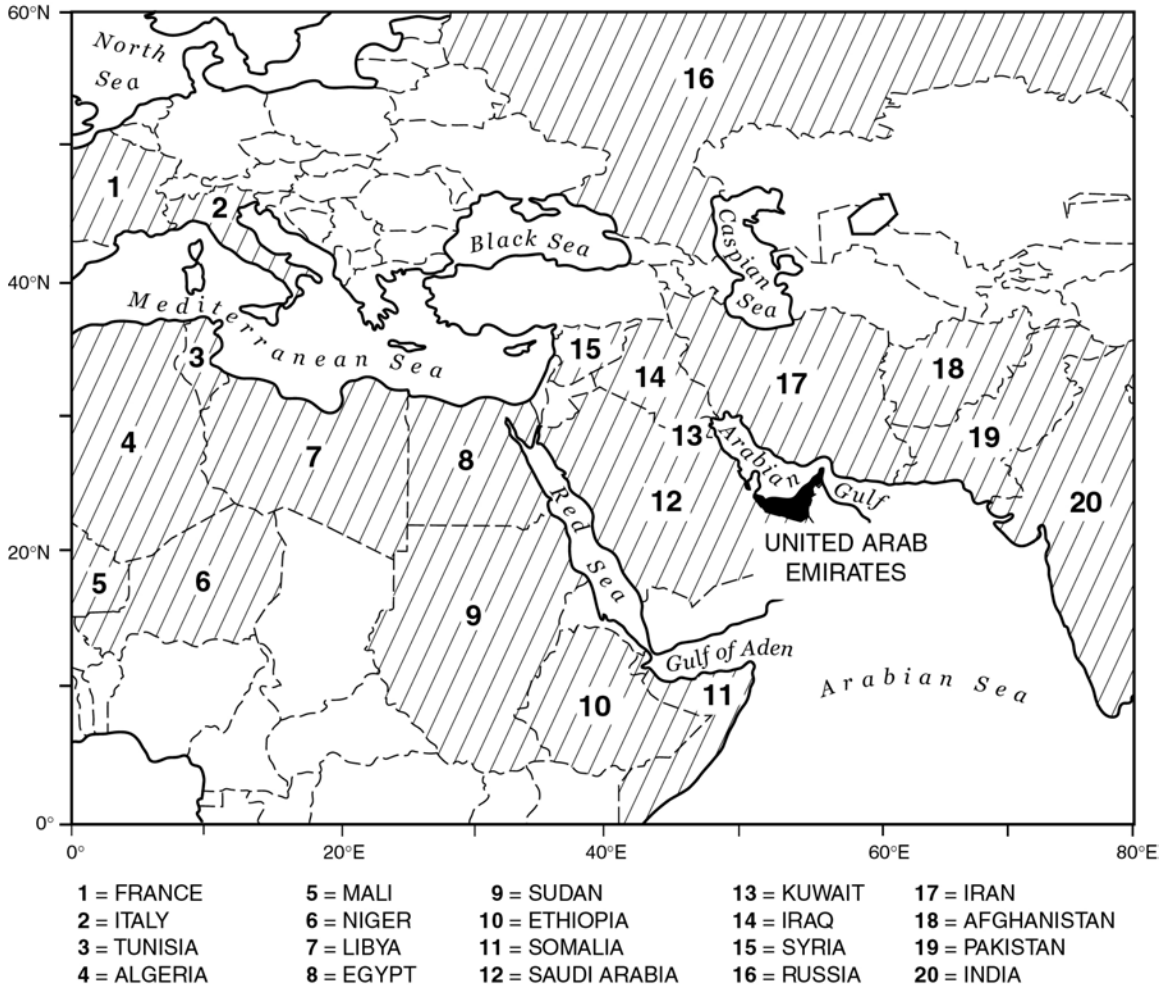

Figure 4.1. A location map of the source regions of pollution to the UAE

The trajectories of the winter and summer seasons of 2001 reveal distinct circulation patterns at the different levels of 1000hPa, 700hPa and 500hPa (Figure 4.2). During winter 2001, the highest frequency of occurrence of airflow into the UAE came from Iran (42, 7%) whereas in summer it was from Iraq (33,8%). The circulation near the surface in winter is focused around the

Gulf region with the inflow of air from Saudi Arabia (20,9%) and Iraq (13,7%). This circulation is possibly determined by the presence of the Siberian High which dominants at the surface during winter. The change in the summer circulation is possibly a result of the weakening of this high-pressure system and the influence of the Indian Ocean High that is situated over the Indian Ocean and advects air from the southwest. As a result air flows in from the southwest from Somalia and across the Gulf of Aden.

At 700hPa Saudi Arabia, Iran and the Arabian Gulf still have a significant effect (39,6% in winter and 71% in summer) but air also flows in from Egypt (8,9%), Sudan (24,2%) and Ethiopia (4%) and across the Mediterranean Sea (4,8%) in winter and from Pakistan (7,3%) and Afghanistan (4,0%) in summer.

At 500hPa the airflow into the UAE is almost completely westerly across North Africa (37,1%) and the Mediterranean Sea (17,1%) during winter. There are some influences from Europe, notably France (0,8%) and Italy (3,2%), which may in part support the MINOS suggestion that the Middle East may be a receptor region for pollution from Europe. The transport pattern appears to follow the path of the westerly trough that dominates the upper atmosphere circulation over the UAE. In contrast the summer airflow

is mostly easterly from India, Pakistan and Afghanistan although Iran (34,7%) is again a major source region at this level.

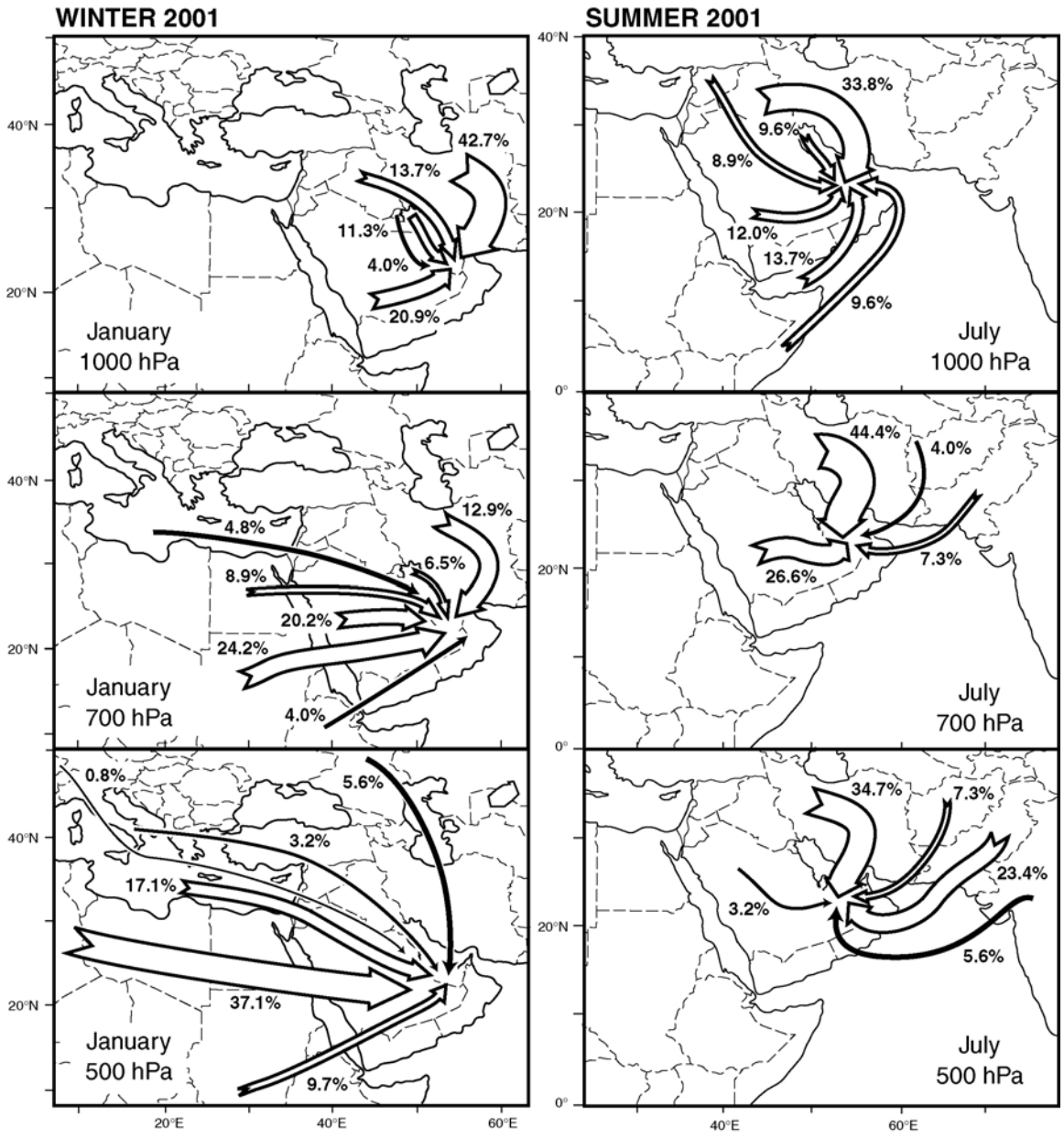

Figure 4.2. Schematic diagrams of the most important pathways to the UAE for winter and summer 2001 at 1000hPa, 700hPa and 500hPa.

The trajectories for 2002 show very similar trends to those in 2001 for the winter and summer seasons (Figure 4.3).

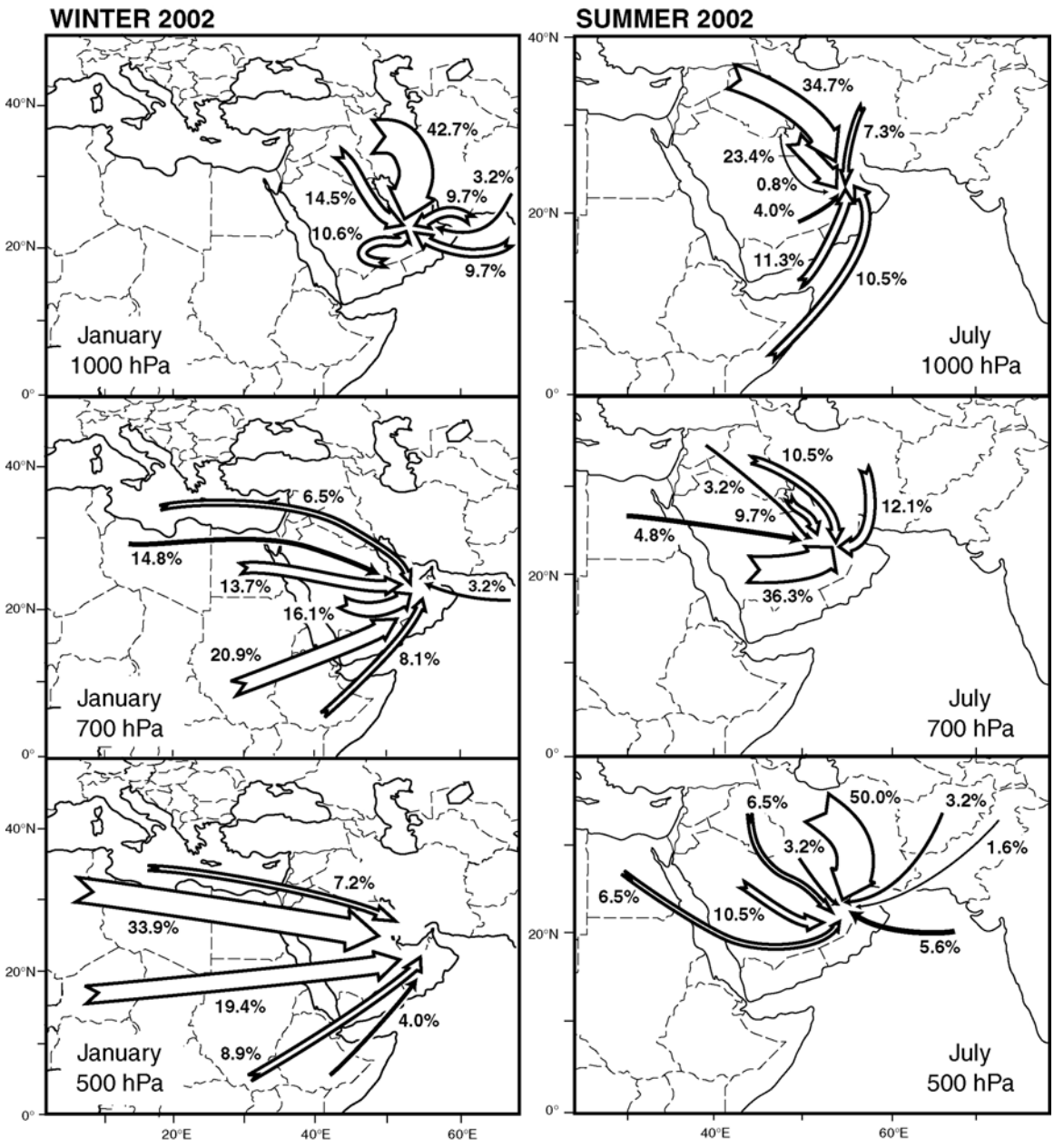

Figure 4.3. Schematic diagrams of the most important pathways of pollution to the UAE for winter and summer 2002 at 1000hPa, 700hPa and 500hPa.

At the surface air circulates around the Gulf in winter with some contribution from the Indian sub-continent. In summer the air flows in from Somalia in the south. At 700 hPa, the flow is westerly in winter with the source regions in North Africa such as Egypt and Libya. In summer the flow is northwesterly across the Middle East and from Saudi Arabia. At 500hpa, the winter flow pattern is predominantly across North Africa and the Mediterranean Sea, whereas in summer air also flows in from Pakistan and Afghanistan.

Distinct pathways of air pollution to the UAE can be identified from the trajectory analysis. These pathways can be distinguished as:

- the circulation of air around the Gulf regions
- across North Africa and the Mediterranean Sea
- from Asia

Pollution coming from each of these regions may impact on the air chemistry of the UAE in different ways depending on the source of the pollution emissions and the types of pollutants released into the atmosphere at the source.

Regional circulation of air around the Gulf Regions

The trajectory analysis revealed that the main sources of airflow into the UAE come from the Middle East regions of Iran, Iraq and Saudi Arabia. These sources were noted as affecting all four of the research regions at the 3 levels computed.

The proximity of these regions to the UAE is an obvious factor but the presence of the Siberian Anticyclone plays a major part in the circulation of air around the Gulf regions. The Siberian Anticyclone dominates over the region in winter and is centred over Iran. The subsiding air of the anticyclone creates an inversion that would trap pollution near the surface in winter. The emissions from the Gulf Regions would be high in SO_2 as a result of the large number of oil refineries found in the region.

Contributions of long-range transport from Asia

The significant contribution to the UAE from Asia comes from Pakistan, India and Afghanistan. The Easterly trough that persists over the area throughout the year is responsible for the airflow from the Asian subcontinent towards the UAE. The influence of the trough depends on the weakening of the Siberian High at the end of the summer season. The

easterly winds associated with these depressions carry pollution from the Indian subcontinent over the Arabian Sea to the UAE.

Lawrence (2004) suggests that emissions from India are characteristic of inefficient combustion processes, especially from burning biomass, bio-fuel and fossil fuels. The rapid growth in population and energy consumption leads to large emissions of pollutants such as CO, organic gases and particulate matter comprised of soot, sulphate and organic compounds. The emission of SO_2 from the Indian subcontinent presently accounts for only 3% of the global average. This value is expected to increase significantly over time (Figure 4.4) in comparison to the reduction estimated for other developed nations (Lawrence, 2004).

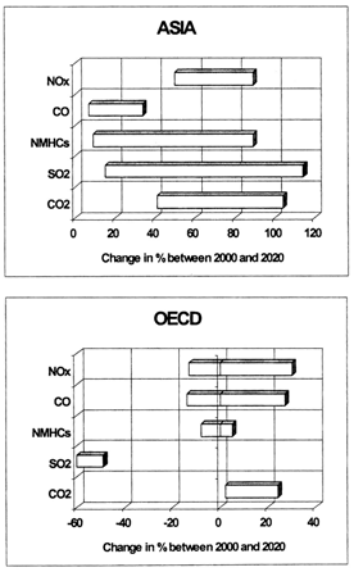

Figure 4.4. Estimated range of likely relative changes in emissions of several trace gases between 2000 and 2020 in Asia and the OECD countries (Lawrence, 2004)

Lelieveld *et al.* (2002) suggested that pollutants are carried into the ITCZ and then transported great distances away from the source of the emission. The changing position of the ITCZ could drive pollution from Asia towards the UAE. The ITCZ passes through the UAE during the summer months, making this a receptor region for pollutants carried along its path. It is then important to the UAE to monitor not only the present effects of these pollutants but also the long-term effect of the rapid increase in emissions over time.

Long-range transport across North Africa and the Mediterranean Sea

The inflow of air from the west passes over North Africa, from Algeria, Libya and Egypt, with some inflow from the south from Somalia and Sudan. Piketh and Walton (2004) suggest that in a simplistic model, it is possible to divide Africa into emission regions in which one particular source dominates the emissions to the atmosphere. The North African regions, determined by the trajectory analysis, fall into the aeolian dust emissions type, whereas Sudan and Somalia fall into the biomass-burning sector.

North Africa is the largest contributor of aeolian dust particles in the world (Piketh and Walton, 2004). Dust is a regional scale climatic forcing agent. The presence of dust in the atmosphere alters the surface radiation budgets that affect surface temperatures, surface-air exchange processes,

thermodynamic structures and therefore the atmospheric dynamics (Piketh and Walton, 2004). When mineral dust transported into the UAE co-exists with sulphates produced locally, the dust particles can become coated with sulphates, making them more active as CCN (NCAR, 2002). The transport of the dust occurs in the upper atmosphere at the 500hPa, which may be significant in affecting the formation of cloud and the resultant rainfall over the UAE. The particles usually form highly continental clouds that have a low rainfall potential. It should be noted that the UAE is also a major source of dust which contributes to the aerosol loading in the atmosphere.

The MINOS study concluded that air pollution crossing the Mediterranean has its source in Europe. The trajectory analysis revealed Italy and France as source regions in Europe. Although the frequency of occurrence from the regions was small (Italy - 3,2% and France - 0,8%), it is a key indicator that Europe does affect the UAE. The major source of anthropogenic emissions in Europe is the combustion of fossils fuels and the main source of SO2 is the burning of sulphur-containing coal in power plants (Huntriese and Schlager, 2004). The emissions in Europe have been relatively constant over the last decade. However, the economic collapse in many eastern European countries has led to significant emission reductions in this region. Sulphur emissions have decreased by about 25% from 1990-1993, although sulphur emissions from Europe account for 19% of the total global emissions

(Huntriese and Schlager, 2004). This has important implications for the UAE as the concentrations of sulphates coming into the region is still significant.

Influence of transport and transformation on the sulphur budget

The concentrations of sulphur dioxide and sulphates are assumed to be the sum of contributions from both distant sources and local industrial activity. The former is expected to show a strong directional dependence whereas the latter could be directionally independent (Bari *et al.*, 2003). It is important to understand the effect of transport on the sulphur compounds to determine the significance of long-range transport to the UAE. Georgii (1978) suggests that SO_2 and sulphate measurements showed an effect from a large industrial area at a distance of about 200 km. At distances more than 300 km downwind of the source area, the vertical distribution of SO_2 did not reveal any significant deviations caused by the industrial SO_2 emissions. In contrast, the distribution of sulphate concentrations was only weakly influenced by the SO_{2-} sources. Georgii (1978) also suggested that the sulphate distribution is much more conservative, with very little spatial variation. As the distance from the source area of SO_2 increases, the transformation of SO_2 to sulphate aerosols becomes less significant. However, sulphates generated from SO_2 may be transported at least hundreds of kilometres and may cause air pollution episodes far from the source of the pollution (Wilson, 1978).

The lifetime of primary atmospheric pollutants (i.e. directly emitted) depends on the efficiency of the sink process (often reactions with OH radicals). The loss rate itself is controlled by meteorological parameters and the concentration of other trace gas compounds (Schultz and Bey, 2004). Assuming, that the source regions produce large amounts of SO_2, the conversion to sulphates along the transport routes could mean an increase in sulphate concentrations over the UAE as the receptor region. These high sulphate concentrations could have a negative effect on the health of the population; it may cause acid rain, which is damaging to the environment; and more importantly, change the cloud dynamics and rainfall potential over the region.

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An analysis of the source regions for the long-range transport of pollution to the region reveals three dominant source regions. The first is the circulation around the UAE from Iran, Iraq and Saudi Arabia. The second is the transport across North Africa from Algeria, Libya, Egypt and Sudan and across the Mediterranean Sea. The third source region is from the west from Pakistan, India and Afghanistan across the Arabian Sea to the UAE. The air chemistry of these source regions is significant as this will determine the impact the pollution from there will have on the UAE.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Sulphate aerosols and their trace gas precursors are known to have a significant effect on the climate of a region. It has been established that the aerosols influence the climate through both the direct and indirect forcing of incoming solar radiation. The purpose of this research report has been to evaluate the SO_2 and aerosol concentrations in the atmosphere of the UAE and to determine whether these concentrations are affected by pollution transported over long distances to the UAE. The important findings that have emerged are summarised with suggestions for possible future research.

Sulphur dioxide and aerosol concentrations

The United Arab Emirates produces large quantities of SO_2 from the industries and oil refineries. The concentrations however, are not equally distributed around the country. Of the four sites referred to, the highest concentrations were recorded over Zirku Island, which is a major industrial area. The maximum SO_2 level reached 500 ppb, which may have a detrimental effect on the health of the population living and working in their area. As has been pointed out, high concentration of SO_2 can cause severe respiratory complications. SO_2 is also a main component of acid rain, which is damaging to the environment. The SO_2 levels recorded over the other 3 sites were much lower.

Sulphur dioxide converts to sulphates through the oxidation process, when it comes into contact with the ambient air. The aerosol concentrations were used as indicators of the sulphate content in the atmosphere. In the four regions studied, the highest concentrations of these particles were expected to occur in the vicinity of the highest emissions of SO_2. This is due to the fact that synoptic conditions are dominated by anticyclonic circulation, with low wind speeds and stagnant air. The pollutants produced by refining activities in the Gulf are also transported onshore by the sea breezes present in the early evening. Aerosol concentrations were found to be highest at identified SO_2 sources. Where sulphate concentrations are high they can scatter solar radiation resulting in a cooling trend. These aerosols can be very effective CCN and therefore have the potential to influence cloud microphysical processes and rainfall production efficiencies. They can form highly continental clouds with low rainfall potential, which would be detrimental to the UAE, which is essentially a desert region in need of rainfall.

There appeared to be no season pattern in SO_2 levels. The average SO_2 concentrations varied across the country and appeared to be a function of the activity of each of the regions. However, these average concentrations were generally higher during the summer months. As a result, aerosol

concentrations where also higher due to the conversion to sulphates and the huge input from aeolian dust.

Transport of air pollution to the UAE

Sulphates generated from SO_2 may be transported for hundreds of kilometres and may cause pollution episodes far from the emission sites. Studies such as MINOS, INDOEX and ARACHNE have shown that pollution has been transported from Europe and Asia over the Mediterranean and Negev Regions with the Middle East and North Africa highlighted as possible receptor regions. In this study, three day backward trajectories were calculated to determine whether the UAE is affected by transboundary air pollution. It was found that air pollution follows three significant pathways: a) circulation around the Gulf Region, b) transport from Asia and c) transport across North Africa and the Mediterranean Sea.

Air pollution from the Gulf would contain large concentrations of sulphates as the region has a high concentration of oil refineries. The main anthropogenic source of airborne sulphur compounds is the combustion of fossil fuels and for petroleum products virtually all the sulphur content of the fuel is emitted. The region is also a significant producer of aeolian dust , which when coated with sulphates produces highly hygroscopic particles.

Air pollution transported across North Africa would consist mainly of aeolian dust as this region is the largest source of aeolian dust in the world. The dust is also a regional climate-forcing agent and may alter the surface radiation budgets and affect the surface temperature.

Air pollution across the Mediterranean Sea would have its source in Europe and in particular Italy and France as revealed by the trajectories. Europe has taken significant steps to reduce the amount of sulphur emitted from industries and therefore pollution entering the UAE may have lower sulphate concentrations. However, these concentrations may be sufficient to contribute to the air chemistry and atmospheric dynamics of the region.

Air pollution from Asia would have high sulphate content as increasing industrial development causes large emissions of SO_2 that will become sulphates. These aerosols are caught up in the ITCZ and transported across international boundaries. Development in Asia is set to increase rapidly over time and this may lead to an increase in the concentration of emissions being transported to the UAE from the Indian subcontinent.

Although air pollution may be transported from each of the regions along different pathways, it is the effect of the combined contributions that are of importance to the UAE.

Suggestions for Future Research

To quantify long range transport of air pollution involves several aspects from different science disciplines: emissions of aerosols and their precursors must be known, not only in their amount but also with regard to their geographic distribution and seasonal variations; wind fields must be available in sufficiently high spatial and temporal resolution; vertical transport processes such as convection or frontal lifting must be captured; and the chemical transformation of pollutants must be considered (Schultz and Bey, 2004).

Sulphur emissions are not equally distributed around the globe. A detailed understanding of source-receptor relationships is needed in order to address such issues as where emission reduction is need (or where it is most efficient) in order to improve air quality at a particular location. It is important for the UAE that a more comprehensive and quantitative analysis of the air chemistry of the source regions be conducted to determine the pollutants transported into the region. This is significant as the type of pollutant and its effects on the microphysical processes of the atmosphere may affect the rain producing processes in the region. In the near future, pollution emissions in Asia are set to increase as a result of rapid population growth and industrial and agricultural development (Lawrence, 2004). As a result, the expected

increase in SO_2 and the resultant sulphate aerosols need to be monitored, as the transport of it into the UAE could be deleterious to the air quality over the UAE.

Future consideration should also be given to the UAE as a source region for pollution and a trajectory analysis should be computed to determine the receptor regions for this pollution. The UAE may be affecting the air quality of a number of receptor regions and the extent of these needs to be analysed.

Much of this work has been based on Langrangian trajectory analysis. Bottenheim (2004) suggests that this introduces an inherently large spatial uncertainty due to the need to consider longer travel time (as much as 10 days) before potential source regimes can be discerned. It is important to consider to what extent does pollution outflow from a given region contribute to the air quality of the receptor regions downwind (Schultz and Bey, 2004).

Conclusion

It has been established that large concentrations of SO_2 are produced in the UAE and that it is possible that a significant (although not quantified) amount of sulphates are transported into the region. These pollutants can have a significant impact on the air chemistry of the affected regions. The pollutants

have a direct effect on the atmosphere by reflecting and absorbing solar radiation and an indirect effect by affecting cloud formation and precipitation processes.

In a region such as the United Arab Emirates, where the demand for water is increasing and the annual rainfall is low, any feature that may affect the air chemistry of the region should be analysed. To this end, this research has highlighted the possible source regions of long-range transport of pollution into the UAE and its significance to the health of the population and the overall air chemistry of the region.

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