

**MODELLING THE EFFECTS OF CLIMATE CHANGE ON
AIR QUALITY IN THE DAMMAM METROPOLITAN AREA,
SAUDI ARABIA, USING AERMOD COUPLED WITH
STATION AND MESOSCALE WEATHER DATA**

BY

MUSTAPHA, BABATUNDE MUHAMMED

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This thesis, written by **Mustapha Babatunde Muhammed** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCES**.

B. S. Tawabini

Dr. Bassam Shafiq Tawabini

John D. Humphrey

Dr. John D. Humphrey
Department Chairman

Suliman Al-Homidan

Dr. Suliman Al-Homidan
Dean of Graduate Studies



Ole John Nielsen

Prof. Ole John Nielsen (Member)

Abdullah A. Alshuhail

Dr. Abdullah A. Alshuhail
(Member)

Date

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2021

I dedicate this work to Almighty Allah for his guidance, protection and mercy.

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LIST OF ABBREVIATIONS

AMS:	American Meteorological Society
AERMOD:	AMS/Environmental Protection Agency Regulatory Model
AERMAP:	AERMOD Mapping Program
AERMET:	AERMOD Meteorological Preprocessor
AD:	Air Dispersion
KFIA	King Fahd International Airport
WRF:	Weather and Research Forecasting System
IPCC:	Intergovernmental Panel on Climate Change
KSA:	Kingdom of Saudi Arabia
WHO:	World Health Organization
AR5:	Assessment Report no. 5
ISC3:	Industrial Source Complex 3
EIA:	Environmental Impact Assessment
USEPA:	United States Environmental Protection Agency
MM5:	Mesoscale Model 5
POPs:	Persistent Organic Pollutants
COVID-19:	Corona Virus Disease of 2019

SO ₂ :	Sulphur di Oxide
API:	Application Programming Interface
NCEI:	National Centre of Environmental Information
NOAA:	National Oceanic and Atmospheric Administration
ISHD:	Integrated Surface Hourly Data
ESRL:	Earth System Research Laboratory
ASTER:	Advanced Space borne Thermal Emission and Reflection Radiometer
WPS:	WRF Preprocessing System
UTM:	Universal Transverse Mercator
FSL:	Forecast System Laboratory

ABSTRACT

Full Name : Babatunde Muhammed Mustapha

Thesis Title : Modelling the effects of climate change on air quality in the Dammam metropolitan area, Saudi Arabia, using AERMOD coupled with station and mesoscale weather data

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Air dispersion (AD) models such as AERMOD are important tools for estimating the environmental impacts of air pollutant emissions into the atmosphere from anthropogenic sources. The outcome of these models is significantly linked to the climate conditions such as air temperatures and wind speeds, which are expected to differ in the future due to the global warming phenomenon. With projections from scientific sources of impending changes to the future climate of Saudi Arabia, especially temperature rise, there is a potential direct impact on the dispersion patterns of air pollutants results from AD models. To our knowledge, no similar studies were carried out in Saudi Arabia to investigate such impact. Therefore, this research investigates the effects of climate change on air quality in the Dammam Metropolitan area, Saudi Arabia, using AERMOD coupled with Station and Mesoscale Weather data using Sulphur dioxide (SO₂)— as a model air pollutant. The research uses AERMOD model to predict the SO₂ dispersion trends on the surrounding area. Emissions from five (5) industrial stacks, on twenty-eight (28) receptors in the study area were considered for the climate period (2010-2019) and future period of mid-century (2040-2060) under different scenarios of elevated temperature profiles (+1°C, + 3°C and + 5°C) and wind speed (+0.6 m/s, +1.2 m/s and +1.8m/s) across averaging time periods of 1hr, 4hr and 8hr. Results showed that levels of SO₂ at the

receiving sites under current and simulated future climactic condition fall within the allowable limit of WHO and KSA air quality standards. Results also revealed that the projected rise in temperature would only have mild increment on the SO₂ concentration levels while change in wind speed will have more significant impacts. The average increase of SO₂ levels were 0.04%, 0.14%, and 0.23% due to the temperature increase of 1, 3, and 5 degrees respectively while the levels reduced by 10.9%, 15.16% and 18.13% when wind speed increased by 0.6m/s, 1.2m/s and 1.8m/s respectively. This indicates that the changes in wind speed had far more significant effects on air pollutant concentration compared to air temperature. In conclusion, outcome of this work elucidates the degree of the effects of global warming and climate changes phenomena on air quality and can help the policy makers in their decision-making, given the significant health challenges associated with ambient air pollution in Saudi Arabia.

Keywords: Air Quality, Sulfur Dioxide, Dispersion models, Global Warming, KSA

ملخص الرسالة

لأسم الكامل: بابتوندي محمد مصطفى

عنوان الرسالة: نمذجة آثار تغير المناخ على جودة الهواء في منطقة الدمام الحضرية ، المملكة العربية السعودية ، باستخدام AERMOD مقروئاً ببيانات الطقس الخاصة بالمحطات والطقس المتوسط.

التخصص: علم البيئة

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هي أدوات مهمة لتقدير الآثار البيئية لانبعاثات ملوثات الهواء في الغلاف الجوي AERMOD نماذج تشتت الهواء مثل من مصادر بشرية. ترتبط تقديرات هذه النماذج بشكل كبير بالظروف المناخية مثل درجات حرارة الهواء وسرعة الرياح ، والتي من المتوقع أن تختلف في المستقبل بسبب ظاهرة الاحتباس الحراري. مع التوقعات بعض المصادر العلمية للتغيرات الوشيكة على المناخ المستقبلي للمملكة العربية السعودية ، وخاصة ارتفاع درجة الحرارة ، هناك تأثير مباشر محتمل على . على حد علمنا ، لم يتم إجراء دراسات مماثلة في المملكة العربية AD أنماط تشتت ملوثات الهواء الناتجة من نماذج السعودية للتحقيق في هذا التأثير. لذلك تبحث هذه الدراسة في آثار تغير المناخ على جودة الهواء في منطقة الدمام بالمملكة (- كنموذج ملوث للهواء SO₂ العربية السعودية ، باستخدام بيانات الطقس وتراكيز انبعاثات لغاز ثاني أكسيد الكبريت)

للتنبؤ باتجاهات تشتت ثاني أكسيد الكبريت في منطقة الدراسة من خمسة (5) مداخل AERMOD يستخدم البحث نموذج صناعية ، على ثمانية وعشرين (28) مستقبلاً في منطقة الدراسة للفترة من (2010 إلى 2019) والفترة المستقبلية لمنتصف القرن (2040 إلى 2060) في ظل سيناريوهات ارتفاع درجات الحرارة المتوقعة بدرجة مئوية واحدة أو 3 أو 5 درجات وسرعة الرياح (+0.6 م / ث ، +1.2 م / ث و +1.8 م / ث) عبر متوسط فترات زمنية 1 ساعة و 4 ساعات و 8 ساعات.

أظهرت النتائج أن مستويات ثاني أكسيد الكبريت في مواقع الاستقبال في ظل الظروف المناخية الحالية والمستقبلية المحاكاة تقع ضمن الحد المسموح به لمعايير جودة الهواء لمنظمة الصحة العالمية والمملكة العربية السعودية. كشفت النتائج أيضاً أن الارتفاع المتوقع في درجة الحرارة لن يكون له سوى تأثير طفيف على مستويات تركيز ثاني أكسيد الكبريت في حين أن التغيير في سرعة الرياح سيكون له تأثيرات أكبر. بلغ متوسط الزيادة في مستويات ثاني أكسيد الكبريت 0.04% و 0.14% و 0.23% بسبب ارتفاع درجات الحرارة بمقدار 1 و 3 و 5 درجات على التوالي بينما انخفضت المستويات بنسبة 10.9% و 15.16% و 18.13% عندما زادت سرعة الرياح 0.6 متر. / ثانية ، 1.2 م / ث و 1.8 م / ث على التوالي. يشير هذا إلى أن التغييرات في سرعة الرياح كان لها تأثيرات أكثر أهمية على تركيز ملوثات الهواء مقارنة بدرجة حرارة الهواء.

في الختام ، توضح نتائج هذا العمل درجة تأثير ظاهرة الاحتباس الحراري وظاهرة التغيرات المناخية على نتائج نمذجة جودة الهواء ويمكن أن تساعد صانعي السياسات في اتخاذ قراراتهم ، بالنظر إلى التحديات الصحية الكبيرة المرتبطة بتلوث الهواء المحيط في المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

According to the World health organization (WHO), about seven million people worldwide lose their lives to air pollution (indoor and outdoor) every year and this is largely because most people breathe air whose quality violates regulatory limits. Overall, air pollution has detrimental health and climate effects (Sahraei et al., 2020). Compromised air quality is usually a consequence of high emission of toxic gaseous pollutant coming from increasing natural and anthropogenic activities (Harrison, 2001).

Outdoor air pollution, which is the focus of this research, claims about four million deaths through lung cancer, heart disease, stroke and other forms of acute and chronic respiratory diseases. One of the most common primary anthropogenic pollutants is Sulphur oxides, particularly Sulphur dioxide (SO₂) (Mokhtar et al., 2014).

Sulphur dioxide (SO₂) is a colorless gas produced mostly by anthropogenic activities like burning fossil fuels and smelting of sulphur-laden mineral ores as well as natural sources like eruption of volcanoes. This pollutant is a significant because it can form Sulphuric acid and compromise environment through deforestation and formation of acidify waterways to endanger aquatic life. In terms of human health, it can cause irritation to the eyes and affect proper functioning of the respiratory system and impede efficiency of the lungs. This can culminate in coughing, mucus secretion as well as aggravated conditions like asthma and chronic bronchitis (Daly et al., 2007).

There is an unsurprisingly close connection between air quality and global climatic health. Most of the channels of air pollution (burning of fuels, etc.) doubles as ceaseless sources of greenhouse gas emissions (Sahraei et al., 2020).

This is why this research aims to help policy makers understand future air quality under certain scenarios in order to benefit human health and our dear climate. This will ensure significant attrition in the number of cases of diseases associated to air pollution as well as help ameliorate any distasteful future climate variability.

1.1 Climate Change

In simple words, climate change is the variation in average weather conditions like temperature and rainfall in a region over a long period of time. According to Intergovernmental Panel Climate Change (IPCC) AR5 reports in 2013, there is a significant rise in earth temperature over the last two decades (IPCC, 2017). This includes warming of the earth caused by human emission of greenhouse gases as well as natural shift in weather patterns.

The significance of climate change research in Saudi Arabia cannot be overemphasized. This is because the country is already hyper-arid with very limited water resources and cannot afford to have its conditions further aggravated with the potential challenges of climate change. Hence, the need effective air quality monitoring and pollution control to forestall the deleterious health and economic effects of climate variabilities.

Because its ecosystem is relatively sensitive and its fossil-fuel dependent economy, Saudi Arabia is particularly susceptible to climate change. Temperature in the kingdom may rise by up to 4.2°C. for mid-century (2040-2069) (Almazroui et al., 2020; Tarawneh et al., 2018; Almazroui et al., 2020) with annual average increase of about 1.2 °C. In terms of awareness, 40% of Saudis are aware of climate change. 40% think it is a threat. 39% thinks it is a consequence of human activities (Gallup, 2009). Increase in temperature extremes may have an impact on environment sectors, including water resource, agriculture and power

generation (Darfaoui et al., 2009; Gallup, 2009).

1.2 Air Quality Modeling

Modeling expresses relationship between the different variables of a system in mathematical terms. It is a validated approach for gathering dependable information on the dispersion of pollutants in environment. Air dispersion mathematical models use predefined logic that considers all important parameters to estimate pollutant atmospheric concentration. There are a number of air quality models that currently in use including ISC3, AERMOD, and CALPUFF, etc. However, in the study, AERMOD was selected to conduct the investigation of the impact of climate change on the distribution of air pollutants.

AERMOD

AERMOD is a robust air dispersion modeling package, which simulates essential atmospheric variables, and supplies refined concentration estimates over a wide scope of meteorological conditions as well as modeling scenarios. It is an efficacious approach that can be used for predicting the concentrations of air pollutants in the ground atmospheric layers based on emission parameters and environment characteristics and for this reason, it is an approved tool for ambient air quality assessment worldwide.

AERMOD has a proven relevance in diverse cases (Kesarkar et al., 2007; Zou et al., 2010; Seangkiatiyuth et al., 2011; Stefanova et al., 2017; Frost et al., 2014, Thepanondh et al., 2016). Its report can be employed as contribution to the Environmental and Social Impact Assessment (EIA) of the proposed projects because they consider the distinctive parts of the proposed project together with cumulative approach taking into account existing states of the ambient air quality.

AERMOD is the most widely used air quality modelling tool and the appropriate application to replace ISCST3 (US EPA Revision to the Guideline on Air Quality Models 40 CFR Part 51) since 2006 (Seangkiatiyuth et al., 2011). The AERMET pre-processor solidifies meteorological observations (e.g., temperature, wind direction, wind, cloud cover, relative humidity) with surface characteristics in the form of surface roughness, albedo, and Bowen ratio. AERMET also calculates station pressure, ceiling height, sea level pressure, sky cover. These variables determine the status of the layer affecting plume mixing and dispersion behavior. AERMOD works with the concentration distribution as Gaussian in both vertical and horizontal directions. It calculates concentrations of the pollutants for each hour of the year and for each receptor within the grid. The maximum values (or average values, depending on the environmental specifications) are calculated for each receptor.

1.3 Meteorology Modelling and Weather Research and Forecasting (WRF)

The concentration of air pollutant in ambient atmosphere is contingent on three things: meteorology, emission rate, and the condition of geography. Of all the three, meteorology plays an indispensable role as the concentration of gaseous pollutant is governed by meteorological fields. In order to fulfill the meteorological requirements of air dispersion modeling, measurement can either be taken from the area of research or data obtained from meteorological models. While it is an important part of air quality modeling, the number of onsite meteorological measurement is limited across the world. Hence, meteorological model can help produce data compatible to run air quality model. With primary purpose of forecasting and simulating weather parameters, meteorological models estimate three-dimensional gridded meteorology with the help of mathematics to predict atmospheric conditions like changes temperature and pressure over time. The primitive prototype of the

meteorological model was the MM5 model. It is used across the world, especially in scenarios where we are modeling for history. The MM5 evolved to WRF. WRF is currently the gold standard for numerical weather prediction. This model configures two dynamic systems; namely, a data assimilation system and a software architecture facilitating parallel computation and system extensibility (Kumar et al., 2017).

CHAPTER 2

LITERATURE REVIEW

2.1 Sulphur Dioxide Dispersion Modeling with AERMOD

AERMOD model can be used to calculate dispersion and downwind concentration of air pollutant (Kesarkar et al., 2007; Jamshidi et al., 2020; Amouzouvi et al., 2020; Yavuz et al., 2012, Darfaoui et al., 2009; Krishna et al., 2014). Because of shortage of meteorological data, in 2006, Amit et al coupled WRF with AERMOD to estimate dispersion of PM₁₀ over Pune, India (Kesarkar et al., 2007). They had a reasonable level of agreement between the observed and predicted and they concluded that WRF was capable of generating reliable meteorological inputs for AERMOD modelling.

B Zou et al (Zou et al., 2010) in 2010 assessed the performance of AERMOD in estimating Sulphur di oxide (SO₂) concentration in Dallas and Ellis counties in Texas. Results suggest that SO₂ concentrations simulated by AERMOD at the 8 h, daily, monthly, and annual intervals match their respective observed concentrations much better compared with the simulated 1 and 3 h SO₂ concentrations.

In 2011, Kanyanee et al (Seangkiatiyuth et al., 2011) applied AERMOD as a tool to analyze NO₂ emissions from a cement complex as part of environmental impact assessment. Also, in the same year, Mark *et. al* used AERMOD to model the air dispersion of point and major line emission of SO₂ in Halifax, Sydney.

Chuturkova et al 2013 used AERMOD to evaluate NO_x emissions from nitric acid production and their effect upon ambient air quality in Devnya region, Bulgaria (Stefanova et al., 2017).

Davis refinery, Billings county, North Dakota, in 2016 used AERMOD to estimate the ambient air quality in the area of the proposed site to support their application for air contaminant discharge permit for Meridian energy group Inc.

With a bid to investigate the accuracy of AERMOD, Frost in 2014 (Frost et al., 2014) predicted hourly ground level concentrations of SO₂ and compared the results with concentrations of full year monitored SO₂ data and he concluded that model performance agrees with widely accepted regulatory performance limits.

In 2015, Sharif et al, analyzed projected temperature changes over Saudi Arabia in the twenty-first century and came up with temperature projections for major cities (Sharif et al, 2015).

In 2016, some researchers in Thailand, Thepanondh et al (Thepanondh S et al., 2016), evaluated the performance of AERMOD air dispersion model in predicting ground level concentration of sulfur dioxide(SO₂) in Thailand. After comparing model result with monitored emitted data from petroleum refinery complex, they concluded that AERMOD modelling had a good agreement with observed SO₂ concentrations. Talaiekhozan et al in 2018 evaluated emission inventory evaluated emission inventory of the pollutants emitted from the municipal solid wastes landfill of the city of Borujer using AERMOD.

There have also be notable work using WRF mesoscale forecast system to provide meteorology for air quality dispersion modeling. (Kumar et al, 2017; Almazroui, 17, Almazroui M et al., 2017)

Early in year 2020, Ruggeri et al used modeled spatial distribution, patterns and source contributions of persistent organic pollutants (POPs) in the atmosphere of Great Mendoza using the WRF/CALMET/CALPUFF modelling system. Great Mendoza is a place in Argentina.

In order to investigate the effects of restricted emission during COVID-19 pandemic, some researchers in India used AERMOD coupled with WRF to investigate concentration of SO₂ between 2017 and 2020. WRF provided level-plain meteorological data, hence they could ascribe difference in results to restricted emission occasioned by the pandemic.

In order to assess the effects on oil refineries on surrounding environment, Jamshidi et al 2020 , simulated the release pattern of SO₂ with AERMOD under different time scales and concluded that AERMOD model was effective for modeling point source in the oil refinery(Jamshidi Angas et al., Jamshidi Angas, 2020).

Kumar et al, 2017, investigated the useability of AERMOD with WRF meteorology forecasting and reported that there was a good agreement between the observed and modeled result (Kumar et al., 2017).

Yavuz et al, 2015, calculated the level of emissions reaching ground level receptors from stack emission and reported effectiveness of the AERMOD model (Yavuz et al., 2018)

2.2 Climate Change in Saudi Arabia

There are numerous reliable research work about climate change in the kingdom of Saudi Arabia (Khan et al., 2018; Howarth et al., 2020; Taskinsoy et al., 2020). Krishna et al, 2014 analyzed maximum and minimum temperature observed in 4 different climactic areas of Saudi Arabia for the period of 1984-2013 and concluded that was a significant rise in temperature over the period and also that the minimum temperature was rising higher than maximum temperature (Krishna et al., 2014). In a bid to understand trend in extreme summer temperature in the kingdom of Saudi Arabia, Rashid et al, 2020, processed meteorological data from 27 stations and analyzed for maximum temperature in summer seasons and concluded that Northern, Central and Coastal regions of Saudi Arabia experience more severe temperature

(Rashid et al., 2020). Mujabar et al, 2018 used remote sensing to analyze land surface temperature of jubail industrial city and reported rapidly rising surface temperature (Mujabar et al., 2018). Tarawneh et al, 2018, assessed the implications of changes in Saudi Arabia climatic change on water resources. He reported that in all scenarios, Temperature rose between 1986 to 2005 in the studied domains (Tarawneh et al., 2018) . Almazroui et al 2018 studied the impact of climate change on water engineering structure in arid regions (Almazroui et al., 2019) . He also investigated rainwater harvesting possibilities under climate change and concluded that stronger and longer wet periods should be expected in the future which may aggravate flood and flash flood issues in the Kingdom (Almazroui et al., 2017). Also in 2020, Mansour et al, modelled seasonal and regional changes in temperature over Arabian Peninsula and their results revealed that central region of Arabian Peninsular –Saudi Arabia and Yemen – will experience higher temperature during all seeason of the 21st century (Almazroui et al., 2020).

In 2018, Khan et al studied the flunctuation of temperature, rainfall and relative humidity in Mekkah, Saudi Arabia and reported notable climatic changes between the years 1985 to 2016 (Khans et al., 2009). Williams et al 2012 investigated impact of global warming and climate change on some animals in Saudi Arabia and reported that temperature was already close to upper lethal threshold in the animals and that global warming will have detrimental effects on these species of animal in Saudi Arabia. (Williams et al., 2012)

2.3 Research Gap

Literature search revealed that regulatory models are utilized to estimate pollutant emission dispersions and most of the work in this niche focus more on assessing model performance. About 95 % of the intellectual and academic work in this area have been based on applying the models to validate their performance by comparing model results with observation as measured from the modeled site. However, this research is exploring the feasibility of using air dispersion models to assess the effect of the global warming issue on the distribution of various air pollutants. In this study, SO₂ was used a target air pollutant. To our knowledge, this subject has not been addressed before in the previous work.

2.4 Research Question

Will the projected climate change (rise in temperature and wind speed) in Kingdom of Saudi Arabia in coming decades (specifically by mid-century 2040-2060) have any impacts on ambient pollutant concentrations and possibly alter Saudi Arabia air quality?

2.5 Significance of the Study

The kingdom of Saudi Arabia is the fourth emitter of Sulphur Dioxide –a known hazardous air pollutant- globally and the largest in the Middle East (Dahiya et al., 2019). This is because its fossil fuel dependent economy makes it inevitable to have polluting oil-based power plants, industries and refinery facilities. In addition, there are projections from reliable scientific sources of impending changes to the future climate of Saudi Arabia, especially anticipated temperature rise and wind speed (Tarawneh et al., 2018). In order to achieve Saudi Arabia's vision 2030, preserving the air environment is essential as this will boost the quality of lives of citizens and residents and protect future generation. This research can help the policy makers in their decision-making, given the significant health challenges associated with ambient air

pollution in Saudi Arabia.

2.6 Objectives

The main objective of this research is to investigate the impact of projected climate change (rise in temperature) in Saudi Arabia by mid-century (2040 - 2060) on the air quality using Sulphur dioxide (SO₂) as a target air pollutant. The specific objectives are:

1. Obtain meteorological data of decade (2010-2019) and vary its temperature parameter to reflect forecasted climate change of Saudi Arabia by mid-century (2040-2060)
2. Using meteorology data from (I), model the SO₂ concentrations for decade 2010-2019 as well as future period (2040-2060) using the air quality dispersion tool (AERMOD)
3. Evaluate the difference in modelled dispersion results of decade (2010-2019) and future period, mid-century (2040-2060), if any.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Model Domain (Study Area)

The release pattern and concentration of SO₂ air pollutant in Dammam region – area of about 35km x 35km – was simulated with AERMOD. The green circle in the image below shows the station where the meteorology data was obtained, the red circle is the industrial part where the sources of emission are located and the yellow part is the location of the sensitive receptors. All located in Dammam, Eastern region, Saudi Arabia.

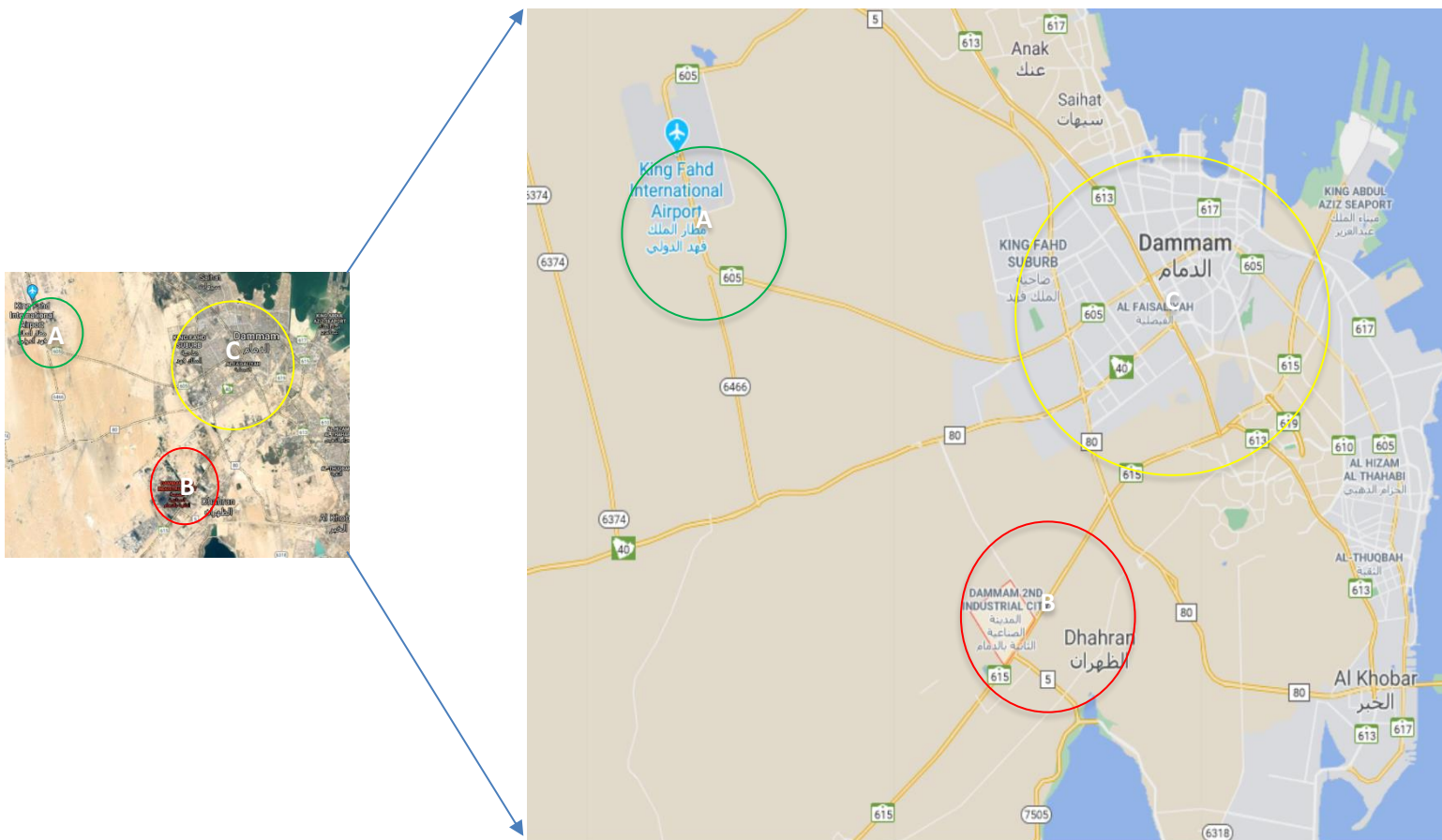


Figure 1: AERMOD modeling domain showing the meteorological station (green), the source of emission (red) and location of receptors(yellow)

3.2Data Collection

Dispersion modeling requires meteorology, terrain data as well as emission inventory of the air pollutant from the source.

3.2.1 Meteorological Data

We processed model ready meteorological data. Raw data were obtained from the nearest National Weather Station observation station (i.e. King Fahd International Airport (KFIA) in Dammam)

3.2.1.1 Surface Data

We obtained and quality assured Surface Data (2010-2019) from KFIA Dammam, Saudi Arabia. The hourly observational data was obtained from KFIA station because it is the closest station to the model domain. The data was obtained through the API's of National Centers for Environmental Information (NCEI), which is a subsidiary of National Oceanic and Atmospheric administration (NOAA) using station ID of 404150. The data were obtained for years 2009 to 2019 in the format of Integrated Surface Hourly Data (ISH)

3.2.1.2 Upper Air Sounding Data

A quality assured Upper Air Sounding Data (2010-2019) from King Fahd International Airport (KFIA). Research-quality radiosonde data of King Fahd International airport (closest available data center) was obtained from the National Oceanic and Atmospheric Administration's Earth system research laboratory (ESRL) using station ID 40417. The data was obtained for years 2009 to 2019 in the format of forecast system laboratory.

3.2.2 Terrain Data

During dispersion modeling, terrain data of the study domain area were needed to assign elevation to sources and receptors. Terrain causes plume centerline to be closer to receptors. For this research, terrain data was obtained from the remote sensing department of Dhahran Techno Valley at KFUPM University campus in Dhahran. We used digital elevation model of 30 meters' resolution produced from ASTER GDEM. The satellite imagery was used in worldview and resampled to 47 cm resolution.

3.2.3 WRF Data

In order to validate the meteorological data obtained from Dammam airport and to understand the trend in Saudi Arabia temperature over the last ten years, WRF numerical simulations were ran using global real analysis data. The WRF has a preprocessing component (WPS) and a major WRF core component.

The WPS has 3 major components: The geogrid, metgrid and the ungrib (as shown in Figs. 2 and 3). The geogrid was used to set the domains of interest, including Saudi Arabia and inner nest of Dammam. The geogrid was used to interpolate some time invariant fields like height, land use characteristics and other parameters that are not time invariant. The ungrib helps to ungrib grib met files which are the basic files for meteorology. The ungrib files were obtained from Copernicus through their Python API.

The metgrid takes the time invariant met field from global models (global modeling system of atmospheric conditions). It interpolates the meteorological files and crop out the area of interest and ultimately produce the actual needed for the main WRF run-Real.exe and Wrf.exe.

The parent id is about the domain reside. From the domain setting below, domain 1 houses itself, domain 2, Kingdom of Saudi Arabia, stays within domain 1 and finally domain 3, Dammam stays within domain 2. I am using integration time step of 180s for each of the nest. The io_form_grid is the format of the processed geogrid which is netCDF. The microphysics option selected is CONUS. The dx and dy grid distance in the x and y direction (Table 1).

Table 1: The Settings Used to Run the WRF Numerical Temperature Simulations

Parameters	Value
WRF Core	ARW
Number of domains	Three nested domain
Parent_Id	1(d01), 1(d02), 2(d03)
Horizontal resolution	15km(outer), 5km(middle), 1km(inner)
Integration time step	180s(outer), 180s(middle), 180s(inner)
Io_form_geogrid	netCDF
Microphysics	CONUS
Dx and Dy	30000, 5000, 1000

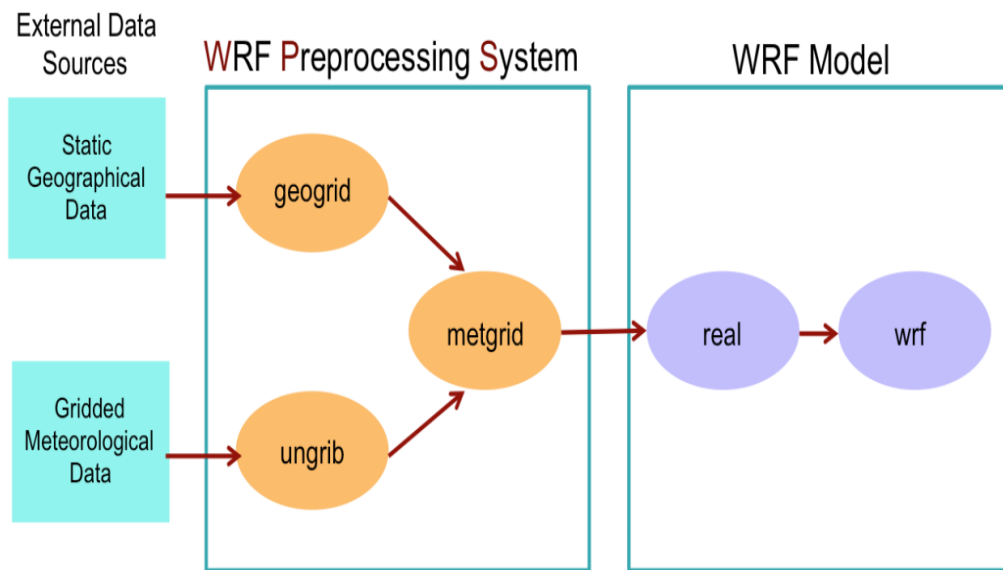


Figure 2: the architecture used to run the WRF numerical temperature simulations (source:<https://anamika.github.io/>)

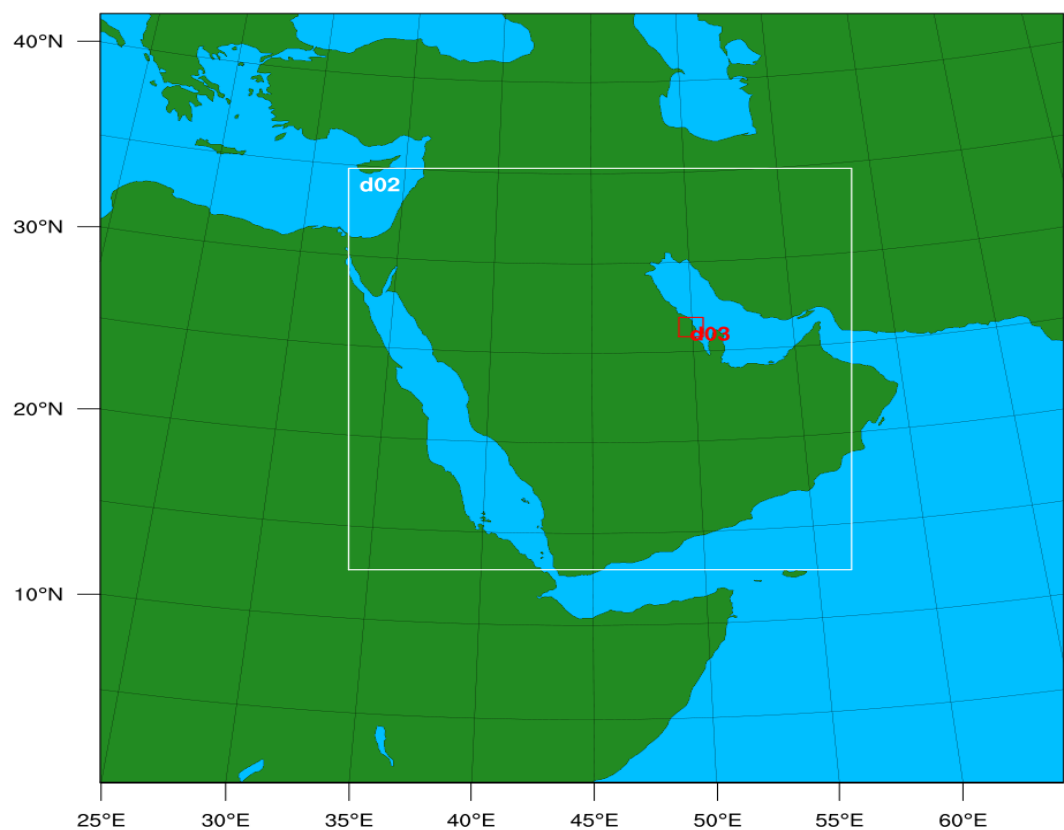


Figure 3: the Geogrid settings used for the WRF simulation, d02: domain 2, d03: domain 3

3.4 Data Processing

After collection of the meteorology and terrain data, preprocessing was carried out using appropriate EPA approved software.

3.4.1 Meteorology Data Preprocessing

AERMOD uses separate program –a preprocessor- to process meteorological data into appropriate format and the software is AERMET.

AERMET has 3 stages and the final output are model ready data files that will be read by the AERMOD model. The major things that the AERMET does is to calculate the boundary layer parameter for a site representative of the modeling domain using the site's latitude and longitude as well as site's characteristics like surface roughness, albedo and Bowen ratio.

3.4.1.1 AERMET STAGE I

Merge quality-assured hourly surface data and upper air sounding data (2010 - 2019) with surface characteristics data, Albedo, Bowen Ratio and Surface roughness.

The stage one extracts and quality assures upper air data and hourly surface data. In order to run stage one, an input file must be created.

The format of the upper air sounding data acceptable by is the forecast system laboratory format (FSL) while the format of the format of the hourly data is integrated surface hourly data (ISHD) as depicted in Table 2.

For this research, we used the following setting for the stage one of AERMET.

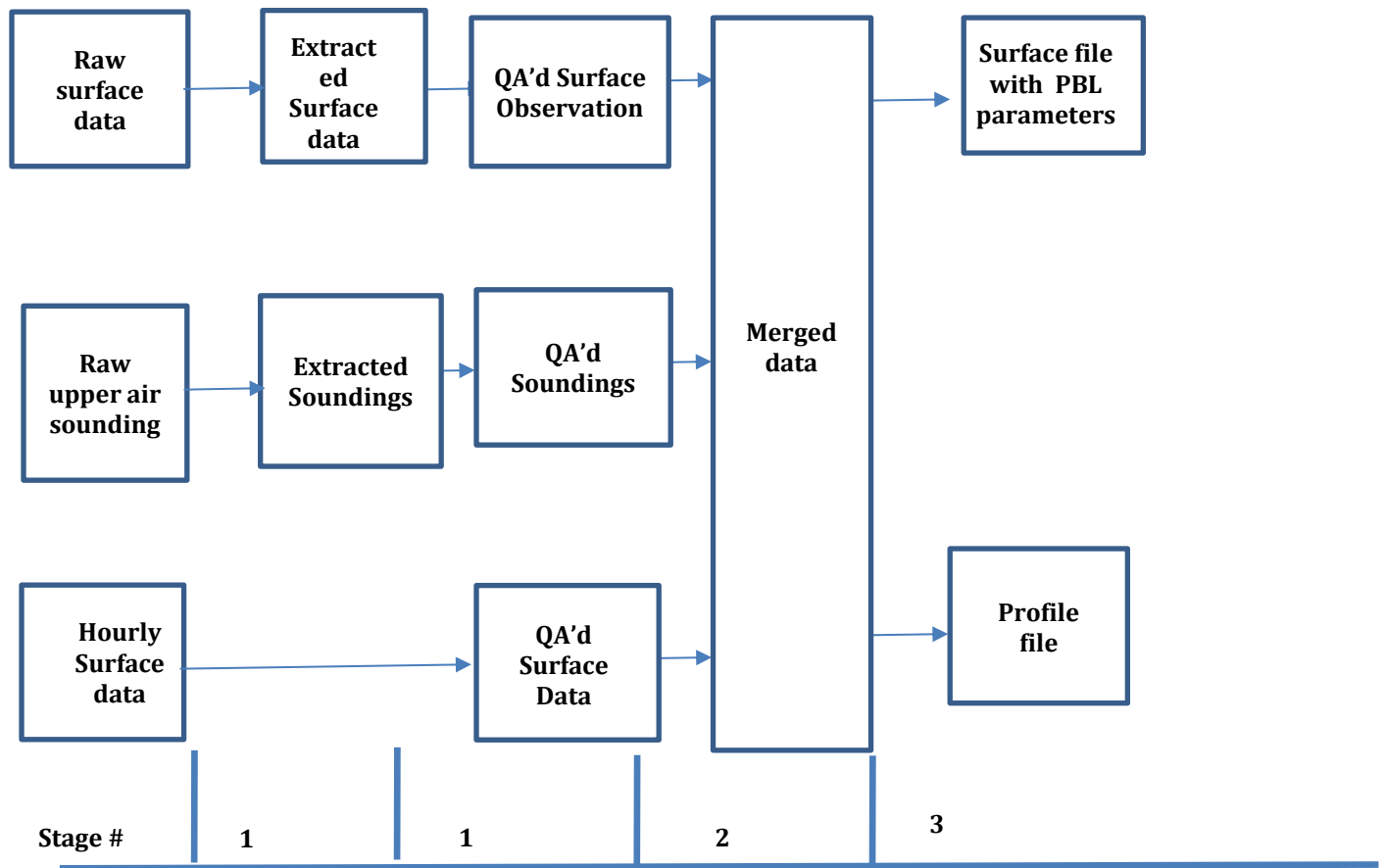


Figure 4: The Stages of Meteorology Processing: Extraction, Quality Assurance (QA'd), Merging the surface Observations and Soundings into a Single File & final stage

3.4.1.2 AERMET STAGE II

After extraction and quality assurance from stage one, the second stage merges the output. For each of the meteorological year processed, we specified the outputs from stage 1 as well as the period being processed.

Table 2: Details of the Radiosonde and surface data obtained from King Fahd international airport

UPPER AIR DATA SETTINGS	
File type	Forecast System Laboratory(FSL)
Station ID	404150
Latitude N/S	26.4500N
Longitude W/E	49.8167E
Domain time zone	3
Stage 2 Quality file	QA-Dammam.dat
Station Height	22m
XDATES	Specific Met Period Being processed
SURFACE DATA SETTINGS	
File type	Integrated Surface Hourly Data (ISHD)
UTM time zone	39
Station ID	404150
Latitude N/S	26.4500N
Longitude W/E	49.8167E
AUDIT Parameters	WSPD WDIR SLVP PRES PRCP PWTH RHUM CLHT TSKC TMPD TMPW DPTP HZVS

3.4.1.3 AERMET STAGE III

AERMET stage 3 processes the output of stage 2 and generate surface and profile files which are the files directly required by AERMOD.

3.4.2 TERRAIN DATA PREPROCESSING

Terrain data obtained from Dhahran Techno Valley was processed using AERMAP, AERMOD terrain preprocessor. In order to process the DEM files to assign elevation to all the sources and receptors, we followed the EPA guideline and defined the control options: which has the path to the DEM files, the datatype of the terrain data. This is followed by the source option, which has settings of the source elevation desired unit, source UTM coordinates. After this, we defined the receptor settings, which contains the desired elevation unit as well as the coordinates of all the receptors. The final setting of AERMAP is the output option, which contains the destination path for the processed source elevations as well as processed receptor elevations as shown in Figure 5.

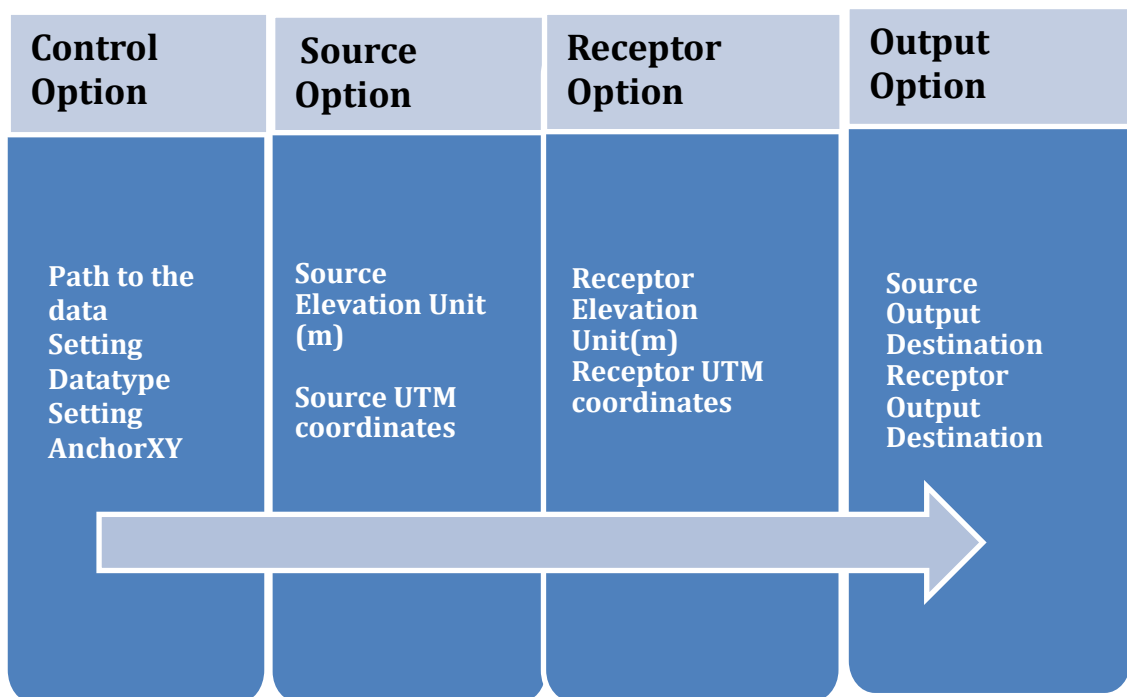


Figure 5: Details of AERMAP Preprocessing stages

3.5 DISPERSION MODELING

The dispersion model was run using the output of data from meteorological preprocessor and the terrain preprocessor as discussed above. These data were supplied to the graphical interface software of TRINITY BREEZE software as summarized in Figure 6 and building on the guideline of Stefanova et al., 2017.

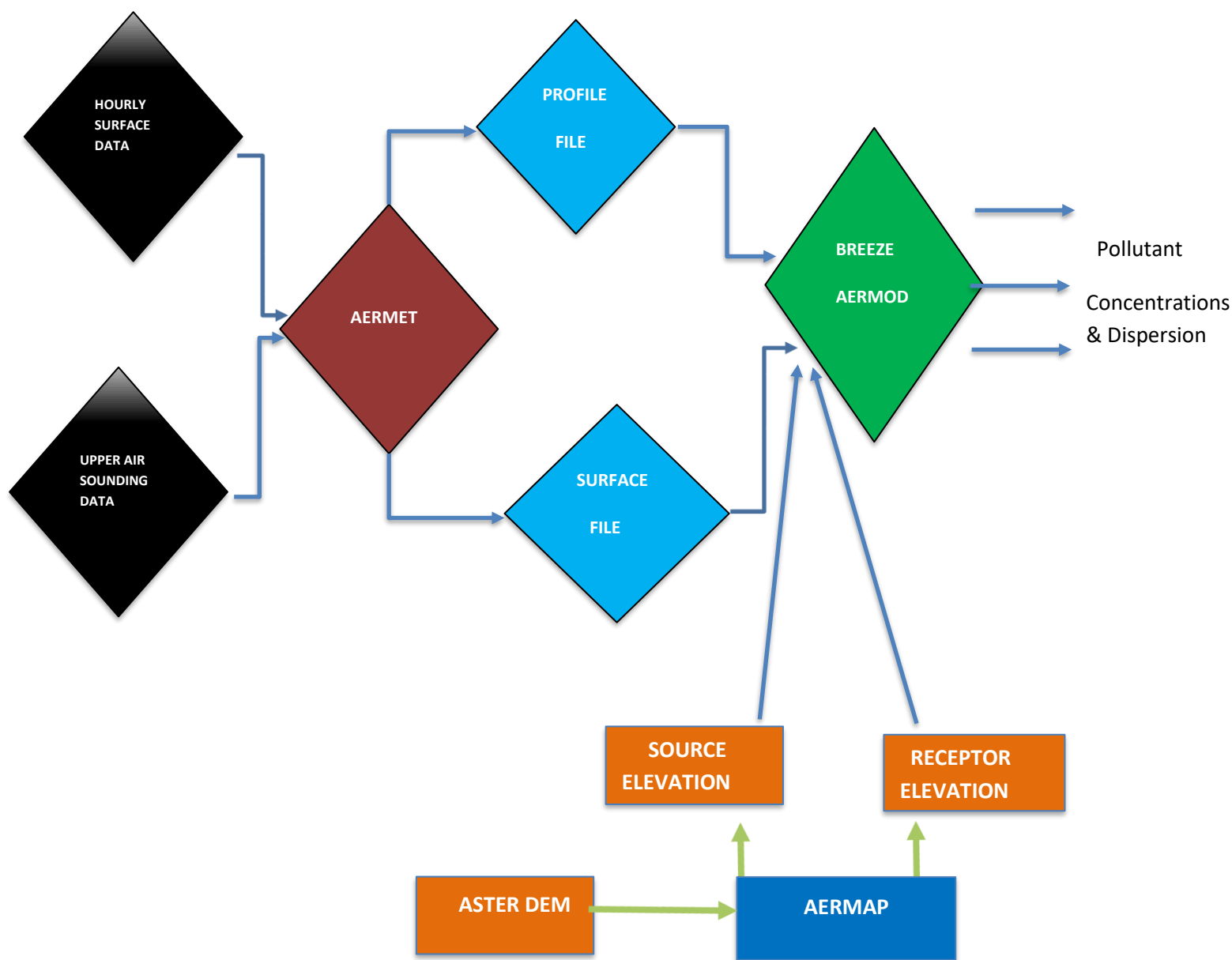


Figure 6: Showing the architecture used for the AERMOD air quality modeling

3.6 Point Sources and Receptors

The AERMOD dispersion modeling of SO₂ concentration was carried out using source and receptors within the Dammam metropolitan area.

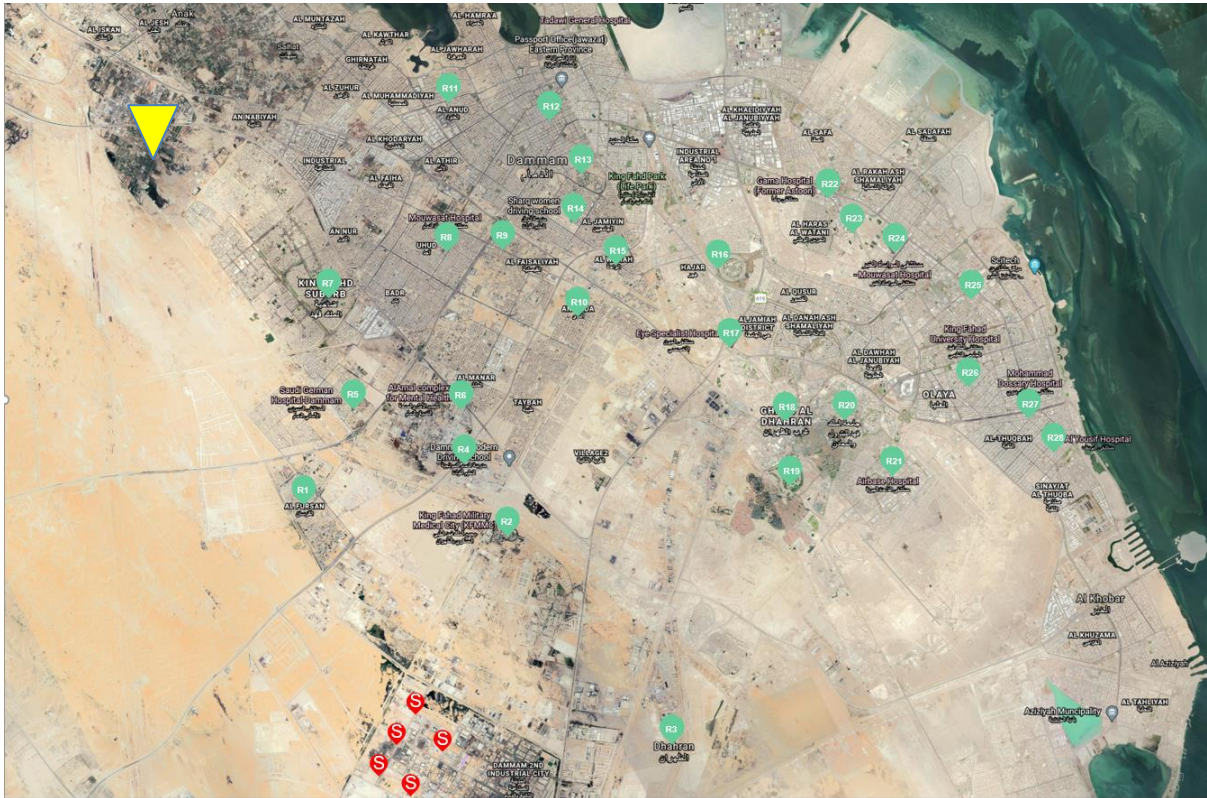


Figure 7: Study Area Showing 5 Point Sources (red) and 28 Sensitive Receptors (green), source of meteorology (yellow)

3.6.1 Emission Source

In this research, we are modeling from point sources. We are simulating release of emission from five well-defined stacks and vents – shown in red color in Figure 7 - from the Dammam 2nd industrial city. There are five (5) important information necessary to build emission inventory of a point source: Stack Height, Exit Temperature of stack gas, Emission rate, diameter, and gas exit velocity from the stack. The stack height is the emission release height above the ground level measured in meters. This value used in the model ranges from 85m to 110m for the point sources. The temperature variable of the

emission inventory is the exit temperature of the stack gas in kelvin. The stack temperature ranges from 405K to 650K as shown in Table 3 below. Since we are only modeling one pollutant (SO₂), it's important to know the pollutant emission rate from the point sources in g/s and the value ranges from between 7.0035 and 15.537 g/s. Diameter value is the inside diameter of the stack or vent in meters and the diameter values in this research varies from 8 to 14 meters and the final information of the point source emission inventory is exit velocity in meters per second. In this research, the value varies from 0.85 to 1.5 m/s.

Table 3: Emission inventory of the air pollutant, Sulphur dioxide

Source ID	Stack Height(m)	Temp(K)	Emission Rate(g/s)	Diameter(m)	UTM(m)	Exit Velocity(m/s)
Point Source 1	100	550	11.5	0.85	409011/2909 433.1	1.5
Point Source 2	110	480	7.2309	0.75	408328.2/29 08431.6	0.85
Point Source 3	85	600	7.0035	0.75	407736.5/290 7248.2	0.85
Point Source 4	90	580	7.122	0.75	409966.9/290 8158.5	0.85
Point Source 5	95	405	15.5370	1.9	408828.9/290 6656.4	0.95

3.6.2 Source Projection

We needed to set the GIS coordinates and projection so that base maps and terrain files can be georeferenced correctly. Since this research is custom to Dammam area of Saudi Arabia, we selected the ‘user-defined’ projection option. Setting this parameter essentially save us from having to reset the parameter elsewhere in the program. The projection is Universal Transverse Mercator(UTM) with units are meters. The UTM zone is 39 because our modelling domain of Dammam is located there and the hemisphere is Northern.

3.6.3 RECEPTORS

Receptors are specific location outside of the source where we need to estimate the concentration and dispersion of the air pollutant.

We modeled the concentration of SO₂ on twenty-eight (28) receptors in the Dammam area as shown in Table 4 and Figure 7. Although most of the receptors are hospitals and medical facilities, some are also schools and residential areas. We carefully selected these areas, as they are very sensitive areas within the model domain where Sulphur dioxide pollution could pose significant threat to human lives.

Table 4: Showing sensitive receptors monitored in the study

	Key	Category	Easting(m)	Northing(m)	Distance from Source(km)
1	R1	Residential	405103.4	2916767.9	14.44
2	R2	Hospital	412216.6	2915638.8	18.04
3	R3	Residential	418012.6	2908412.6	19.94
4	R4	School	410748.8	2918198.1	18.67
5	R5	Hospital	406836.9	2920061.6	18.15
6	R6	Mental Health Center	410602.3	2920061.6	20.08
7	R7	Residential	405965.6	2923951.4	21.36
8	R8	Hospital	410073.2	2925569.6	24.7
9	R9	Hospital	412064.8	2925694.1	25.59
10	R10	Restaurant	414709.9	2923360.2	25.29
11	R11	Residential	410166.6	2930859.8	30
12	R12	Medical Center	413714.1	2930206.3	30.5
13	R13	Hospital	414865.5	2928339.2	28.8
14	R14	School	414554.4	2926658.8	28
15	R15	Residential	416048.1	2925134	27.5
16	R16	School	419657.8	2925009.5	29.7
17	R17	Hospital	420000.1	2922239.9	28.19
18	R18	Residential	421991.7	2919625.9	28.06
19	R19	School	422178.5	2917416.5	26.95
20	R20	School	424107.8	2919750.4	29.91
21	R21	Hospital	425757.1	2917758.8	30.08
22	R22	Hospital	423516.6	2927499	34.02
23	R23	Residential/Tourism	424356.8	2926316.5	33.82
24	R24	Hospital	425850.5	2925569.6	34.21
25	R25	School	428495.6	2923920.3	25.19
26	R26	Hospital	428433.3	2920870.7	33.9
27	R27	Hospital	430518.3	2919750.4	35.5
28	R28	Hospital	431451.9	2918536.8	35.8

CHAPTER 4

RESULTS AND DISCUSSION

4.1 ANALYSIS OF METEOROLOGICAL CHANGES OVER DAMMAM IN LAST DECADE

4.1.1 Peak and Troughs of Dammam Temperature (2009 -2019)

The peak and trough temperature changes over Dammam for the past ten years have been fairly uniform with extreme temperature in the summer and lowest in winter as shown in Fig. 8 below.

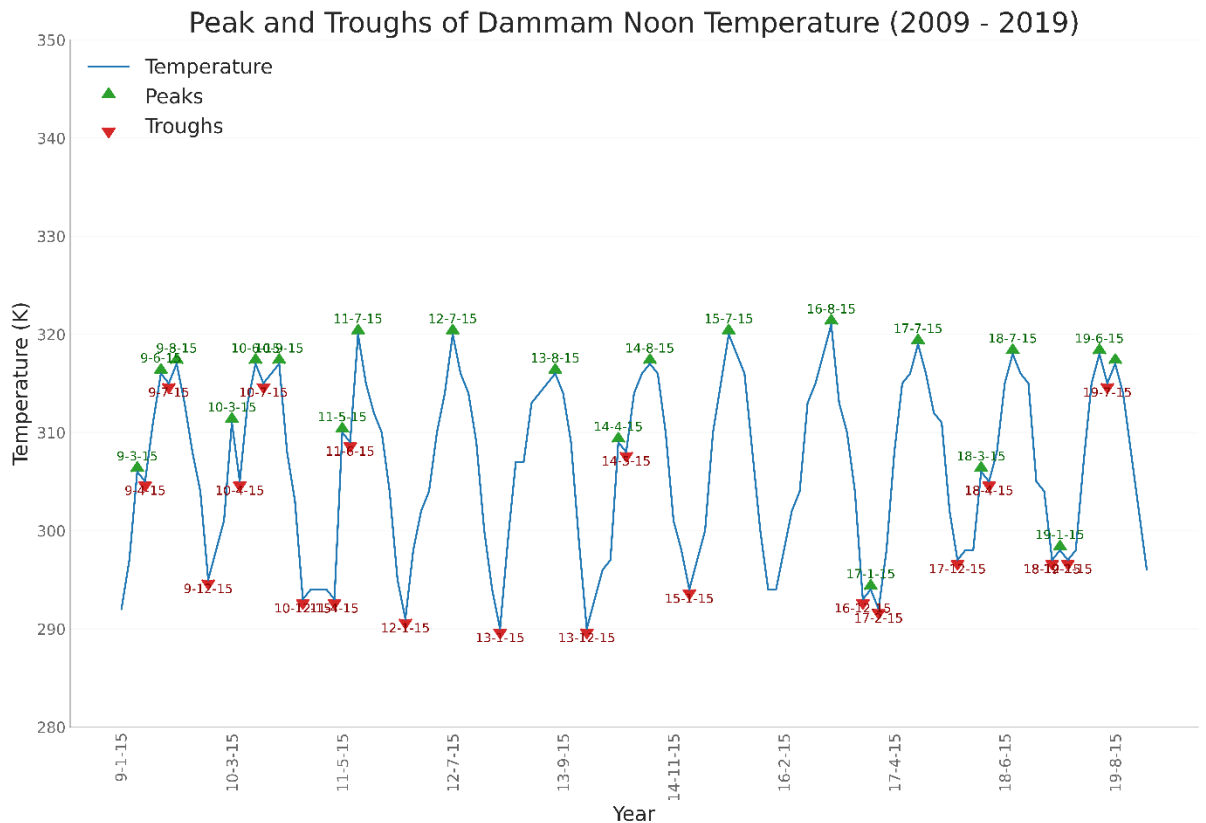


Figure 8: Showing Peak and Troughs of Dammam Noon Temperature (2009-2019)

4.1.2 Dammam Average Annual Temperature (2009 -2019)

Analyzing the meteorological data shows that Dammam average annual temperature has risen by 1 °C over the last ten years as shown in Fig. 9. This accentuate other works in literature that predict mean decade rise of about 1.2 °C in the Saudi Arabia ambient temperature.

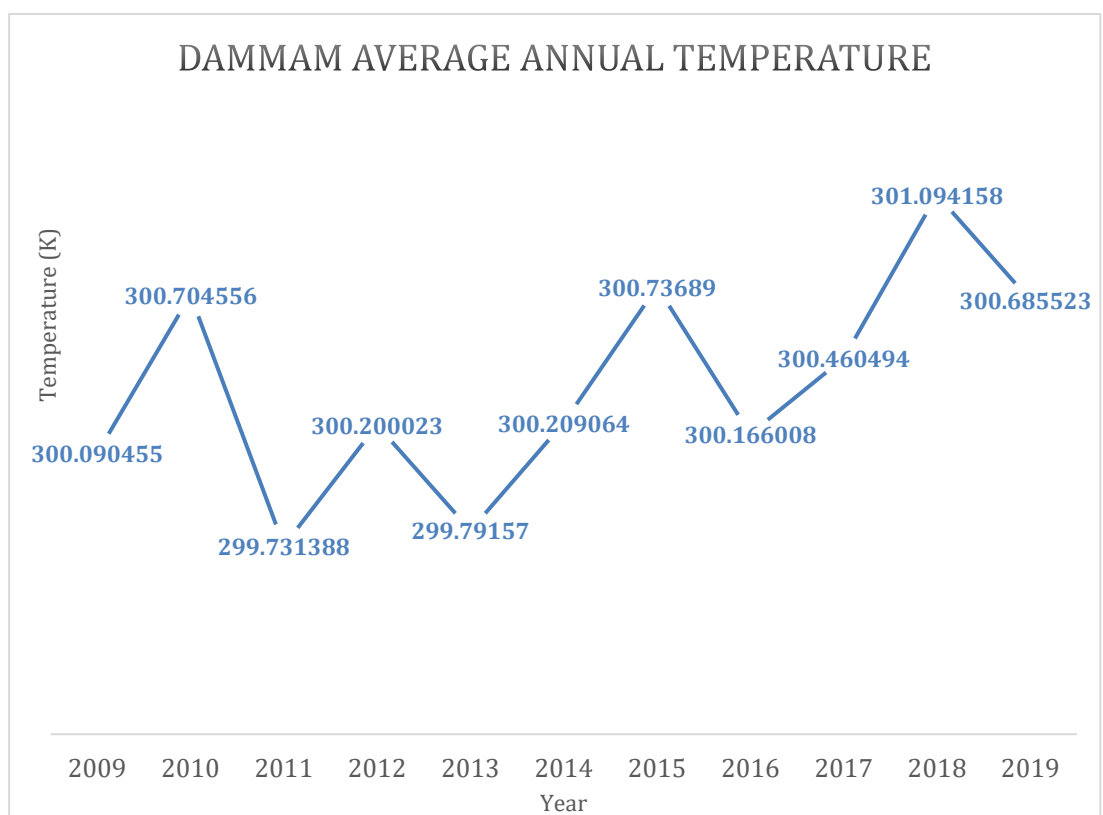


Figure 9: Dammam Average Annual Temperature over the last decade (2009 - 2019)

4.1.3 Temperature Numerical Simulations

WRF simulations shows the temperature distribution in Kingdom of Saudi Arabia during the major seasons of summer (Fig. 10) and winter (Fig. 11) for the last decade (2009-2019). KSA summer temperature for the last decade hovered around 283 to 323 K while Dammam summer temperatures were between 304 to 320K. This shows Dammam was still one the hottest part of Kingdom during summer for the last decade.

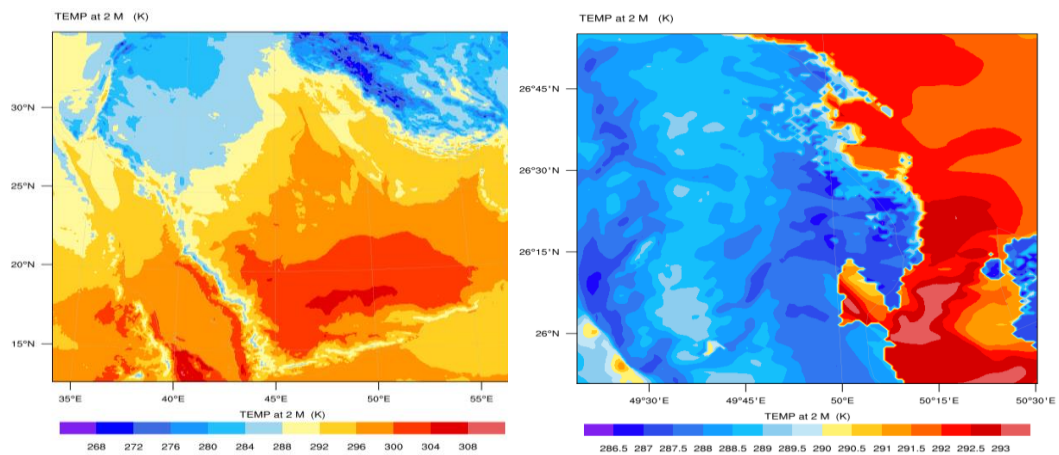


Figure 10: Average summer temperature distribution at 2m of Saudi Arabia over the last 10 years

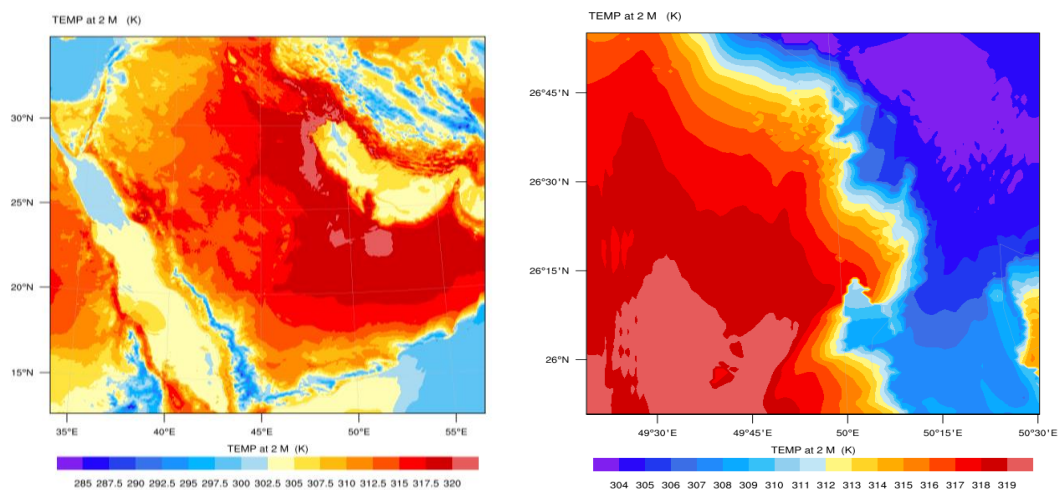


Figure 11: Average winter temperature distribution at 2m of Dammam over the last 10 years

4.1.4 Changes in Dammam Wind Speed over the Last 10 Years

Analysis of the meteorological obtained from the Dammam international airport revealed the trend in Dammam wind speed for the last decade (2010-2019) as revealed in Fig.12. The dominant wind class throughout the last decade was the 3.6-5.7 m/s class and the average annual wind speed has dropped about 0.6m/s over the last 10 years (Fig. 13).

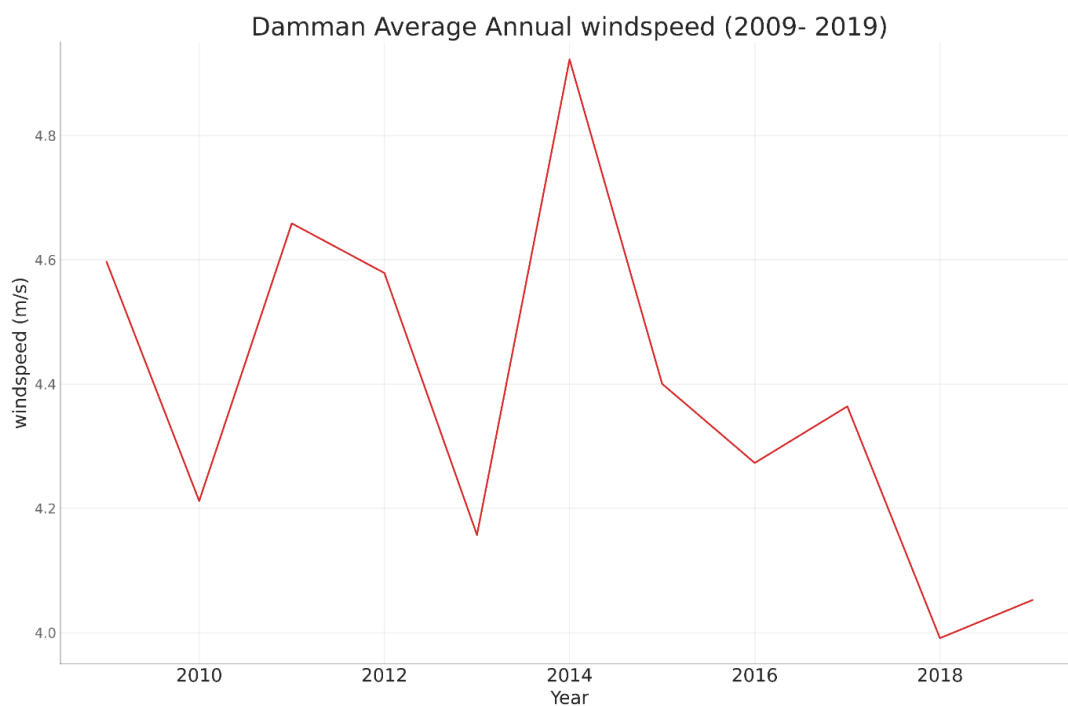


Figure 12: The average annual wind speed of the Dammam area for the last decade (2009-2019)

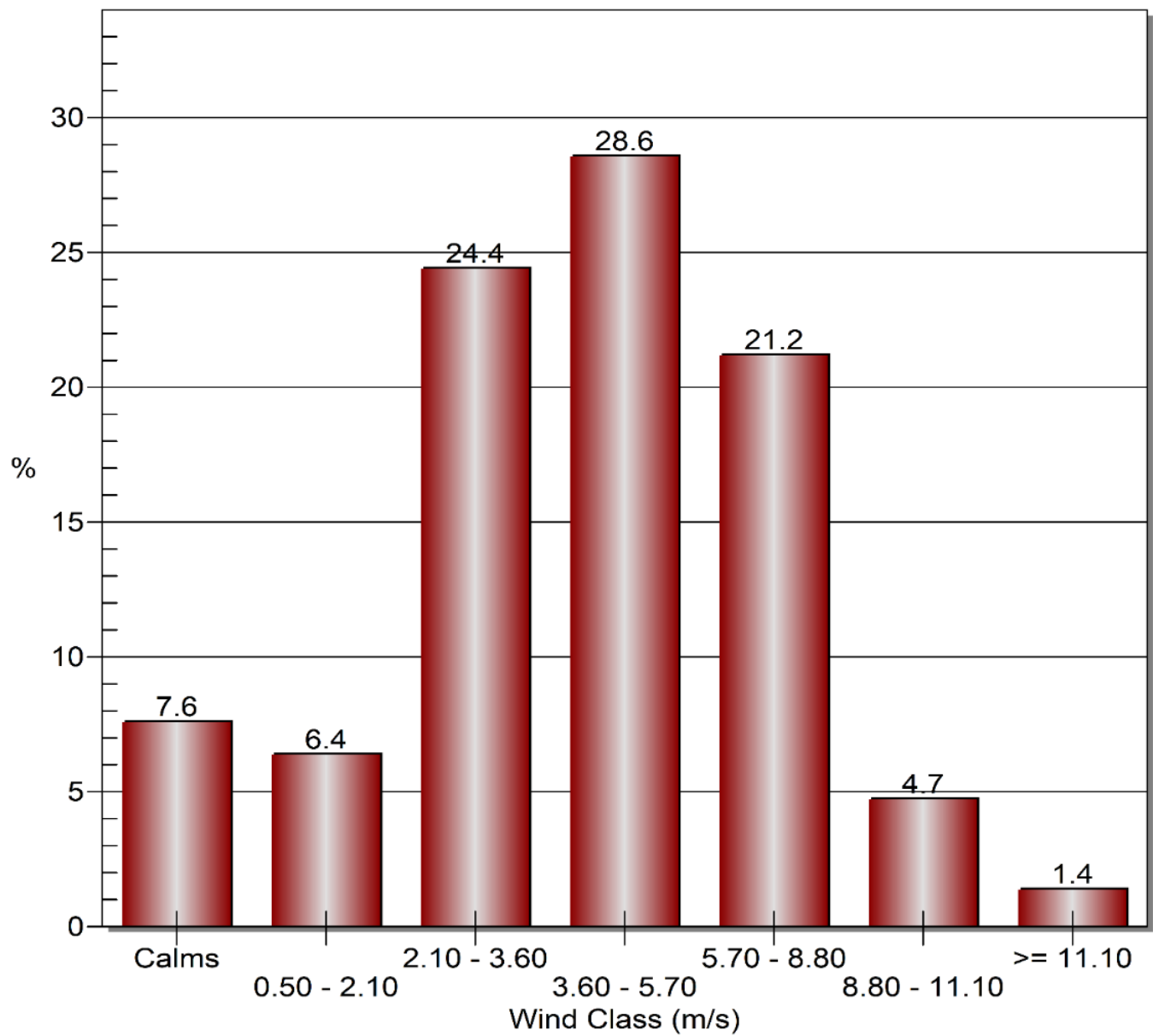


Figure 13: Wind speed classes and their frequencies over the last ten years in Dammam

4.1.5 Changes in Dammam Wind Direction over the Last 10 Years

Analysis of the meteorological obtained from the Dammam international airport revealed the trend in Dammam wind speed for the last decade (2010-2019). Wind direction has been majorly towards southeastern part of the Dammam area over the last 10 years (Fig. 14). This direction is the direction of source of the Sulphur dioxide air pollutant in our model domain from the king Fahd international airport.

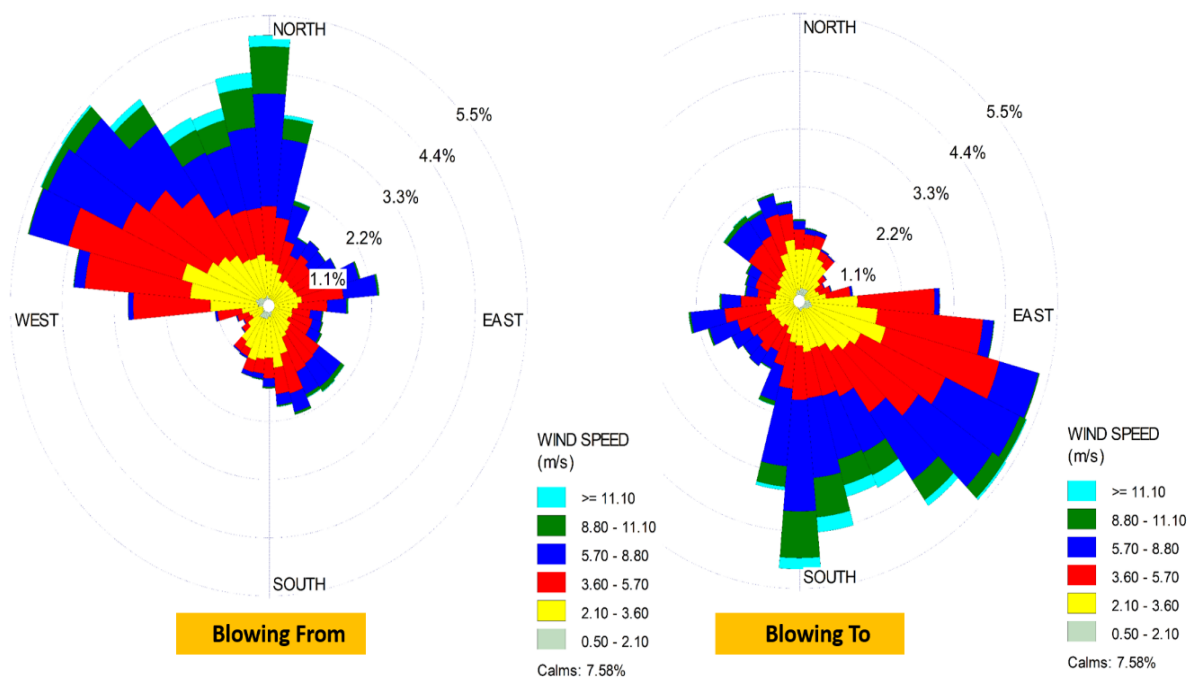


Figure 14: Plot showing the wind rose and wind direction for the last decade in Dammam

4.2 Dispersion Model Results Based on Temperature Changes

4.2.1 Current Vs Future Temperature Climate (1hr averaging period)

Using the processed meteorological and terrain data, we obtained downwind concentration for SO₂ under current ambient temperature as well as for future climatic condition (when the temperature is raised by 1°C, 3°C & 5°C) for the 1hr time scale (Figure 15 A, B, C and D). Under the current ambient temperature, sensitive receptors close to the source of emission: R1, R2, R3, R4, R5, R6 have downwind concentrations of 39.04337µg/m³, 52.1379µg/m³, 36.89988µg/m³, 46.39599µg/m³, 41.05924µg/m³, and 42.94982µg/m³ respectively.

Meanwhile, when we raised the ambient temperature by 1 °C using the same 1hr time scale, the receptors recorded higher pollutant concentration levels - 39.04651µg/m³, 52.14713µg/m³, 36.91133µg/m³, 46.40812µg/m³, 41.07157µg/m³, and 42.96242µg/m³ respectively which is an average of about 0.024% rise across the 6 receptors compared to the baseline concentrations. The concentration of SO₂ produced corresponding increment when ambient temperature was raised by 3°C & 5°C. Beyond the six closest receptors, a consistent result was obtained for the other 22 farther receptors as well. Overall, the rise in temperature did not have significant effects on the concentrations of Sulphur dioxide across the receptors for the 1-hr period as explained above.

The future projection of plus 1 degree Celsius had an average impact of 0.033% increment in SO₂ concentration (Figure 16), the future projection of plus 3° C had an average impact of 0.103% increment in SO₂ concentration while the future projection of plus 5°C had average increment of 0.175% in SO₂ concentration (Figure 16). SO₂ changes was directly proportional to temperature rise, with the exemption of few receptors where changes in the temperature produced higher effects (receptor 11, 21, 24, 26, 27). This may be due to the relatively longer distances of these receptors from the source. (33km, 30.8km, 34.21km, 33.9km, 35.8km). The accuracy of AM to predict pollutant concentrations at receptors

reduces with distance. This may explain why most receptors within a distance range of 14km to 30 km show reasonable consistency of SO₂ change with change in temperature while most receptors within distance range of 30km to 38km do not (Figure 16).

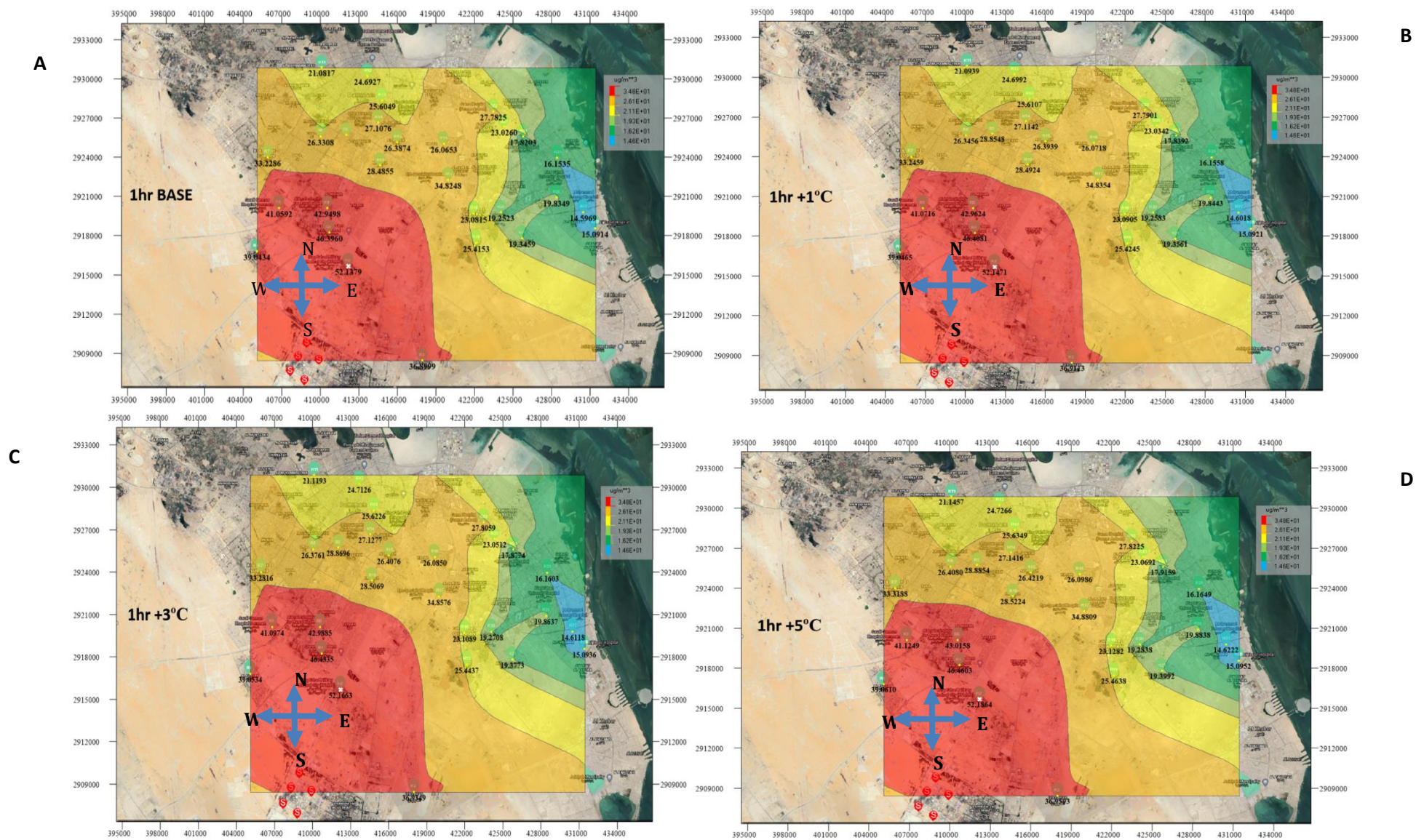


Figure 15A, 15B, 15C, 15D Comparison of 1hr time scale of current climate and that of future periods under 1°C, 3°C & 5°C temperature rise respectively

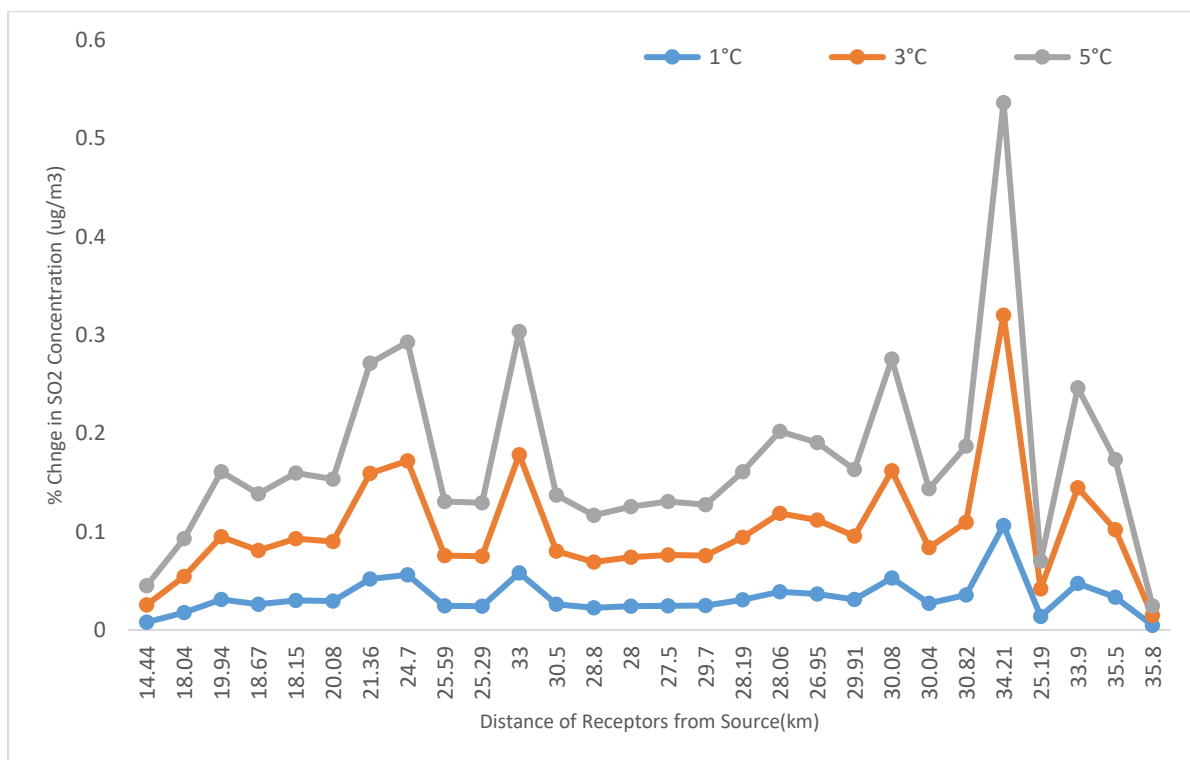
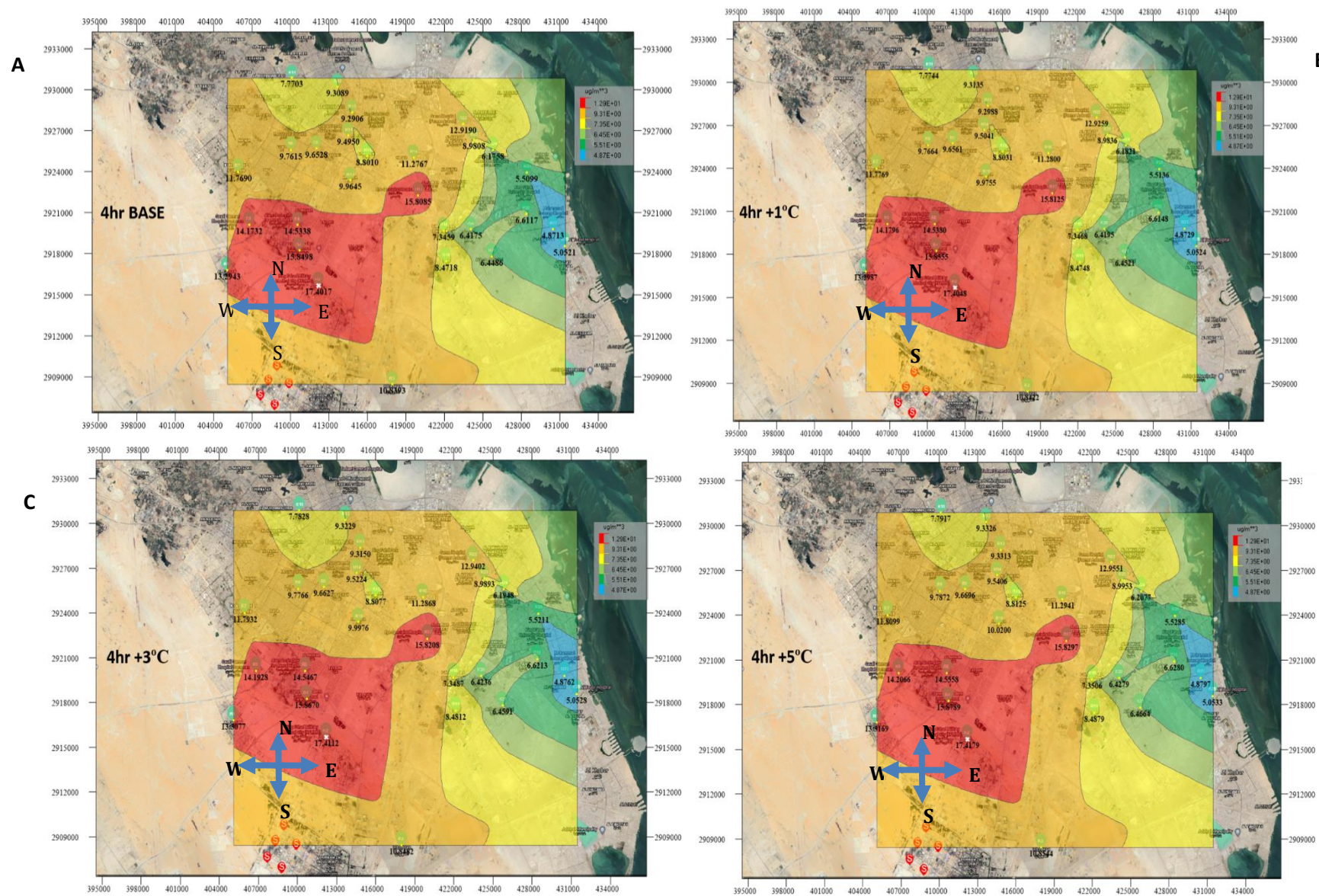


Figure 16: 1-hour time scale percentage rise in SO₂ concentration when temperature was raised to simulate future climate

4.2.2 Current Vs Future Temperature Climate (4hr time scale)

Analysis of the Sulphur dioxide concentration on the receptors for the 4-hr time scale shows that baseline concentration of the pollutant reduced as we moved from 1-hr average to 4-hour average. The average concentration of the pollutant on the receptors dropped from 27.948 $\mu\text{g}/\text{m}^3$ to 9.92 $\mu\text{g}/\text{m}^3$ from 1-hr time scale to 4-hr under the current climatic temperature. Comparing the baseline concentrations of Sulphur dioxide with concentrations when temperature is raised by 1°C, 3°C & 5°C for the 4-hr time scale revealed that concentration at each receptor increases, though not significantly, with temperature (Figure 17). The receptors closer to source of emission R1, R2, R3, R4, R5, R6 had worst pollutant concentration compared with those farther apart R22, R23, 24, R25, R26, R27 (Figure 17). This is most likely because of their proximity to the source of the pollution. This proximity makes them unsurprisingly vulnerable to highly concentrated SO₂ pollutant coming directly from the industrial stacks, thus making them to have higher pollutant concentrations.

For the 4-hr time scale the average percentage changes across the receptors were 0.046%, 0.140% and 0.24% for Plus-1, Plus-3 and Plus-5 temperature rise respectively (Figure 18). The dispersion of the pollutant was uniform across the different temperature scales. This shows that temperature changes or global warming does not affect air pollutant distribution but mildly influence concentrations.



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Figure 17A, 17B, 17C, 17D Comparison of 4hr time scale of current climate and that of future periods under 1°C, 3°C & 5°C

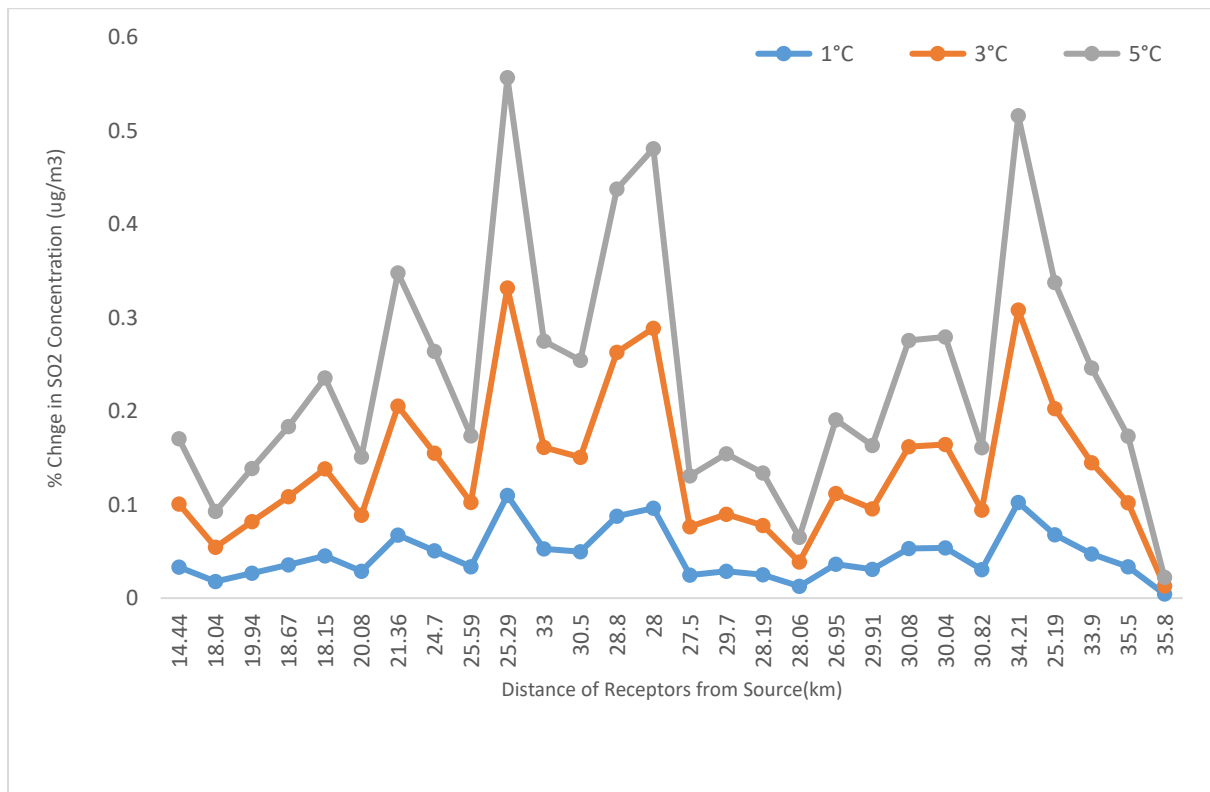


Figure 18: 4-hour time scale percentage rise in SO₂ concentration when temperature was raised to simulate future climate

4.2.3 Current Climate Vs Future Temperature Climate (8hr averaging period)

Using the processed meteorological and terrain data, we obtained dispersion results for Sulphur dioxide concentration as well as concentration and distribution when ambient temperature is raised with varying temperature for the 8-hour averaging period. Results shows that generally the 8-hr time scale had lower pollutant concentrations on the receptors compared with the 1-hr and 4-hr averaging periods. The most significant temperature effect under this time scale occurred when the temperature was raised by 5°C for receptor 13 and 14. The value jumped from 5.02253 $\mu\text{g}/\text{m}^3$ and 4.86107 $\mu\text{g}/\text{m}^3$ to 5.06876 $\mu\text{g}/\text{m}^3$ and 4.90723 $\mu\text{g}/\text{m}^3$ respectively- about 1% rise in Sulphur dioxide concentration (Figure 19). This means these receptors are more sensitive to temperature changes to trigger change in SO₂ concentrations than others. The average percentage changes were 0.054%, 0.164% and 0.276% for Plus-1, Plus-3 and Plus-5 temperature raise respectively (Figure 20). Just as other time scales discussed above, the concentration level of the air pollutant on each of the receptors increases as we increased the temperature (Figure 21). The fact that we have similar behavior in response to temperature changes –mild changes in the concentration of SO₂- under different time scales strongly suggests that projected rise in future ambient temperature of Saudi Arabia will not have significant effect on air pollutant concentrations (Figure 21). The percentage changes across the time scales are different because the concentration values vary across these time scale. Generally, the more the time scale the lower the concentration values because of the increasing divisor. 8-hr, 4-hr, and 1-hr will have 8, 4, and 1divisor values respectively (Figure 21).

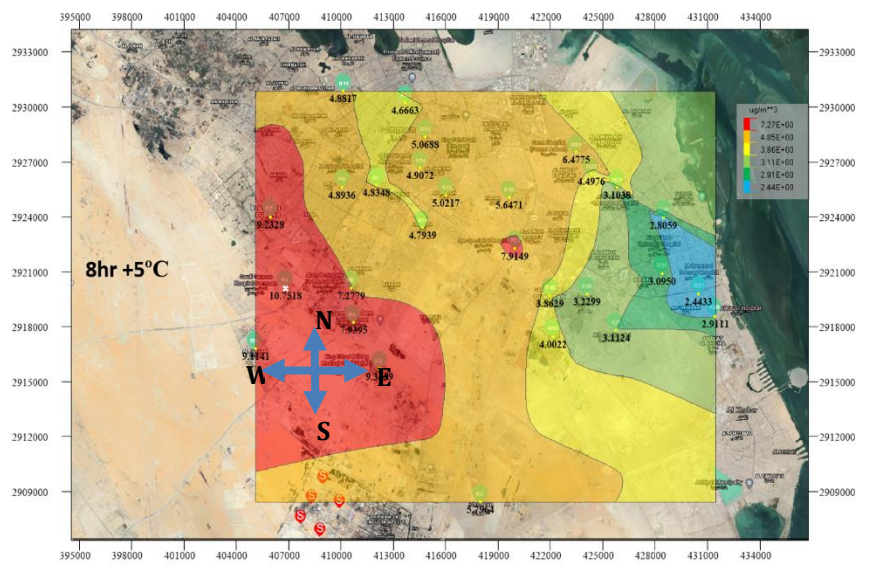
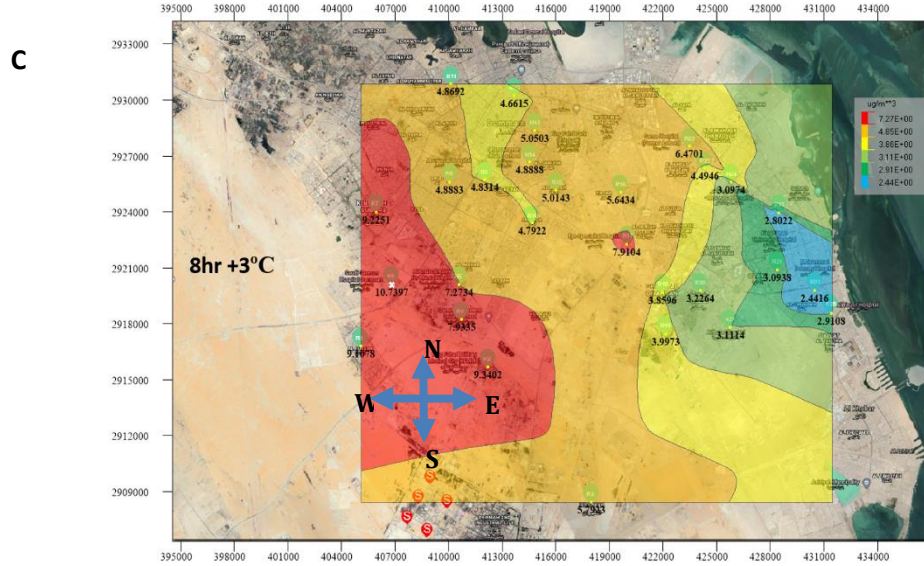
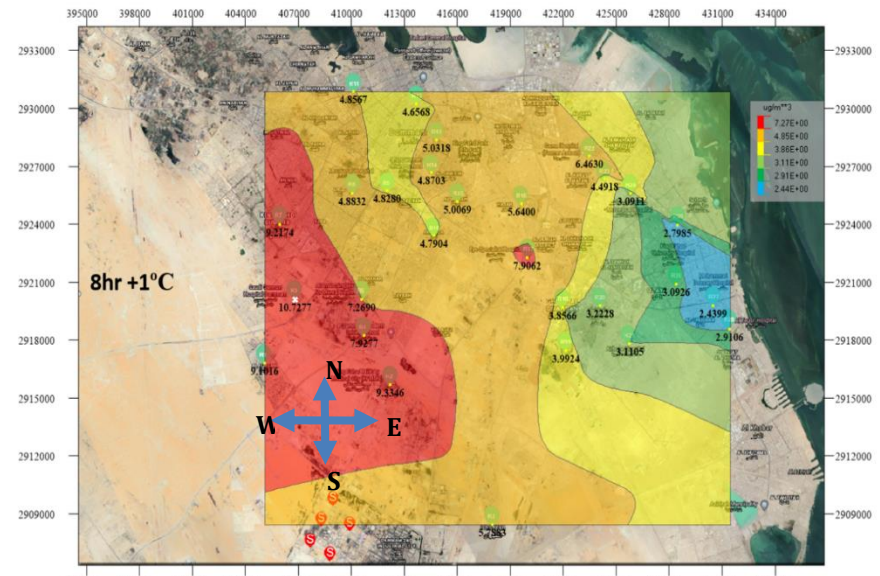
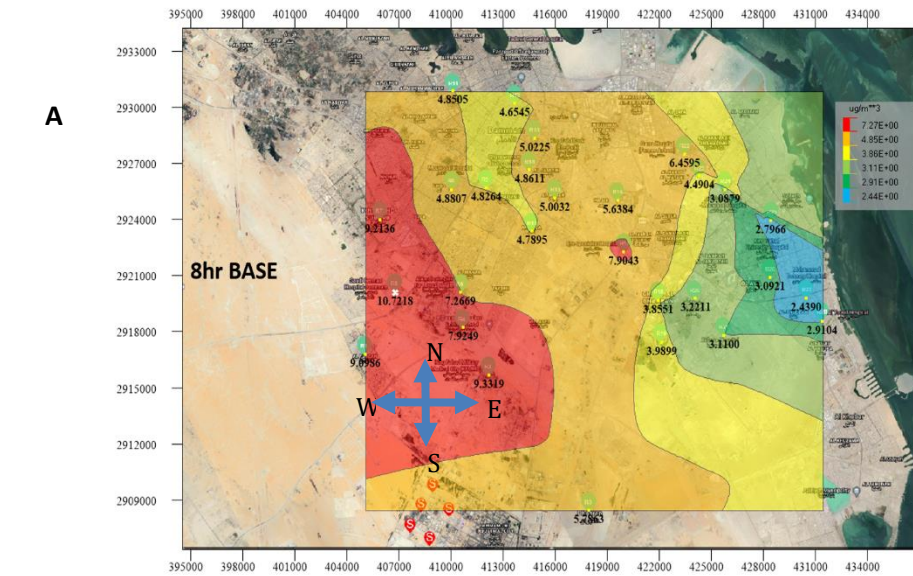


Figure 19A, 19B, 19C, 19D: Comparison of 8hr time scale of current climate and that of future periods under 1°C, 3°C & 5°C

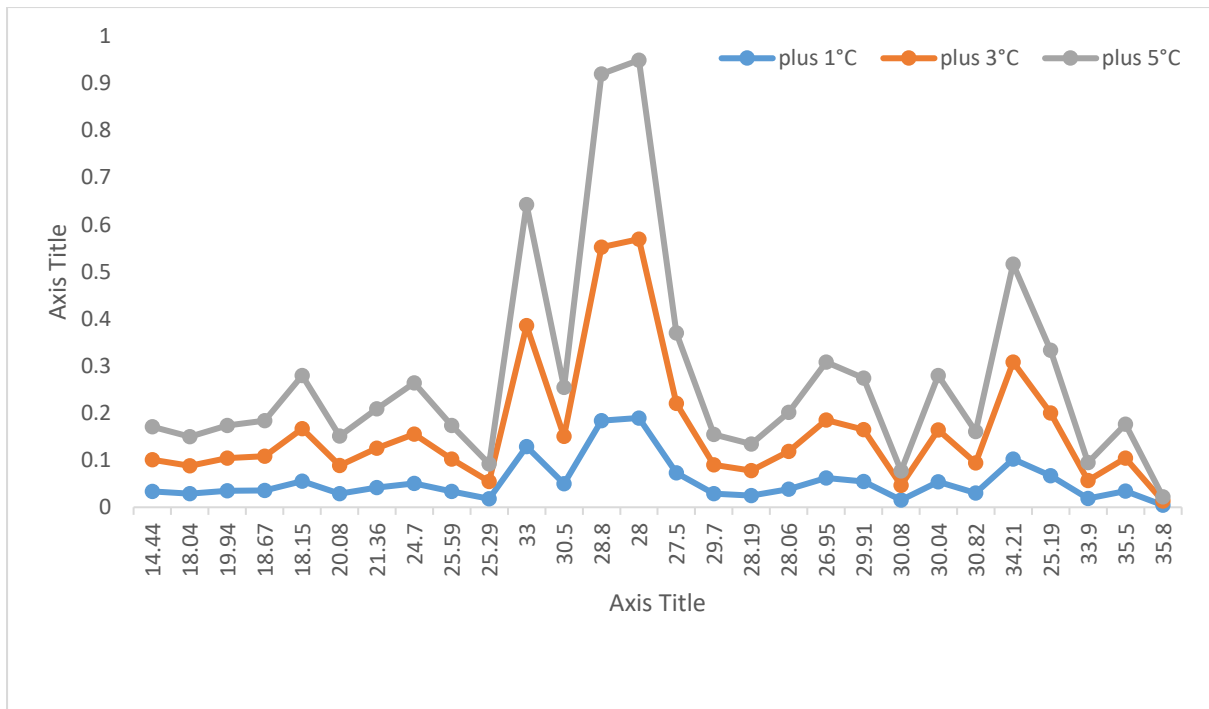


Figure 20: 8-hour time scale percentage rise in SO₂ concentration when temperature was raised to simulate future climate

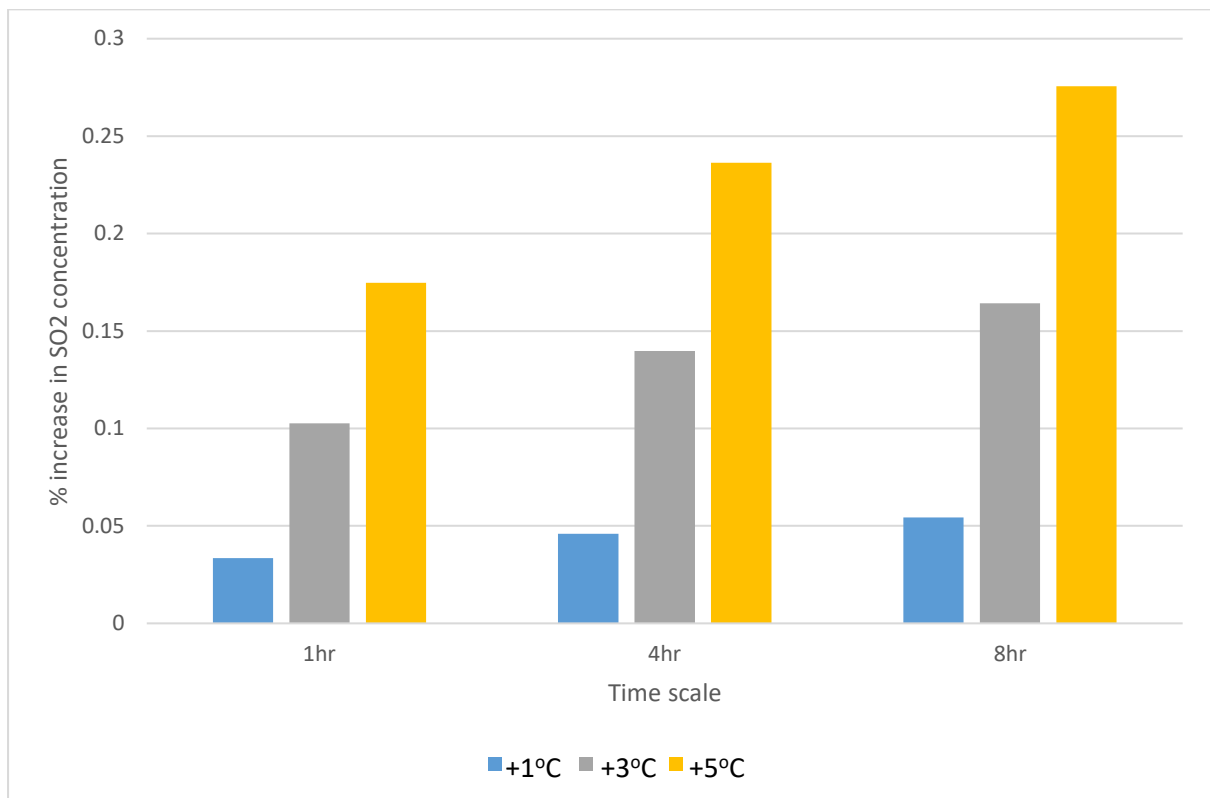


Figure 21: Summary of the effect of air temperature changes on downwind SO₂ concentrations

4.3 Dispersion Model Results Based on Wind Speed Changes

4.3.1 Current Vs Future rise in wind speed (1hr averaging period)

After observing the impact of temperature rise on Sulphur dioxide downwind concentration and distribution, we also subjected the model to changes in wind speed and obtained corresponding effects of increased wind speed of 0.6m/s, 1.2m/s, 1.8m/s on the pollutant concentration and dispersion. We adopted wind changes in multiples of 0.6m/s based on analysis of decade-long Dammam wind data, Figure 12, which revealed that Dammam wind speed dropped about 0.6m/s between 2009 and 2019. For the 1hr time scale, we realized that as we increased the wind speed --from 0.6m/s to 1.8m/s – the concentration of pollutant on each of most receptors significantly reduced as shown in Figure 22. The reduction is likely due to increased velocity of the wind, which could have diluted the pollutant concentrations and produced lower levels of SO₂ at the receptors. However, some outlying situations were observed. When we increased the concentration of the wind speed by 0.6m/s and 1.2 m/s, the Sulphur dioxide concentration at receptor eight (R8) increased from 26.33078µg/m³ to 27.25164µg/m³ and 26.56832µg/m³ respectively (Figure 23). A similar anomaly was obtained on receptor eleven (R11) when wind speed was raised by 0.6m/s, 1.2m/s and 1.8 m/s. The rise in pollutant concentration with rise in wind speed was also obtained on receptor twelve (R12) when wind speed was raised by 0.6m/s. It was also noticed on receptor twenty-six (R26), twenty-seven (R27) and twenty-eight (R28). This rise pollutant concentration with rise in wind speed was seen in 6 out of the 28 receptors hence we can say this trend is not statistically significant and conclude that for the 1-hour averaging period increase in wind speed mostly reduces Sulphur dioxide concentration at the receptors. In addition, receptors closer to the source of emission (R1, R2, R3, R4, R5, R6) with average distance of about 18.22km from the emission had greater concentration difference when wind speed changed compared receptors

farther apart from the emission source. Generally, if wind speed is increased by 0.6m/s, 1.2m/s and 1.8m/s, for the 1hr time scale, it can result in about 4.3%, 10.99%, 17.52% attrition in Sulphur dioxide concentration across the receptors (Figure 22). This effect is significant, especially compared with impact of temperature as we discussed earlier.

The outlier result of increased SO₂ concentration with increased in wind speed were only obtained at farthest receptors from the source: R11, R25, R26, R28 with distance of 33km, 34.2km, 33.9km and 35.8km respectively. Hence, the abnormal results may be because of the extensive distance from the source, which might have made the wind speed to reduce before it gets to these destination thus affecting dispersion calculation results (Figure 23).

The relationship between the changes in wind speed and consequent outcome on pollutant concentration across the modeled receptors (Figure 22 & Figure23) can be explained with few hypothesis. The increased wind speed probably reduced the plume rise and buoyancy thereby resulting in distribution of the SO₂ on the receptors. In addition, the increased wind speed might have influenced the ambient air to actively dilute the pollutant towards the receptors. In this case, the farther receptors will have more dilutions and experience lower pollutant concentrations.

The increased wind speed might also bend the plume and mix them quickly with surrounding receptors, thus making closer receptors have higher concentrations.

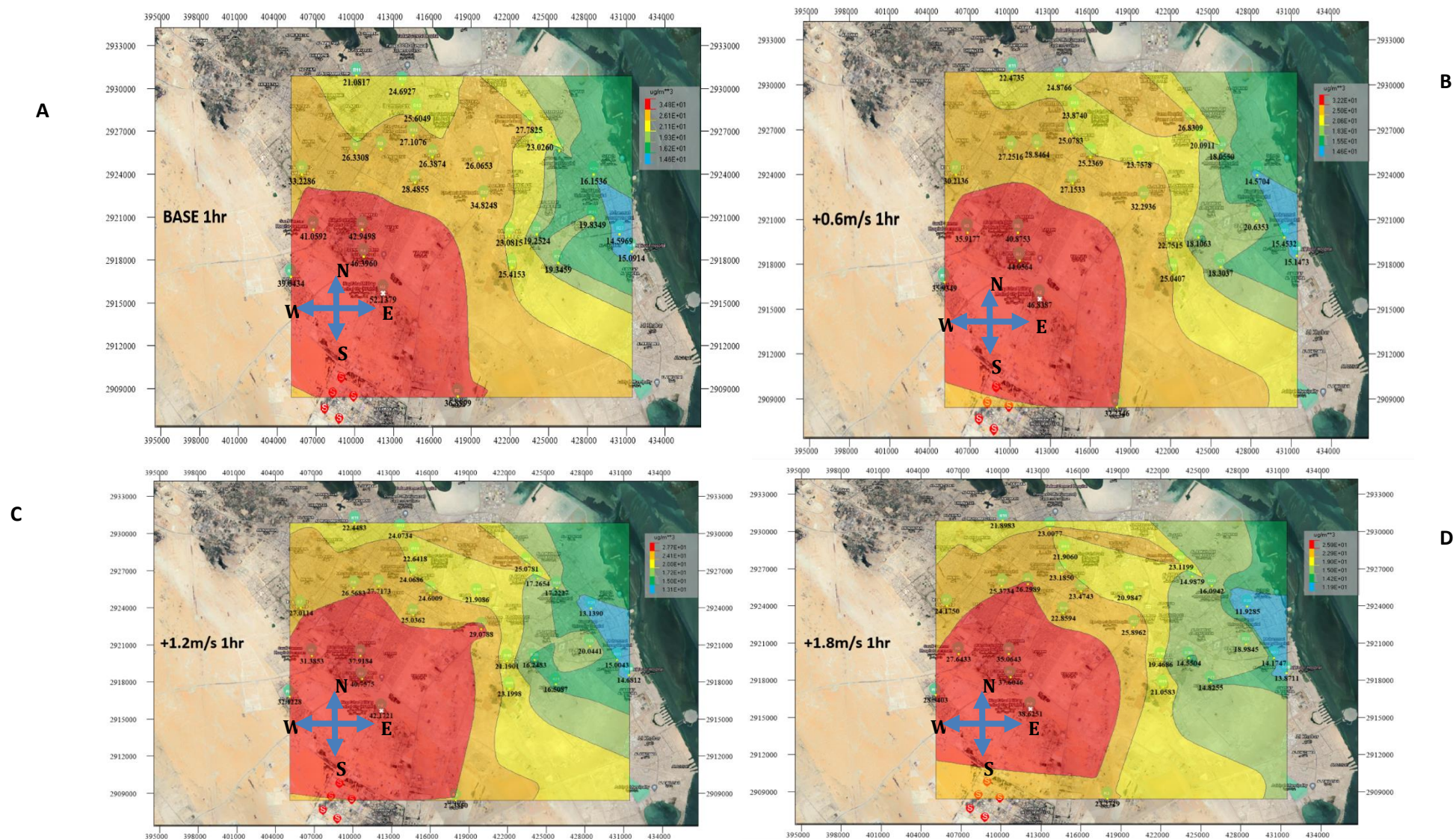


Figure 22A, 22B, 22C, and 22D: Comparison of 1hr time scale of current climate (BASE) and that of future periods under 0.6m/s,

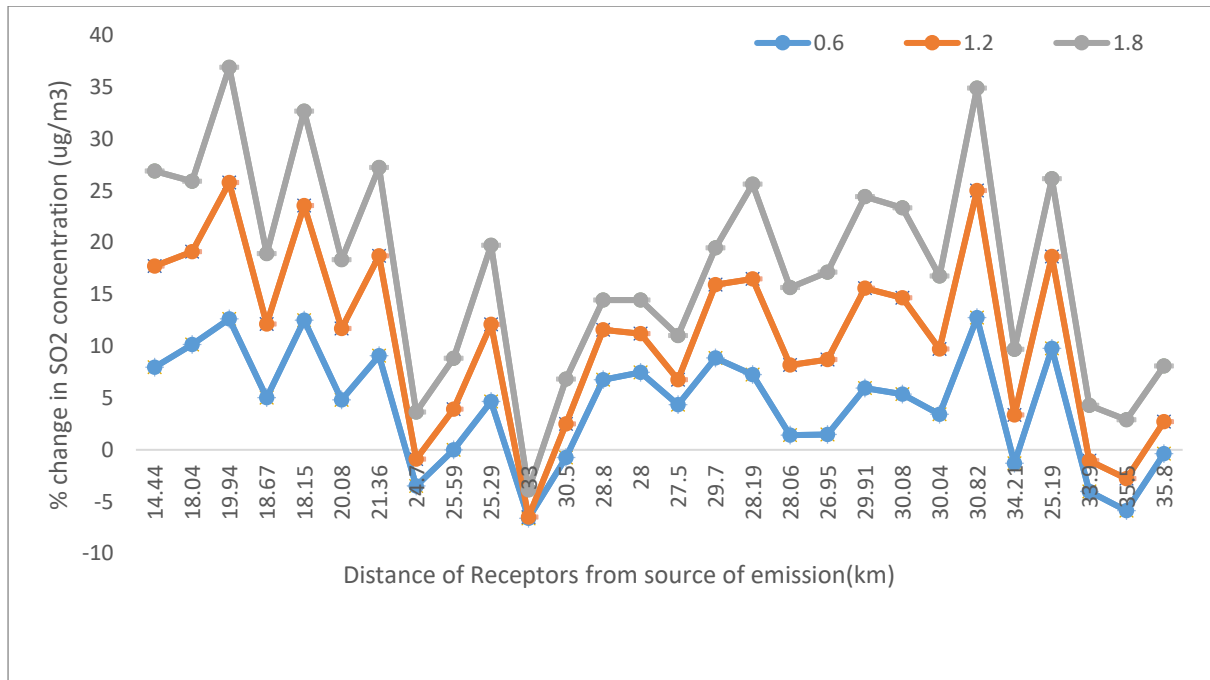


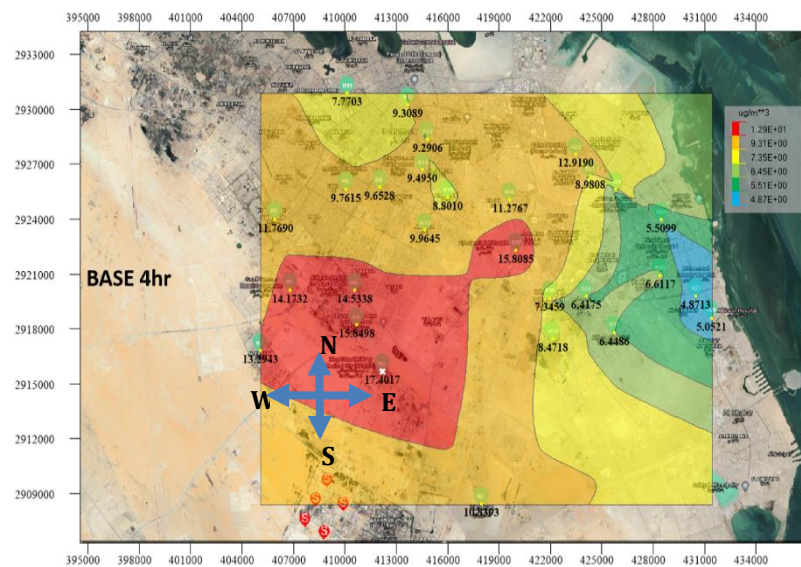
Figure 23: Percentage Increase in Sulphur Dioxide concentration at the receptors with varying wind speed under the 1-hour

4.3.2 Current Vs Future rise in wind speed (with 4hr averaging time)

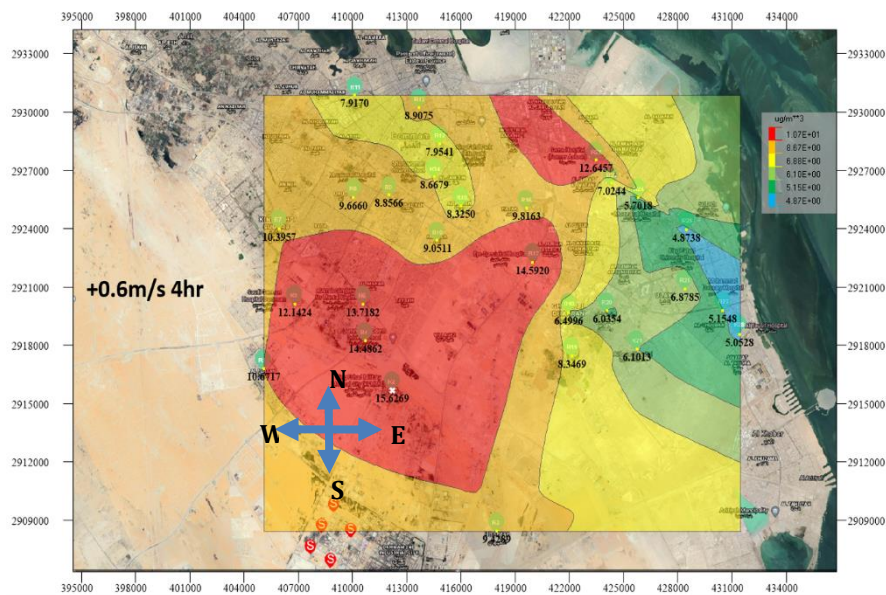
Similar to the observation with the baseline and 1-hr period, we realized that as we increased the wind speed --from 0.6m/s to 1.2m/s and 1.8m/s – the concentration of pollutant on each of most receptors significantly further reduced for the 4-hour time scale. Meanwhile some outlier situations were observed. When we increased the wind speed by 0.6m/s, pollutant concentration under the 4-hour period for receptor 11 (R11) increased from $7.77029\mu\text{g}/\text{m}^3$ to $7.91702\mu\text{g}/\text{m}^3$ (Figure 24). However, when we further raised the wind speed by 1.2m/s and 1.8m/s the pollutant concentration on the receptor reduced as expected. A similar anomaly was obtained for receptors farthest from source emission (R26, R27, R28) with average distance of about 35 km from the point of emission. The anomaly obtained for these receptors may be due to extreme distance from emission source and the chances that the meteorology parameter might have changed before the air pollutant get to them. It is also possible that the inconsistent result obtained for farthest receptors was due to the fact the wind speed might have changed and reduced before it gets to those points thereby making not to have expected reducing effects on the pollutant concentrations.

On a general note, the air pollutant concentration reduced with increase in the wind speed. If wind speed is increased by 0.6m/s, 1.2m/s and 1.8m/s, for the 4hr time scale, it can result in about 7.53%, 15.32%, and 22.7% (Figure 25) reduction in Sulphur dioxide concentration across the receptors, which is a further reduction compared to the 1-hr time scale.

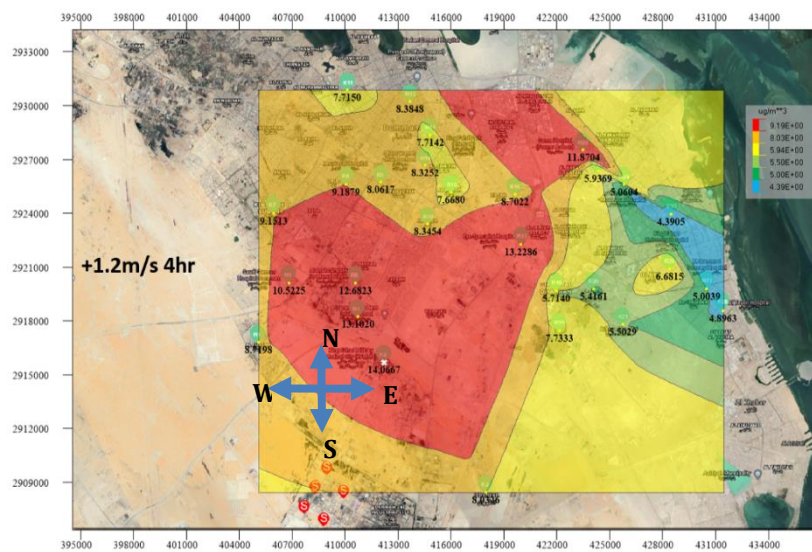
A



B



C



D

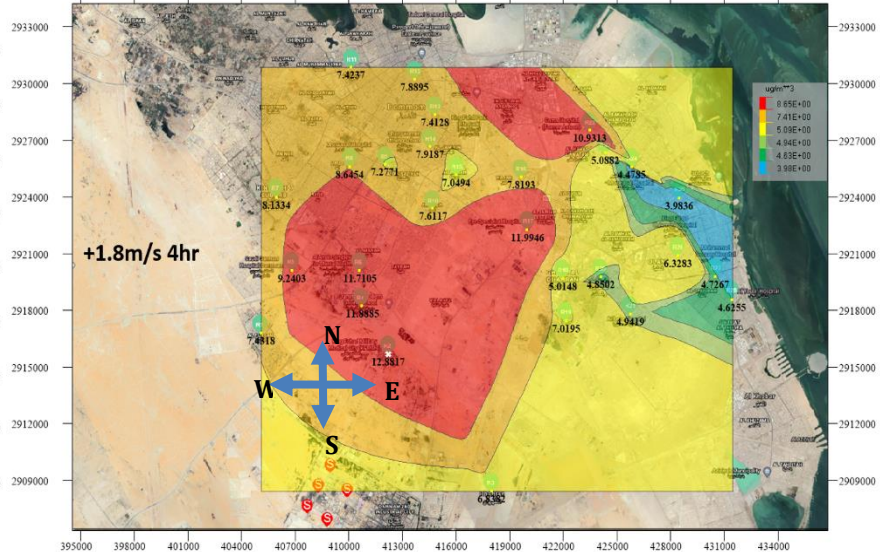


Figure 24A, 24B, 24C, 24D: Comparison of 4hr time scale of current climate and that of future periods under 0.6m/s, 1.2m/s & 1.8m/s

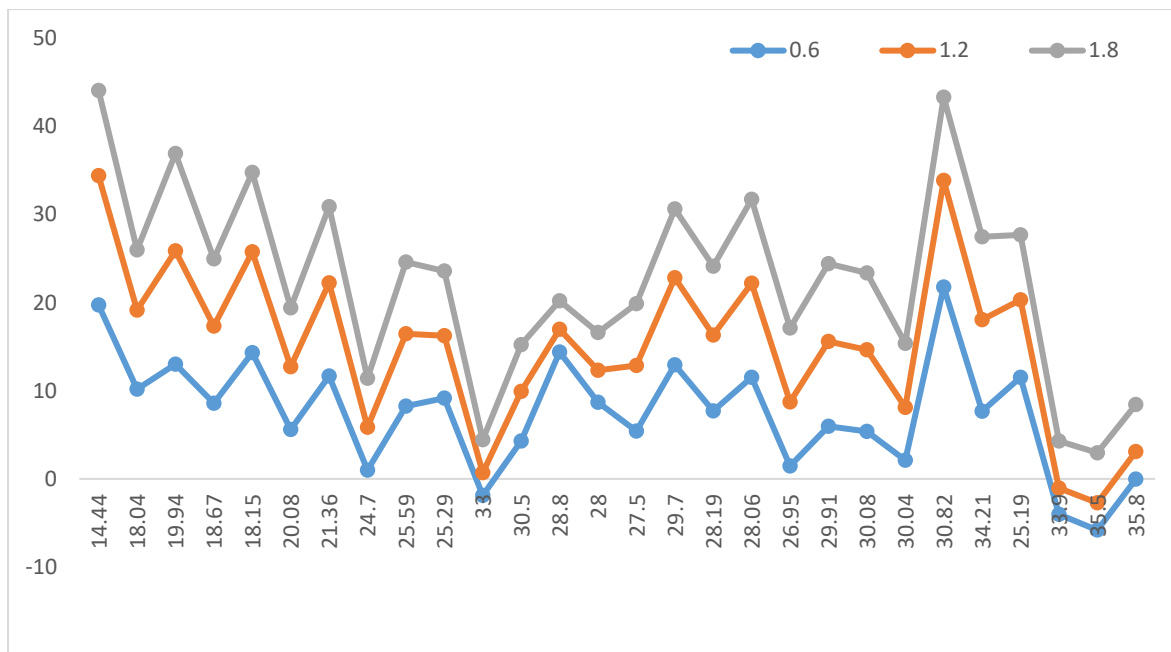


Figure 25: Percentage Decrease in Sulphur Dioxide concentration at the receptors with varying wind speed under the 4-hour averaging

4.3.3 Current Climate Vs Future rise in wind speed (with 8hr averaging time)

Analysis of the impacts of varying wind speed on Sulphur dioxide concentration at the sensitive receptors monitored for the 8-hour time scale showed that, for most receptors, the concentration reduces with increased with speed. Unlike the two previous time scales (1hr and 4hr), there was minimal anomaly with this time scales. The only receptor that showed some anomaly result was receptor twenty-seven. When we increased the wind speed by 0.6 m/s, the pollutant concentration also went up from 2.43903ug/m³ to 2.5796ug/m³. This condition later regularized with further increase in wind speed by 1.2m/s and 1.8 m/s as the pollutant value dropped to 2.50564ug/m³ and 2.36997ug/m³ as expected (Figure 26). This was not the situation for other extremely far receptor (R27). The minimal anomaly under this time scale may well mean that the AERMOD model is relatively more effective with long distance under this time scale compared with other time scales discussed earlier. On a general note, if wind speed is increased by 0.6m/s, 1.2m/s and 1.8m/s, for the 8hr time scale, it can result in about 10.50%, 18.5%, 25.4% reduction in Sulphur dioxide concentration across the receptors (Figure 28), which is a further reduction compared to the 4-hr time scale. (Figure 27)

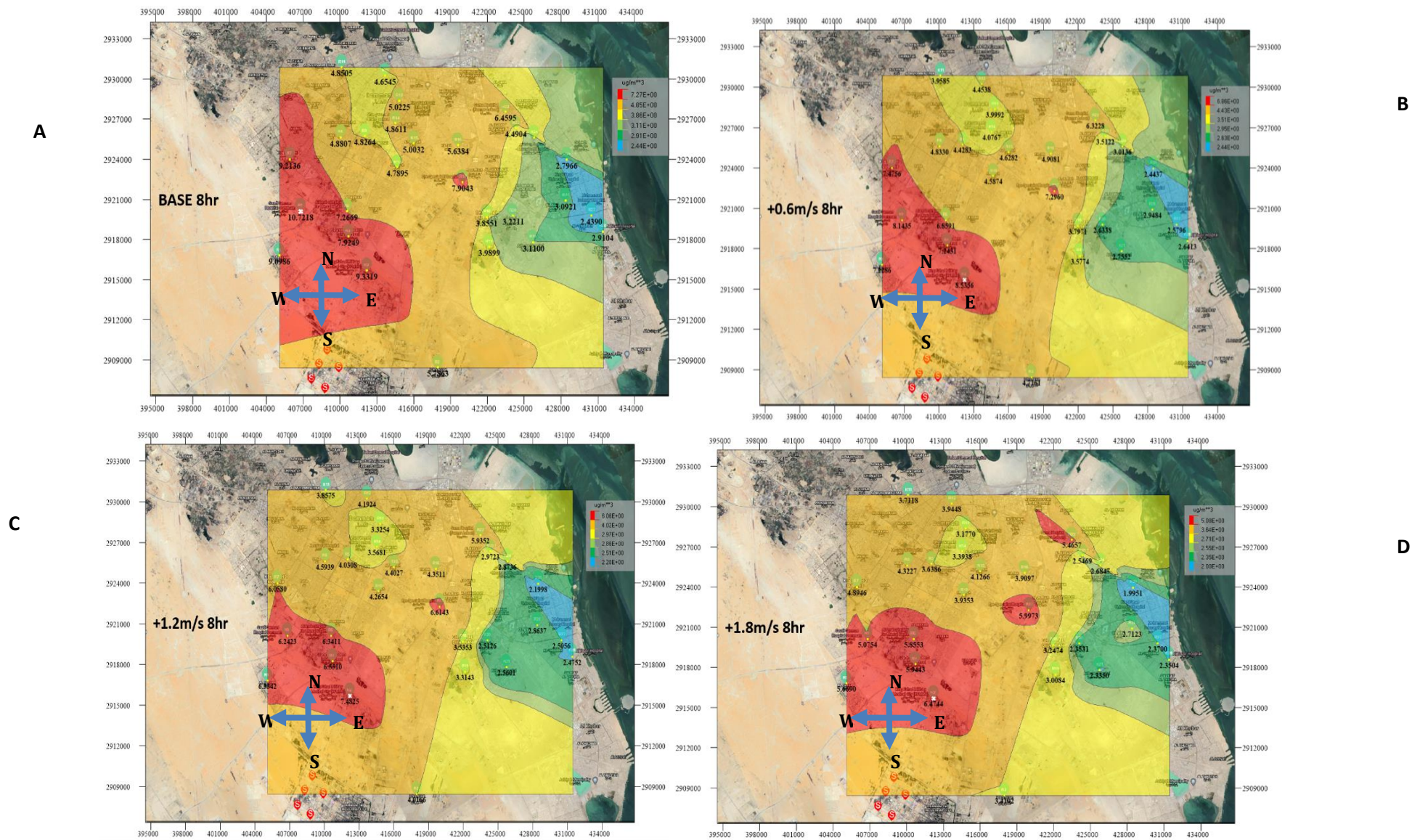


Figure 26A, 26B, 26C, 26D: Comparison of 8hr time scale of current climate and that of future periods under 0.6m/s, 1.2m/s & 1.8m/s wind

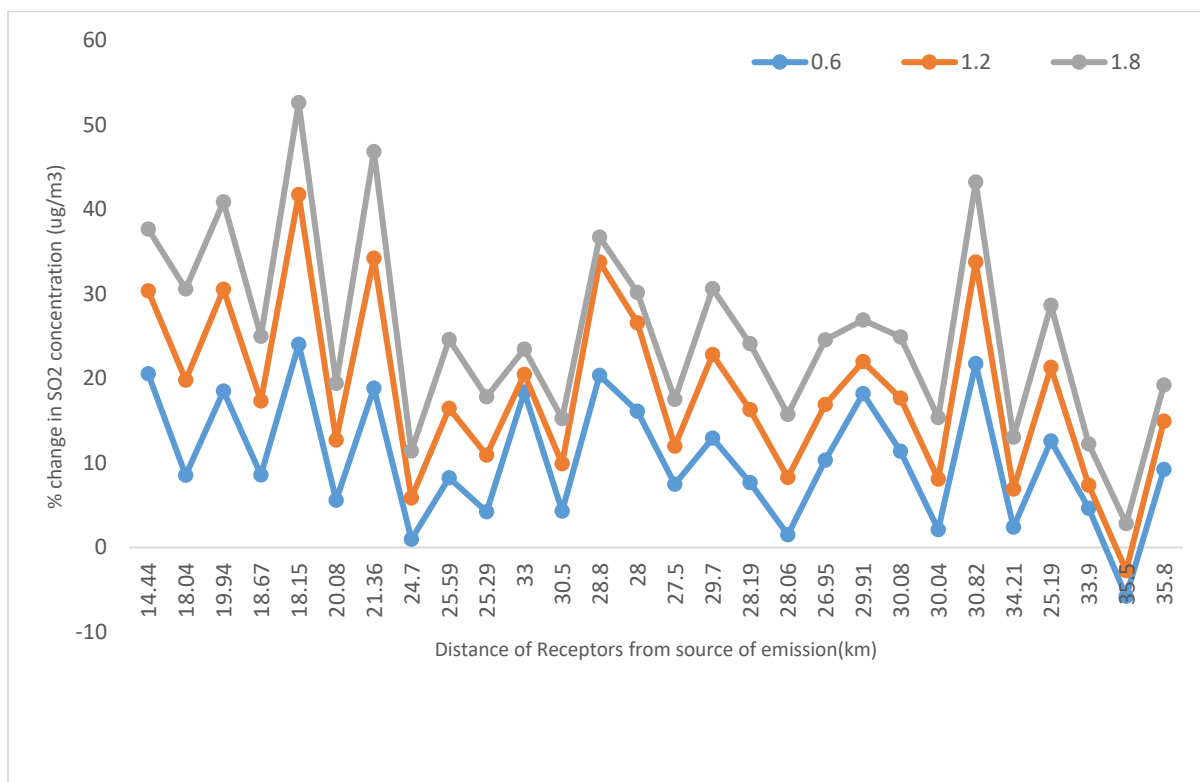
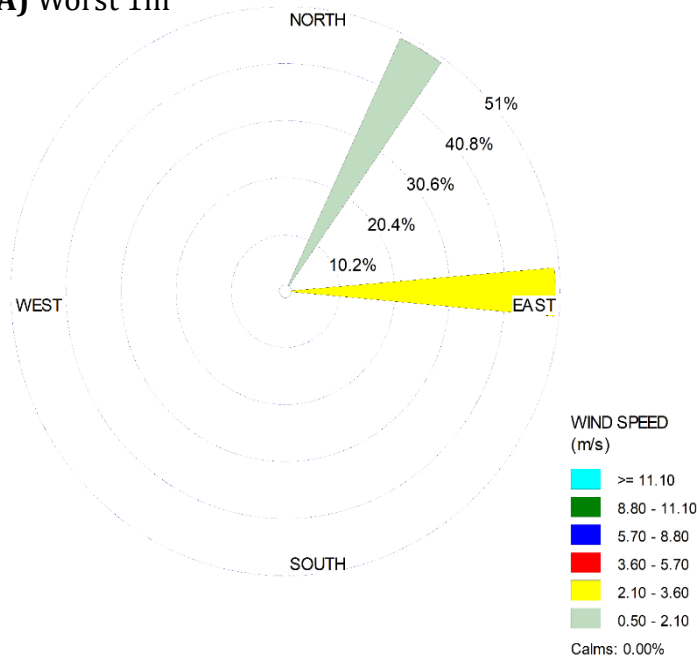


Figure 27: Percentage Change in Sulphur Dioxide concentration at the receptors with varying wind speed under the 8-hour averaging

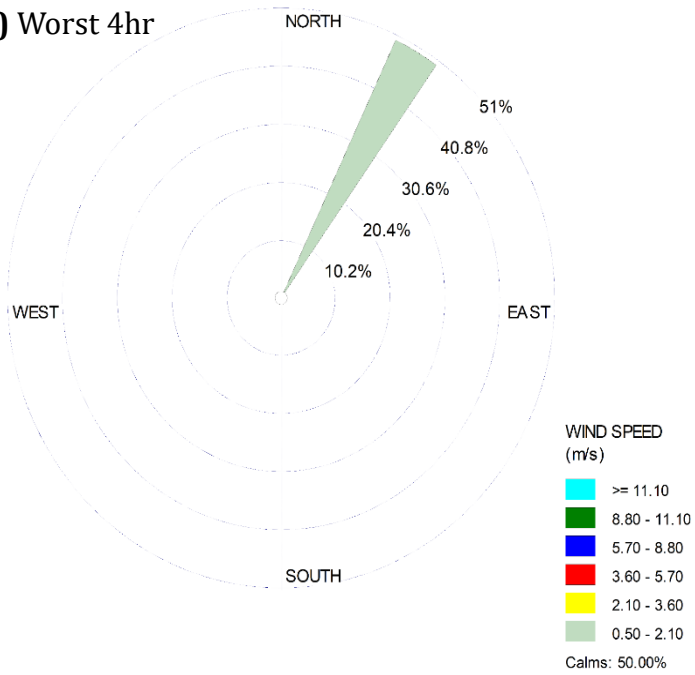
4.3.4 Wind Directions of the worst averaging periods

In order to understand the main driver behind the plume movement, we looked at the relationship between the plume movement and wind direction using the worst/highest concentrations of the averaging periods in order to know how the wind was blowing during the times we had those worst concentrations. When we extracted the specific hours that had worst air pollutant concentrations and checked for the direction of the wind at those hours, we realized the plume movement aptly mirrored the direction of the wind. This is evident in the way plume direction in Figure 22, Figure 24 and Figure 25 follow the wind direction in Figure 28 (A), Figure 28 (B) and Figure 28 (C) respectively.

A) Worst 1hr



B) Worst 4hr



C) Worst 8hr

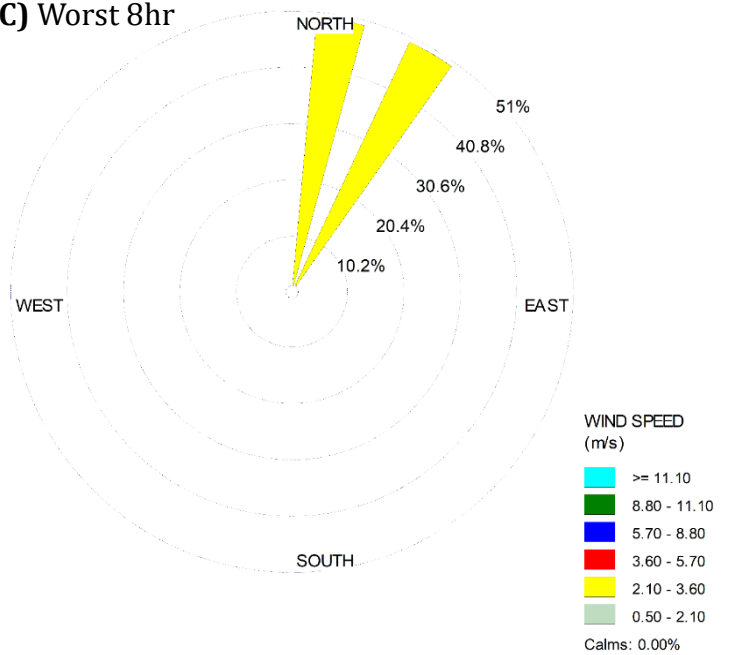


Figure 28A, 28B, 28C: Wind Speed and Direction during the worst averaging periods: 1hr, 4hr, and 8hr respectively

4.3.5 How wind speed changes affect air pollutant concentration across the averaging periods

It was important for us to perform the experiment with multiple averaging periods -1hr, 4hr, and 8hr. This eliminates chances flukes in our results. We observed that the result of the effect of wind speed changes on air pollutant concentration was consistent among all the time scales tested. As shown in Figure 29, for the 1hr averaging period, as we increased the wind speed, the concentration of SO₂ air pollutant decreases, by 4.3%, 7.5% and 10.5% when the wind speed was raised by 0.6m/s, 1.2% and 1.8m/s respectively. A similar trend is observed for the 4hr and 8hr averaging periods (Figure 29), reiterating that the wind speed has same effects on pollutant concentration regardless of the time scale.

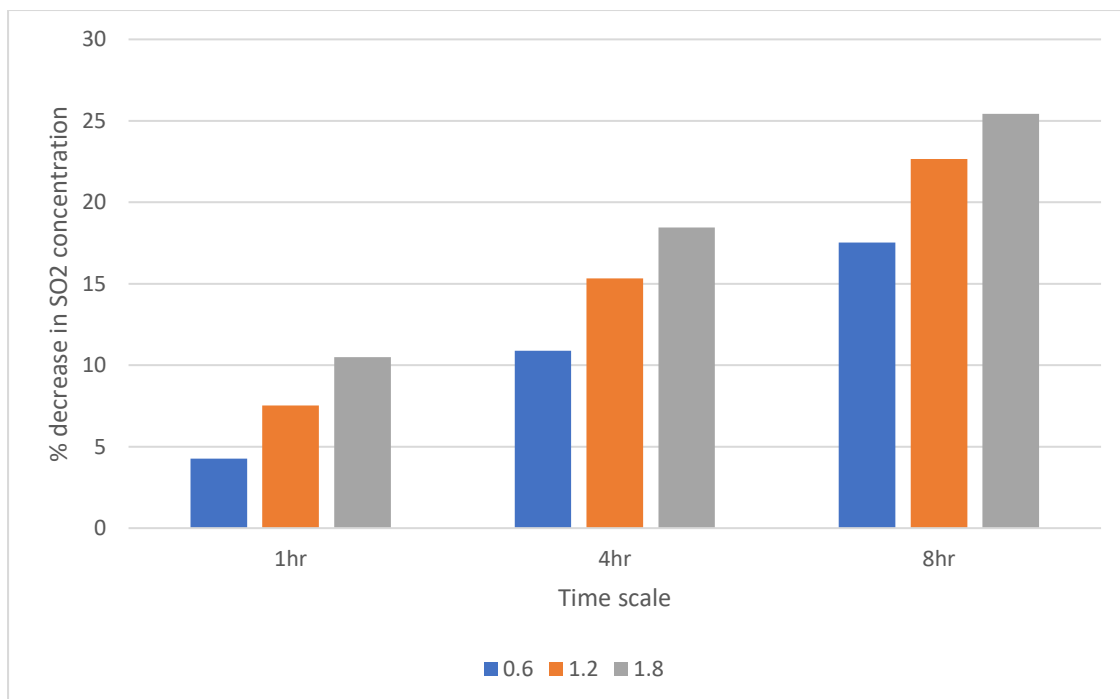


Figure 29: Summary of the effect of Changes in Wind Speed on concentration of air pollutant.

4.4 Relationship between impact of wind speed and distance of receptor from source

Investigation of the relationship between the effects of wind speed and distance of receiver from source shows that the more a receiver is far away from the source, the lower the effects of the wind speed (Figure 30). This might be due to the fact that the farther away a receiver is from the source, the lower the dilution effect that wind speed can have on pollutant concentration at that receiver. The relationship was initially tested with the 1-hour averaging period and the result was later confirmed with other time scales, 4hr and 8hr (Figure 30).

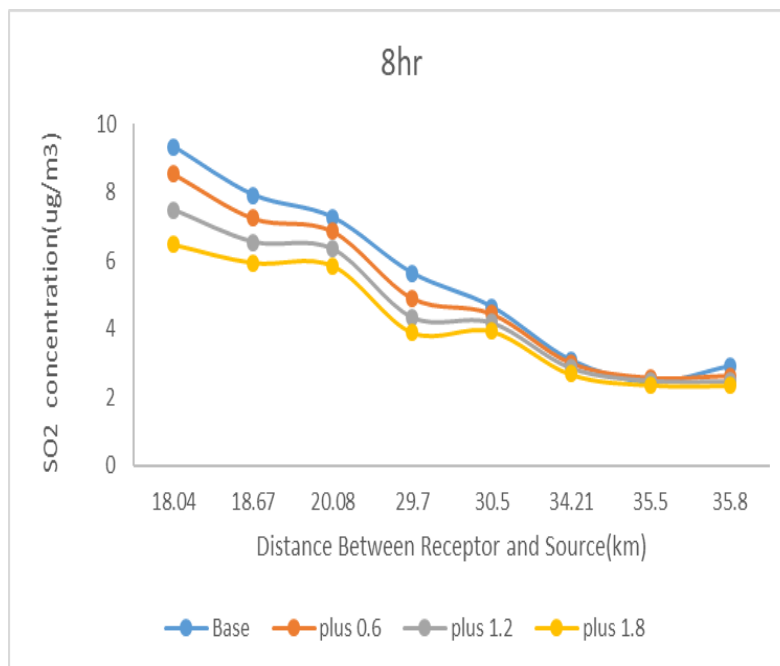
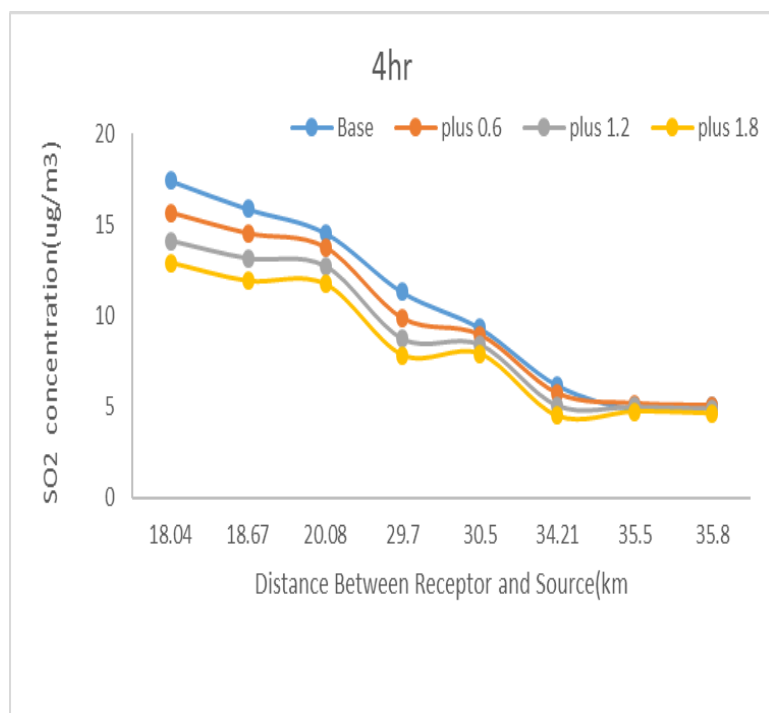
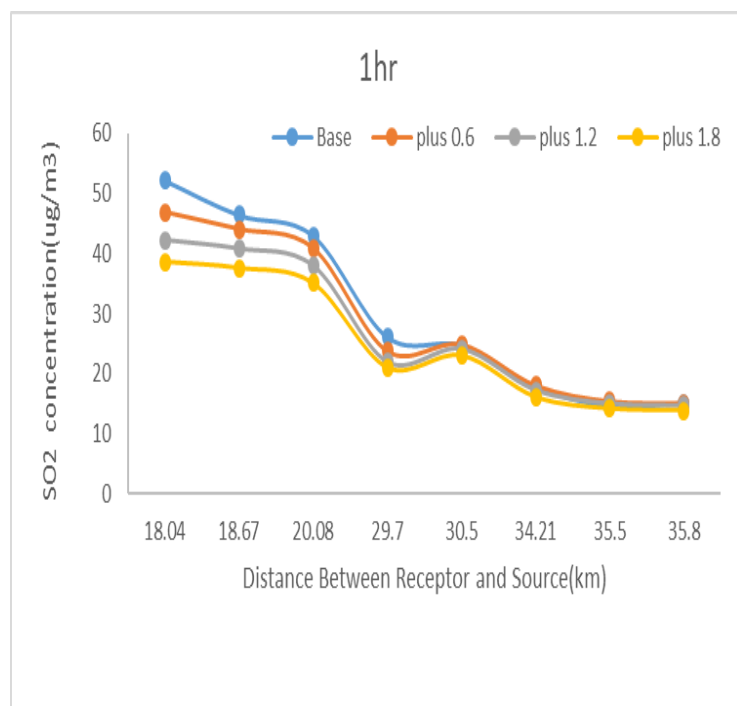


Figure 30: Influence of distance on the effects of wind speed on air pollutant concentrations

4.5 Effects of ambient temperature and wind speed

If future ambient temperature of Dammam, Saudi Arabia, goes up by 5 degrees as speculated by reliable scientific literatures by mid-century, it will only cause about 0.2% increase in the concentration of SO₂ across 1hr, 4hr and 8hr time scales. However, wind speed increase of 1.8m/s can cause up to 22.68% change in the concentration of the air pollutant (Figure 31).

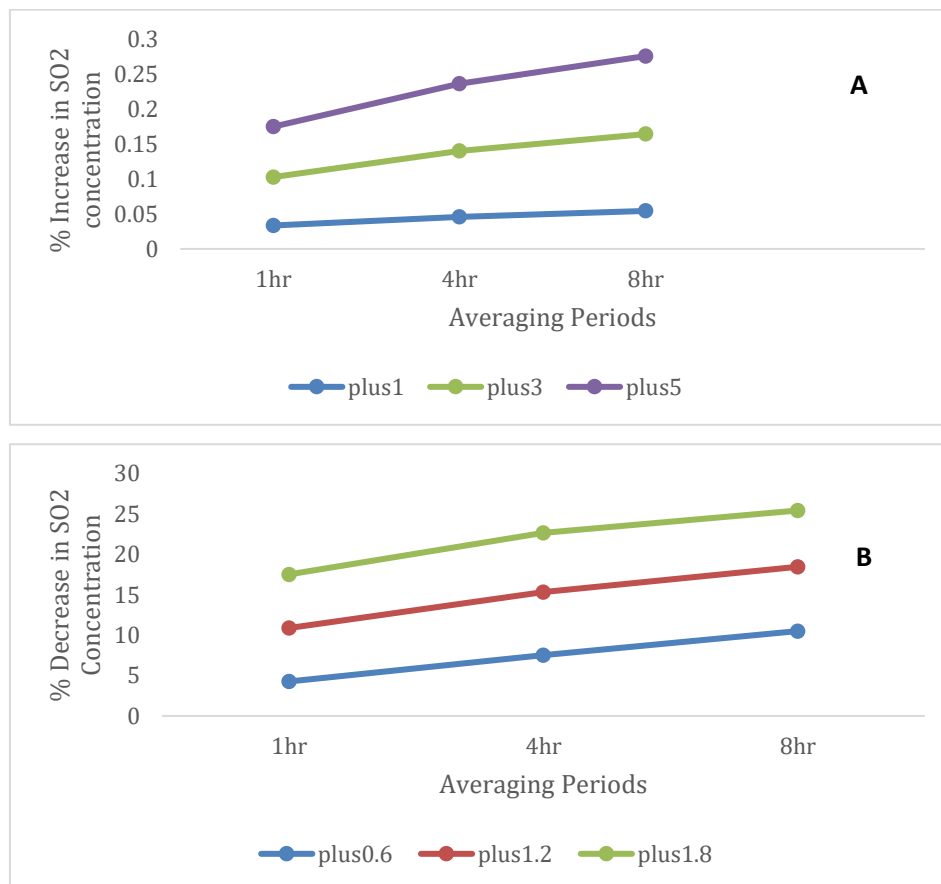


Figure 31: Comparison of effects of air temperature (A) and wind speed (B) on SO₂ concentration

4.6 Model results and SO₂ regulatory standards

We compared model results- for both current climate and simulated future climate- with regulatory standards and the results fall within the allowable limits (Table 5A, Table 5B). Generally, there were significantly lower SO₂ concentration at the receptor compared to the minimum values required by regulatory bodies and this may be due to the fact our model used high exit velocities and stack heights. This means that under these settings in conjunction with other conditions -Source inventory, meteorology, and terrain - SO₂ emission from Dammam industrial location, Saudi Arabia will not constitute any environmental health danger to the neighboring sensitive receptors of schools and hospital.

Table 5A & 5B: Model results (TEMPERATURE SCENARIO & WIND SCENARIO) compared with regulatory standards

Averaging Period	Standards (ug/m3)			Base(ug/m3)	1(ug/m3)	3(ug/m3)	5(ug/m3)
	KSA	WHO	USEPA				
1hr	730	500	730	52.1379	52.14713	52.16629	52.1864
4hr	650	400	650	17.4017	17.40482	17.41121	17.41791
8hr	500	310	500	10.7218	10.72774	10.73971	10.75179

Averaging Period	Standards (ug/m3)			Base(ug/m3)	0.6(ug/m3)	1.2(ug/m3)	1.8(ug/m3)
	KSA	WHO	USEPA				
1hr	730	500	730	52.1379	46.84	42.17	38.63
4hr	650	400	650	17.4017	15.63	14.07	12.88
8hr	500	310	500	10.7218	8.54	7.48	6.47

5 CONCLUSION

Analysis of Dammam meteorological data for the period of 2009 to 2019 shows decade climatic changes, which corroborates other works in literature regarding changing climate of the Kingdom of Saudi Arabia. Projected rise in Kingdom of Saudi Arabia future ambient temperature will have only mild increment on Sulphur dioxide downwind concentration. Receptors closer to the source of emission, R1, R2, R3, R4, R5, R6, with average distance of about 18km from the source had the least concentration and lowest impacts using the baseline meteorological data as well as when the meteorological data was spiked to simulate future change in Saudi Arabia climate.

Rise in Kingdom of Saudi Arabia future near surface wind speed will potentially have significant reduction effect on Sulphur dioxide downwind concentration and dispersion because as we raised the wind speed the sulphur dioxide concentration at the most of the receptors reduced. However, there were few anomaly results- Pollutant concentrations at receptor increases with increase in wind speed. However, the occurrence of the anomalies was statistically insignificant and may be ascribed to the fact the receptors were much farther away from the source and the dispersion tool could not do effective dispersion calculation for the long distance under the particular time scale.

6 RECOMMENDATION

More Meteorological parameter

Further research is needed to investigate effects of other climactic parameters like Precipitation on air quality dispersion model results.

More Atmospheric Pollutant

Since we used only Sulphur dioxide in this research, future work should assess potential effects of Saudi Arabia future climate change on other air pollutants like PM10, NOx using dispersion models like AERMOD

7 OUTPUT

Abstract submitted to International Conference on Air Quality and Pollution
March 28-29, 2022 in Sydney, Australia.

Abstract submitted to The 7th International Conference on Environmental Pollution, Treatment and Protection (ICEPTP'22).

Journal paper submitted to The Advances in Climate Change Research.

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CURRICULUM VITAE

Mustapha Babatunde Muhammed

mustaphaalade@gmail.com

No. 19, Adeyemi Lawson street, Ikoyi, Lagos. P.O. Box: 1000001

PROFESSIONAL SUMMARY

Mustapha is a graduate student in the Department of Geosciences, running the Environmental science program. He bagged a First class in Biology from University of Lagos. His research interests are Air quality modelling, Machine Learning, Artificial Intelligence

EXPERIENCE

Graduate Student/Teaching Assistant | Geosciences Department, KFUPM 2019-till date

The Department of Geoscience, KFUPM, takes a balanced approach between education and research to nurture students who are competent in theory and application, for the skills needed in their industrial or post-graduate careers.

- Was assigned to multiple faculty to serve as Teaching assistant
- Invigilated Undergraduate/Graduate Examinations
- Assessed students' quizzes and homework
- Was responsible for other tasks as designated by the Faculties

Programmer | Dropque 2016-2018

Dropque is an innovative software company that is using the power of artificial intelligence and one-way video to reduce the cost and time of recruitment as well as accelerate hiring in emerging markets

- Co-ordinate back-end development of the app using ruby on rails.
- Responsible for adding new features and formulation of logic and database structure
- Represented the company at the Peace Tech Accelerator in the United State where I shared the amazing vision and mission of Dropque with a cross section of Tech thought-leaders from around the world.

Software Development Intern | Meltwater Entrepreneurial School of Technology | Accra, Ghana 2015-2016

MEST is a Pan-African entrepreneurial training program, seed fund, tech incubator and hub that trains world-class talent to become globally successful software engineers and entrepreneurs.

- Went through software development internship for 12 months
- Built scalable web software with ruby on rails, and Django

- After impressive performance during the program, my team received a 50,000 USD investment to start our software company.

EDUCATION

MSc Environmental Science | KFUPM |, Saudi Arabia
(3.9/4.0) **2018-till date**

Bachelor Biology | University of Lagos |, Nigeria
FIRST CLASS **2007-2011**

CERTIFICATIONS

Graduate Record Examination (GRE): Quantitive 157, Verbal 157 **2015**

MEST Software Engineering Certificate **2016**

PROFILES

HackerRank: <https://www.hackerrank.com/mustaphaalade>
Github profile: <https://github.com/sulphur1010?tab=repositories>
Personal site: <https://sulphur1010.github.io>
Linkedin: www.linkedin.com/in/sulphur1010

CONFERENCES/PAPERS

6th Water Arabia conference and Exhibition | Saudi Arabia
February 2020

The 6th Water Arabia Conference & Exhibition The 6th Water Arabia Conference & Exhibition was organized by Saudi Arabian Water Environment Association (SAWEA) and the Water Environment Federation (WEF) . It was a three-day Conference and Exhibition dedicated to water and wastewater treatment, which was held at Al-Khobar, Saudi Arabia.
<http://sawea.org/waterarabia2020/>

- Submitted my research on waste water treatment and was approved and invited to speak
- Delivered a technical session on : Efficiency of cerium modified palm oil fly ash in the catalytic ozonation of phenol (Mustapha Babatunde M, Dr. Bassam Shafiq Tawabini, Oyehan Tajudeen A, Eyad Safi)

EAGE ANNUAL 82nd Conference +Exhibition| Amsterdam, Netherland June 2021

The 82nd EAGE Annual Conference & Exhibition is the largest, most comprehensive multi-disciplinary geoscience and engineering event in the world, consisting of a large conference and exhibition. <https://eage.eventsair.com/eageannual2021/>

- Submitted my research on application of Machine Learning in Geoscience and was approved and invited to speak
- Either myself or a representative of the team will deliver a technical session on: Microseismic source localization using an artificial neural network(Qi Hao, Umair bin Waheed, Mustapha Babatunde, and Leo Eisne)