SOLAR INFLUENCE ON METEOROLOGICAL PARAMETERS IN THE EARTH'S LOWER ATMOSPHERE

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by

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I Shristy Malik hereby certify that the work which is being presented in the thesis entitled “Solar Influence on meteorological parameters in the Earth’s lower atmosphere” in partial fulfillment of the requirements for the award of the Doctor of Philosophy, submitted in the Department of Applied Physics, Delhi Technological University is an authentic record of my own work carried out during the period from 2018 to 2024 under the joint supervision of prof. A.S. Rao and Prof. S.K. Dhaka.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

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Solar Influence on meteorological parameters in the Earth's lower atmosphere

SHRISTY MALIK

ABSTRACT

In the present thesis, Sun and its activities on a seasonal and longer time scale (solar cycle with ~11 years' time period) and its influence on meteorological parameters such as on temperature, wind, relative humidity and surface pressure for the Indian landmass and its isles have been extensively studied using data from several locations. Data used over locations, which are confined over India and its isles Lakshadweep (Arabian sea side) and Andaman and Nicobar (Bay of Bengal side). The study has been divided into three major areas, first being the study of solar insolation and its influence on particle pollution over Delhi, India. The motivation for this area lies in the fact that particle pollution ($PM_{2.5}$) is rising at an alarming rate specially in the capital city, Delhi. We aimed at studying the probable reasons for rise in high pollution episodes in New Delhi, especially during winter and its dispersion with incoming solar radiation. This objective was successfully achieved in our study and we aim to dig deeper into the reasons obtained and the necessary actions that can be taken by us to reduce the high pollution episodes. The concentration of $PM_{2.5}$ presented using a Compact and Useful $PM_{2.5}$ Instrument (CUPI) from Nov 2018 to Oct 2019. A high-time resolution data (~2 min interval) was recorded at Dwarka (West Delhi), New Delhi, to investigate difference in the concentration of ambient particulate matter outdoor as well as indoor. Association between diurnal variation of solar irradiance and dispersion of $PM_{2.5}$ is clearly seen, decrease in $PM_{2.5}$ is well linked with rise in solar irradiance. Diurnal variation of solar radiation showed a consistent increase from 9 am to 2 pm, while relative humidity declined considerably from 10 am to 4 pm (local time); these two factors correspond to less concentration in both indoor and outdoor environments. However, there is no significant difference between outdoor and indoor concentration during summer and monsoon season. This has been described in chapter 3 of thesis.

The second objective of our study was focussed on understanding the solar influence on meteorology for six stations in India viz. Delhi, Kolkata, Mumbai, Chennai, Kochi and Trivandrum during 1981-2021. For this, we made use of MERRA-2 data and tried to understand the role of solar sun spots on temperature, wind and surface pressure for these stations and presented the results in chapter 4. We were able to interpret the implications sun has on our troposphere, some being direct and some indirect. It turns out that the Sun does play a crucial role in atmospheric dynamics, however, it is not the sole force responsible in driving the dynamics of atmosphere. Decrease in wind speed with the sun spot numbers decline coincides suggesting a relationship, however, this is found more on latitude dependent confining around 10-15^{0}N. We expanded it further in the next chapter 5 which is performed during 1981-2021 using datasets from MERRA-2 over several stations. The third subject is the extension of the preliminary findings (second subject). While the second subject's core analysis was directed towards understanding meteorological parameters such as wind speed decline, temperature rise etc. in major metro cities of India over a given period. However, the third subject majorly explores oceanic and land studies (Andaman and Nicobar Islands in Bay of Bengal, Lakshadweep Islands in Arabian Sea and Coastal Areas and small cities in land areas of different topography). This is mentioned in details in chapter 5.

It helped us to understand the role of atmospheric dynamics in the context of Indian region and a very striking feature gained our attention. It is the atmosphere-ocean dynamics which comes into play when our islands climatology is taken into consideration. This objective was successfully achieved using datasets and the outcomes which indeed helped us understand the role of Sun in the atmospheric dynamics for Indian region. We aim to advance our research in such a manner that it will be beneficial to the society to upgrade the living standards in which environment, environmental health and human health will remain of prime importance. The dynamics of energy emissions from the sun and its varying magnetic field makes it the fundamental energy source of Earth. The amount of energy that we receive from the Sun just outside the Earth's atmosphere is defined as the total solar irradiance containing every possible solar wavelength. Past studies have shown that the sunspots correlate with the solar radiation, in fact, the concentrations of solar magnetic fields occurring at the photosphere are known as sunspots. These are identified by an umbra dark zone in the centre having a vertical field and surrounded by penumbra with a horizontal field. During the Small Ice Age period no sunspots were observed, in the wake of sunspots absence, there has been a suspicion that the solar cycle has an influence on Earth's climate. Furthermore, sun is the main source of energy on Earth's surface, thus it is liable to influence Earth even by a small fluctuation.

Hence, we aimed to study the influence of solar cycle on meteorological parameters over the Indian region. Sun-climate connection has been the most debated topic, which is helping to upgrade the understanding on the natural variability of climate and its atmospheric components vis-a-vis anthropogenic factors. To elaborate this thought further, we investigated changes in temperature, wind, and relative humidity, and their association with El- Nino Southern Oscillation (ENSO) and sunspot numbers patterns etc. in the Indian region. ENSO and Sun spot numbers are two such natural variations, which have the significant influence over atmospheric and meteorological parameters, which is selective and more prominent in different latitudes and altitudes. Quasi-periodic fluctuations in temperature (which is linearly rising) closely relates with the ENSO parameter (correlation coefficient 'r' using 6 locations spread over Arabian sea and Andaman and Nicobar ranged from ~ 0.20 to 0.34; which is statistically significant and larger towards Andaman Islands). The value of 'r' increased considerably (> 0.5) during 2000-2021, confirming rapid increase in temperature along with ENSO linear rise with synchronized quasi-periodic fluctuations. Wind speed, in general, showed larger magnitude over Andaman and Nicobar Islands (~ 5.0 m/s yearly averaged) in comparison to Arabian sea (~ 4.0 m/s) and also over landmass (~ 2.2 m/s). Solar cycle (sun spot numbers) and wind speed reflects a weak positive correlation coefficient (< ~ 0.40) though it is statistically significant while no consequential correlation found between solar cycle and relative humidity. Detailed analysis suggests that relative humidity decreased over landmass as well islands during 2000-2021, temperature increased more rapidly between latitudes 7.03ºN and 12.91ºN post 2000 in comparison to other stations located above 15ºN. Increase in temperature in the lower latitudes (< 15ºN) seems thoroughly controlled by the ENSO signal. These findings are displaying a complex interplay between meteorological parameters and ocean-atmosphere interaction.

Future course of action is also proposed and described in chapter 6, which can prove a significant improvement in our understanding and set a new narrative for the policy makers and scientific community.

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This thesis is a gift to my parents who provided me with nurturing environment and invaluable lessons which have been the cornerstone of my growth, shaping me into the person I am today. I am forever indebted to them for instilling in me the values of perseverance and compassion. Their selfless sacrifices and endless encouragement have empowered me to pursue my dreams with confidence and determination.

SHRISTY MALIK

Dedicated to my supportive family and friends

whose unwavering encouragement and love

lifted me throughout the journey.

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CHAPTER 1

INTRODUCTION

1.1.Thermal Structure

Earth's thermal structure, especially how temperature is distributed inside the planet, is a major factor in the formation of many Earth systems, including those that are pertinent to atmospheric science. Knowing the thermal structure is essential to understand and realise how the atmosphere, oceans, and solid Earth interacts with each other. The Earth's thermal structure encompasses heat flows and tectonics to mantle plumes to earth's radiative budget, thereby representing the earth's thermal evolution and its climate history which paves way to understand the linkage between these systems and thus the Earth as a single unit [1]. The distribution of continents, ocean, and mountain ranges is influenced by the internal heat flux of the Earth and the related processes. In consequence, wind and precipitation regimes, as well as other atmospheric circulation patterns are influenced by these geological features. The radiative budget of the Earth is influenced by its thermal structure, which affects the amount of solar radiation that is received and released [2].

Surface temperatures, weather patterns, and climate dynamics are all impacted by solar radiation. Geological, hydrological, and atmospheric processes are by and large connected. To fully understand the atmospheric behaviour, we need to include influence of several other sources originating from the Sun and some phenomenon of the ocean origin [3].

The planet's temperature regime has a significant impact on climatic patterns, atmospheric circulation, and even the possibility of habitability, in addition to forming its physical characteristics. With climate change and environmental issues looming large, it is critical that we have a thorough grasp of Earth's thermal dynamics in order to make wise decisions and adopt sustainable behaviours. Moreover, studying the Earth's thermal complexity becomes essential for forecasting and reducing environmental risk in a time when climate change is fundamentally altering the planet's conditions [4].

Complex interaction between the Earth's surface and atmosphere is a key factor which influences weather patterns, climate systems, and atmospheric circulation. Deciphering the intricacies of atmospheric processes and their wider consequences for climate research necessitates an understanding of the Earth's atmospheric horizontal and vertical thermal structure.

The Earth's surface emits infrared radiation when it is heated by solar radiation. As a result, the atmosphere both absorbs and re-emits this radiation, resulting in a dynamic energy balance that regulates temperature and atmospheric circulation. Convective processes are propelled by temperature gradients that arise from the thermal structure of the Earth both horizontally as well as vertical. Cooler air at higher latitudes sinks to form high-pressure systems, whereas warm air at the equator rises to form low-pressure systems. This convectional circulation plays a major role in determining weather systems and forming global wind patterns [5].

The atmospheric circulation cells, which mainly comprised of the Hadley, Ferrel, and Polar cells, are primarily determined by the Earth's thermal structure. The aforementioned cells arise from the distinct heating of the Earth's surface, which propels extensive air circulation patterns that influence the global distribution of temperature and precipitation. The direction of atmospheric circulation is also affected by the Coriolis force, which is a consequence of the Earth's rotation interacting with the thermal structure[5]. Global wind patterns are further shaped by this process, which works in tandem with temperature-driven pressure gradients to create the trade winds and polar wind systems.

The formation of monsoons and seasonal weather patterns is largely influenced by the land and ocean heating contrast during summer. Seasonal fluctuations in temperature and precipitation are influenced by the beginning and severity of monsoons, which are basically influenced by the differential heating of the land and ocean. The El Niño and La Niña phenomena, which are of ocean origin, can cause variations in the thermal structure and alter atmospheric circulation patterns significantly. These phenomena, which are defined by fluctuations in sea surface temperatures (SST), have an impact on global weather patterns, affecting storms frequency, floods, and droughts etc.[6]. From above mentioned concepts and narratives, it is learnt that vertical thermal structure of atmosphere is influenced by various short- and long-term processes. In the following, we briefly introduce different layers of atmosphere.

1.1. (a) Layering structure in the Atmosphere:

The Earth’s atmosphere, a blend of gases and trace amounts is a natural haven for numerous physical and chemical processes. From being made up of a mixture of gases to receiving solar radiation, atmosphere is what gives rise to the uniqueness possessed by Earth i.e. the climate. The air mixture is mainly composed of nitrogen, oxygen, argon, and trace gases. At elevations, this gaseous mixture becomes less dense and the exact point where the atmosphere terminates continues to be a speculation. Our atmosphere is in close agreement to the hydrostatic balance vertically (vertical pressure gradient and downward gravitational force), with the exception that the weight of horizontal atmospheric slabs is supported by pressure difference between the upper and lower surfaces. Theoretically, the combination of equations describing the hydrostatic balance and ideal gas law, we come across a hypothetical isothermal atmosphere wherein both the pressure and density would fall exponentially with altitude. However, in the real scenario, the atmosphere is indeed a non-isothermal envelope portraying that the pressure and density are still close to exponential form with an additional e-folding feature visible at a height of around 7 to 8 km [5]. This striking feature points to density stratification in the atmosphere produced by gravity.

Due to the density stratification, a portion of air that is displaced upwards from its mean position becomes negatively buoyant with respect to its surroundings and similarly a portion of air going down from its mean position becomes positively buoyant with respect to its surroundings and thus both air parcels will move towards equilibrium positions. This makes buoyancy a restoring force in the atmosphere and makes the atmosphere stably stratified. This stratification stability varies from layer to layer in the atmosphere. This is how the atmospheric layers come into picture. Whether we say that a place has weather and not climate or the opposite, it is the lowest layer of earth's atmosphere that we are talking about. This layer of atmosphere where weather is confined and its averaged phenomenon which is climate is studied is nothing but the troposphere [see Figure 1.1 for vertical variation of temperature].

The troposphere is marked by atmospheric turbulence and has approximately 75% of the gaseous mass of atmosphere and virtually all the water vapour and aerosols. This layer is distinguished by the display of a decrease in temperature with height at a mean rate of ~ 6.5ºC/km. It is so because air is compressible and its density decreases with altitude, favouring the expansion of rising air and thereby cool it.

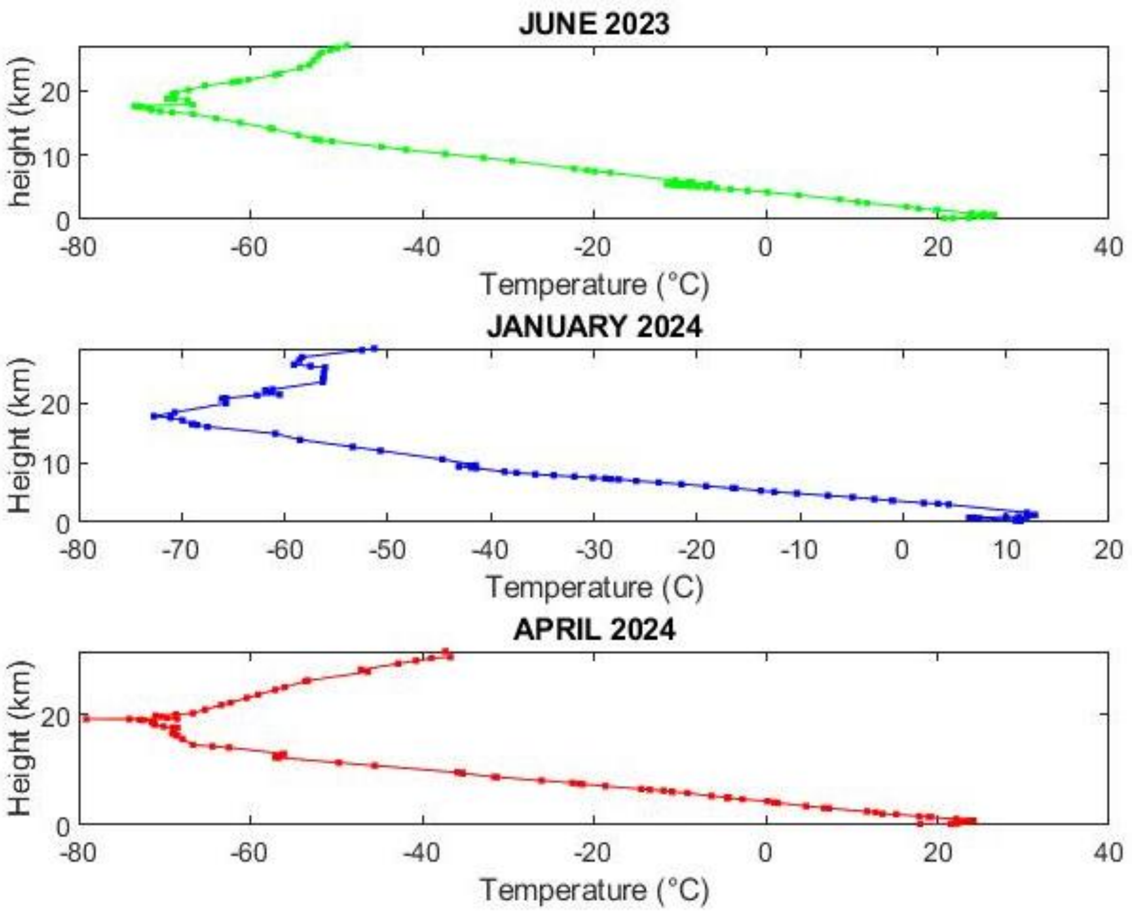


Figure 1.1: Graphical illustration of the vertical variation in temperature over New Delhi for summer (June 2023), winter (Jan 2024) and Spring (April 2024).

Moving towards outer space, next we have stratosphere extending from tropopause (coldest layer of upper troposphere) to about 50 km. Blistering cold, cloudlessness, thin dustless air and a major proportion of ozone makes up the stratosphere. The maximum temperature associated with the absorption of Sun's ultraviolet radiation by ozone occur at the stratopause which is the transition zone between stratosphere and mesosphere, the next layer. The mesosphere is well known for ‘noctilucent clouds’ observed over higher latitudes in summer season. The average temperature decreases to a minimum of about 140 K in this layer. Beyond the mesosphere we have thermosphere. Temperature increases with altitude due to absorption of ultraviolet rays by molecular and atomic oxygen. Above 100 km, solar X-rays, cosmic radiation, ultraviolet radiation cause ionization and hence the formation of ionizing particles in the atmosphere, this is the Ionosphere. The spectacular phenomenon of auroras that we encounter is happening because of the presence of these particles present in atmosphere. Generally, ionosphere is the term used for all layers near and above 80 km (commonly known as D region, E region, and F region) [5] [7]. Ionospheric layers in the upper atmosphere are feasible for electrical conduction which are helpful in short wave radio transmission possible over long distances. All these layers have their own importance in explaining dynamics of atmosphere. Satellites, radars, and weather balloons launched in the upper strata provide us with delicate information regarding the conditions of atmosphere [7]

1.1 (b) Convection and Dynamical features in the lower and middle atmosphere

The lower and middle atmosphere play a pivotal role in governing the Earth’s climate system. Lower atmosphere is another term commonly used for troposphere by meteorologists, which is the weather zone of our atmosphere. Lower atmosphere is facilitated by the presence of precipitation, cloud formation and convective currents which forms a complex yet inseparable part of our climate system. Despite the fact that carbon dioxide and water vapor are greenhouse gases, they aid in the maintenance of earth’s surface temperature by trapping heat and contributing to greenhouse effect. Middle atmosphere comprises of both the stratosphere and mesosphere, of which mainly the stratosphere contains ozone layer. This layer helps trapping harmful ultraviolet radiation from the sun to reach earth’s surface and serves the purpose of a protective layer crucial for life existence. Unlike the troposphere, stratosphere betokens temperature inversion in which the temperature increases with increasing altitude. Stratosphere gets its name from the word strata which means layers, and this stratum not only limits the movement of air vertically but also influences the weather patterns in lower atmosphere.

Thus, both lower and middle atmosphere are responsible for the kind of climate dynamics we encounter and in doing so contribute to the overall stability and functioning of the Earth’s climate system [8]. Even if the troposphere and stratosphere form two distinct layers, yet there is an exchange of air masses and substances vertically between them. This signifies the inter-dependence and influence of the two layers on each other and thus defines current state of the climate system. Moreover, the circulation patterns in lower atmosphere have a profound impact on the circulations and dynamics of middle atmosphere [9].

The weather and climate of troposphere is coupled with the thermal structure, evolution and dynamics of ozone layer in the stratosphere [10][11].The troposphere affects stratosphere mainly through vertical transport and propagation of waves (Figure 1.2)[12][13] however, the stratosphere reflects these changes slowly but they have a long-term impact on the weather and climate in troposphere [10]

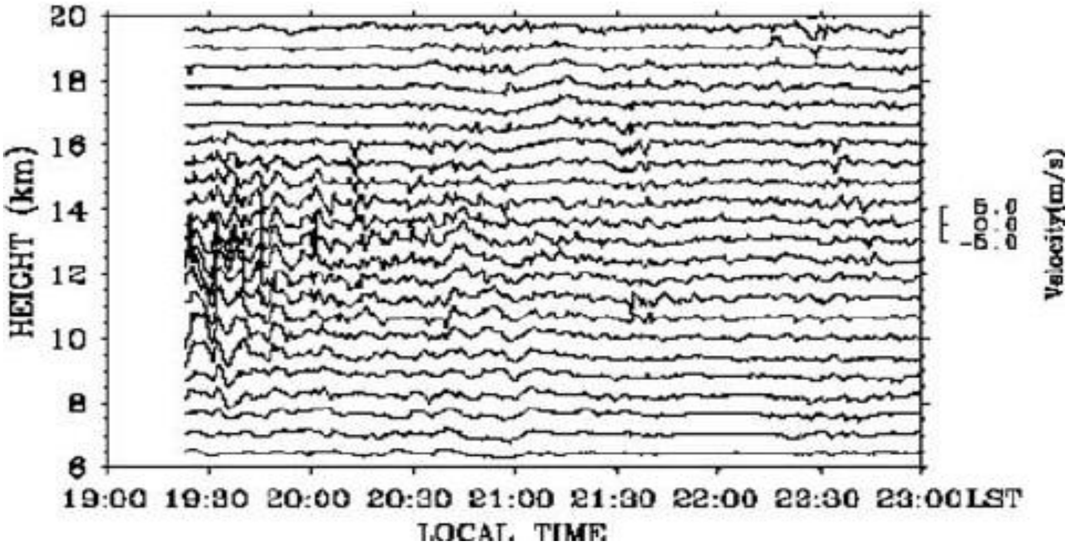


Figure 1.2: Graphical representation of the vertical transport and propagation of waves in the troposphere. (https://doi.org/10.1029/2002GL014745)

Climate and atmospheric dynamics on different temporal and spatial scales are interlinked and essential for unravelling the intricacy of the climatic system. Atmospheric dynamics governs the redistribution of heat across the planet, ocean-atmosphere interactions, behaviour of weather systems, distribution of greenhouse gases and response to the regional circulations. Thus, dynamics emerges as a fundamental aspect to model, analyse and predict climate patterns over a particular place and region. From the above-mentioned discussion, significant influence of atmospheric dynamics can be understood to present the recent past climatic trends and it may be useful to predict the futuristic climate over a particular location.

Ocean-atmosphere interaction (experienced in the entire troposphere) through rapid and shallow convection in the Indian and Pacific Ocean is also shown by [14]. Intensity of the association via strong convection is measured using correlation coefficient between lower and upper tropospheric dynamical processes with increasing latitudes from equator [14] [15].

To understand behaviour of lower atmosphere is quite complex as it is highly location dependent. Vertical thermal structure of lower atmosphere at a place (for instance near equator, in tropics or in coastal and ocean body) needs further examination; though some serious efforts have been made in the recent past [16][17][18][19][20][12][13][21][22][23][24][25][26] using rocket data [27], radar observations, radiosonde [19]and satellite data, along with reanalysis products such MERRA-2, ERA-5.

In the past decade, [28][15][29] have emphasised that solar cycle signals detected in temperature both in the lower and upper troposphere (near tropopause). It was revealed in their analysis that ~ 11-year solar cycle signal was clear in the order of ~2-3^0 C degree nearly at 100 mb level mainly in the tropics over Indian region. However, in the lower and middle troposphere, solar signal, if any, can be obscured easily due to strong convection processes and weather phenomenon.

Long term climatic trends and changes in various meteorological parameters (such as temperature, wind speed, relative humidity, and pressure etc.) over Indian region is not yet explored systematically, which is taken up in the current thesis. It is quite complex to separate out the influence and contribution on temperature from solar origin and/ or anthropogenic activities [29].

1.1 (c) Solar irradiance and its influence on different time scales in the lower atmosphere:

The Earth's climate is a complex interplay of various factors, and one significant external driver is the Sun. The Sun undergoes a natural and rhythmic cycle known as the solar cycle, marked by variations in solar activity such as sunspots, solar flares, and changes in solar irradiance. Over an approximately 11-year period, the Sun transitions from a period of solar maximum to solar minimum and back again, influencing the overall energy balance of our planet. In this context, understanding the solar cycle's impact on the temperature of the Earth's lower and middle atmosphere becomes crucial for unravelling the intricacies of climate dynamics. On the other hand, small changes in solar irradiance and insolation within a year from one season to another also makes lot of difference in terms of dispersion of the pollutants and clearing the early morning haze [30]. Therefore, it becomes very important to examine the solar influence starting from a very fine time scale (daily) to 11 years (solar cycle) and longer period (> 11 years).

As mentioned earlier, the lower and middle atmosphere, comprising the troposphere and stratosphere, plays a pivotal role in shaping weather patterns and climate conditions on Earth. The interaction between solar radiation and the Earth's atmosphere leads to a cascade of complex processes that ultimately affect temperature distribution [31]. While the direct influence of solar irradiance is evident, the mechanisms through which solar variability can modulate atmospheric temperatures are multifaceted and not fully understood [3] [32].

This synoptic exploration aims to delve into the connections between the solar cycle and temperature variations in the lower and middle atmosphere. By examining existing research, observational data, and simulations, we seek to unravel the nuanced ways in which solar activity may influence atmospheric temperatures.

Climatic changes and its manifestations cannot be expected to remain uniform throughout the planet, though climate change is happening globally. Due to lack of observational data, there is a mysterious representation when it comes to studying the climate at a regional scale [33]. At a global scale we find relatively sufficient data and ongoing research for the climatic domain. However, we need to understand the climatic changes at the regional scale in a much-sophisticated way (for instance Indian sub-continent is less explored due to its diverse topography) so that the administration and government policies be ready for future disaster management.

Indian subcontinent shows a very complex dynamics of the atmosphere-hydrosphere-lithosphere-cryosphere system [33]. Recently, it has been discussed that the regional climatic changes in the past decades have been influenced by anthropogenic factors along with the other natural process [29]. It is felt necessary to understand the climatic regimes and their changing behavioural patterns over Indian region as well as globally using satellite data. COSMIC/ FORMOSAT-3 data used in examining quasi-biennial oscillations (QBO) in the lower and middle stratosphere and its influence on temperature distribution in the upper troposphere [34] [35]. The uniqueness of the topography of India supports diverse climatic zones, flora and fauna and micro climatic areas.

The World Meteorological Organization (referred to as WMO from now onwards) is a specialized agency for promoting international cooperation on atmospheric science, geophysics and climatology. With the increased frequency of weather extremes and expeditious climate change, it becomes even more important to revisit the meteorological parameters affecting the climatic trends in the Indian landmass and its surrounding isles [4]. The WMO report on 'State of Climate in Asia 2022' clearly points to the fact that Asia is warming faster than the global average.

In the following, we will explore key aspects of solar variability, its impact on atmospheric processes for instance, from regional circulation including pollution dispersion to the large-scale circulation (planetary scale). Also, we need to examine the empirical evidence supporting the link between the solar cycle and temperature variations in the lower and middle atmosphere. This synoptic investigation aims to contribute to the ongoing dialogue on climate change, offering insights into the interconnected relationship between solar activity and Earth's atmospheric temperatures vis-a-vis anthropogenic sources.

1.2 MOTIVATION AND OBJECTIVES OF THE THESIS

The study of solar influence on temperature in the lower atmosphere is motivated by several compelling factors, each contributing to a deeper understanding of Earth's climate dynamics and its potential implications. The key motivations are broadly mentioned below for better understanding of ongoing atmospheric processes and mechanism on the subject.

1. Climate system complexity-The Earth's climate system is highly complex, with numerous interacting factors influencing weather patterns and long-term climate trends. By investigating the impact of the solar cycle on atmospheric temperatures, wind, relative humidity, and pressure etc., scientists aim to unravel a crucial component of this intricate system, enhancing our comprehension of the mechanisms that govern climate variability.
2. Baseline for Climate Change Assessment- Understanding natural climate variability, including the influence of Sun, provides a crucial baseline against which anthropogenic climate change can be assessed. Distinguishing between natural and human-induced climate variations is

essential for accurately attributing observed temperature changes and refining climate models to project future trends.

3. Impacts on Atmospheric Circulation- Solar variations (from day-to-day variability i.e. on 24 hours' time scale to ~ 11 years solar cycle) have been linked to changes in atmospheric circulation patterns, particularly in the troposphere/ stratosphere. Diurnal variability in solar irradiance is quite helpful in dispersing pollutants, removing hanging tiny water droplets and reducing haze formation etc., especially in northern India during winter and spring season [3]. Combination of diurnal variation in solar irradiance and meteorological parameters is useful to predict air quality and weather system etc. On this aspect, new results are shown in the thesis. Improved understanding on the above-mentioned factors would be helpful for better predictions of regional climate patterns, extreme weather events, and phenomena such as the stratospheric polar vortex etc. This knowledge is invaluable for developing more effective climate adaptation and mitigation strategies
4. Educational and Public Awareness- Studying the solar influence on atmospheric temperatures fosters public awareness and understanding of climate science. It enables educators to convey the interconnected nature of Earth's climate system and the role of external factors, such as long-term solar variability, in shaping our planet's climate.

In the present thesis, solar cycle and its influence on meteorological parameters including temperature, wind, relative humidity and surface pressure for the Indian landmass and its isles have been extensively studied using data from several locations.

The study has been divided into three major areas, first being the study of solar insolation and its influence on particle pollution for the North India. The motivation for this area lies in the fact that particle pollution is rising at an alarming rate specially in the capital city, Delhi. We aimed at studying the probable reasons for rise in high pollution episodes in New Delhi, especially during winter [36]. This objective was successfully achieved in our study and we aim to dig deeper into the reasons obtained and the necessary actions that can be taken by us to reduce the high pollution episodes.

The second objective of our study was focussed on understanding the solar influence on meteorology for five stations in India viz. Delhi, Kolkata, Chennai, Kochi and Trivandrum. In this study we tried to understand the role of solar sun spots on temperature, wind and surface pressure for these stations. We were able to interpret the implications the sun has on our troposphere, some being direct and some indirect. It turns out that the Sun does play a crucial role in atmospheric dynamics, however, it is not the sole force responsible in driving the dynamics of atmosphere. This constraint led us to increase the domain of our study from some major cities to a larger set of cities and our islands for studying the lower atmospheric dynamics.

The third objective of our study is highly motivated by our second objective. This area of research is primarily focussed on Indian landmass and its isles. It helped us understand the role of atmospheric dynamics in the context of Indian region and a very striking feature gained our attention. It is the atmosphere-ocean dynamics which comes into play when our islands climatology is taken into consideration. This objective was successfully achieved using long datasets and the outcomes which indeed helped us understand the role of Sun in the atmospheric dynamics for Indian region.

Having done the significant and useful analysis for Indian region (chapter 3, 4, and 5), we propose to seek different perspectives in our future studies. We aim to expand our research in pollution related aspects and its impact on human health. For this, we aim to add the study on black carbon content, its sources and the health implications thereof. These studies will help to understand our environment better and frame the policies accordingly by the government agencies and national organisations. We aim to advance our research in such a manner that it will be beneficial to the society to upgrade the living standards in which environment, environmental balance and human health would remain of prime importance.

1.3 OVERVIEW OF THE THESIS

Six chapters make up this thesis' structure in order to meet the objectives of the planned research. Each chapter is structured such that it may be read alone and connected all together. All chapters of the thesis have their own uniqueness and motivation as cited above.

In **Chapter 1,** introduction of the theme of the research topic, literature survey over the past decades, and the deficiency in understanding and the unresolved issues were discussed. The theme of the current work is proposed in a systematic way.

Chapter 2 is dedicated on data and methodologies. Collection of the data from different instruments and state of art technologies, including of a very smart and compact device of measuring $PM_{2.5}$ and MERRA-2 (global data consisting of meteorological parameters etc.) will be described.

Chapter 3 involves detailed analysis and the description of new results. It includes an explanation of the linkages between solar insolation and particle pollution in New Delhi. Solar insolation stands for incoming solar radiation, the insolation received on earth governs the life that originates here on earth for which the sun acts as a primary force. This chapter includes the study of indoor and outdoor pollution, the role of meteorology in dispersal of pollutants from both the ambient environments is discussed and the new results are presented. Finally, the role of solar irradiance and insolation on meteorology and thus on dispersal of pollutants from the indoor environments and outdoor areas is highlighted [25].

Particle pollution is an emerging area of concern as regards to human health in the present times. The instances of high particulate pollution have become quite common in Delhi NCR region, India, especially during winter period [36]. Air pollution over north India and more specifically over Delhi has attracted both public and scholastic group. Outdoor air pollution has detrimental health effects and is responsible for more than 4 million deaths every year globally [36], resulting in substantial global and regional decrements in life expectancy. India experiences high ambient air pollution, with an annual population-weighted $PM_{2.5}$ (particulate matter with diameter less than 2.5 μm) mean of 74 and experiences the highest number of deaths [37] [38].

Therefore, the ambient $PM_{2.5}$ exposure to the human being is quite large that affects our daily life. The sources of $PM_{2.5}$ are present both indoors and outdoors. Indoor activities such as cooking, frying, tobacco smoke, kerosene heaters, etc. produce pollutants. Since the size range of $PM_{2.5}$ is very small, thus it permits to pave way into the respiratory tract, thereby reaching the lungs. Even its short time exposure is capable of eye, nose, throat irritation, shortness of breath, and many more such effects. Prolonged exposure to $PM_{2.5}$ can prove hazardous as it can vary from showing mild symptoms to severe health conditions such as asthma. Hence, it is important to study $PM_{2.5}$ both indoor and outdoor, which is not done systematically partly due to the poor understanding that indoor air quality is better and safe. Indoor measurements of $PM_{2.5}$ is equally important, and there is a need to provide the real-time status of the air quality.

In this chapter, the concentration of $PM_{2.5}$ presented using a Compact and Useful $PM_{2.5}$ Instrument (CUPI) from Nov 2018 to Oct 2019. A high-time resolution data (~2 min interval) was recorded at Dwarka (West Delhi), New Delhi, to investigate difference in the concentration of ambient particulate matter outdoor as well as indoor. CUPI instrument records data at a very fine time scale [30].

Chapter 4 describes the solar cycle links with meteorology in major cities of India. The study helped us in improving understanding of how temperature, wind and surface pressure are influenced by solar sun spots. The influences have been studied from 1981 to 2021, which is a large period of time to interpret the climatic changes.

In the recent decades, it has been a serious concern to investigate the linkages of solar cycle influence on different atmospheric parameters mainly focused in the troposphere[15][28]. Kumar et al. (2018) have investigated the influences of the solar cycle on temperature using radio occultation measurements by COSMIC/FORMASAT-3 satellite covering fairly large region of the tropical belt from 2007 to 2015 [34]. Though, it has been quite challenging to detect the signal due to presence of various atmospheric oscillations such as seasonal, annual, quasi-biennial, an El Niño southern oscillations (ENSO) in the troposphere and lower stratosphere. A consistent rise (1.5ºC) in the interannual variation of temperature was observed along with minimum to a peak in the solar cycle. However, it was an averaged feature using huge data set in the tropics, though influence of solar cycle remains dissimilar in different regions.

In the earlier related studies, [15] over Indian region, solar cycle influence was shown in temperature, using radiosonde data, in the upper tropospheric region (at 100 mb pressure level) with a magnitude of ~ 2-3ºC, which was prominent near 10^0N only, and no relation was seen over Delhi and Kolkata stations.

There has been serious concern about the decreasing intensity of the peaks of solar cycle; sunspot numbers are on decline in the last 3-4 consecutive solar cycles (solar cycle 21, 22, 23, and 24). Therefore, it is important to examine the solar cycle influences on the meteorological parameters. Recent study by [31] over the Peru region, using 5 stations in Mantaro valley, have emphasized that solar cycle effect could not be seen in temperature data, rather they concluded

that anthropogenic factors dominated and were responsible for the warming. Thus, the solar cycle's direct impact on temperature on Earth's surface is not uniform.
In this chapter, we mainly focused on the climatic trend in wind speed variability on a time scale covering a few solar cycles (~ 11-year periodicity) over Indian region covering from tropical latitudes down to equatorial region. Additionally, temperature and pressure data were also analysed over the same period. Sun linkages with the lower atmosphere is apparent in the form of a natural variability of various parameters. For the sake of brevity, we provide in the following some scientific evidences of connection between sun and lower atmosphere.

The dynamics of energy emissions from the sun and its varying magnetic field sets it aside as the fundamental source of energy for Earth. The amount of energy that we receive from the Sun just outside the Earth's atmosphere is defined as the total solar irradiance containing every possible solar wavelength [39]. Past studies have shown that the sunspots correlate with the solar radiation[39][40]. The concentrations of solar magnetic fields occurring at the photosphere are known as sunspots. These are identified by an umbra dark zone in the centre having a vertical field and surrounded by penumbra with a horizontal field [31]. Sun activity varies over a period of solar cycle, having a periodicity of nearly 11 years, and sunspot number gives us a quantitative description of the sun's energy [41]. During the Small Ice Age period no sunspots were observed, in the wake of sunspots absence, there has been a suspicion that the solar cycle has an influence on Earth's climate [42] .

Furthermore, sun is the main source of energy on Earth's surface, thus it is liable to influence Earth even by a small fluctuation [43][3]. Hence, in this chapter, we aim to study the influence of solar cycle on meteorological parameters over the Indian region. In a recent study [3], solar influence showed its long-term influence on cloud formation by changing the regional circulation. It is therefore apparent to examine the solar cycle influence in the basic meteorological parameters, though it is quite complex and latitude dependent [40].

The main concern of the study is to contemplate about the decrease in wind speed over Indian mega cities for the last 40 years, and its link with the solar cycle as a natural variability. Wind speed plays a dominant role in the dispersion of the pollutants and hence its long-term change would surely be affecting air quality of the region [36]. Decrease in wind speed show an immediate impact on worsening the air quality especially during winter. Chetna et al. (2023) have shown the indication of decline in wind speed at Income Tax Office (ITO) station, New Delhi during 2007-2021, and this is supposed to be one the reason of adverse impact on non-dispersal of pollutants. It is therefore, necessary to examine the reason for this decline in wind speed. We have investigated and present the results by looking at the natural variability of sunspot numbers (varying intensity of solar cycle) and the impact on meteorological (especially wind speed variability) parameters in the Indian region. Analysis over a period of 1981-2021 is presented in this chapter.

Chapter 5

In this chapter, we intend to decipher the trends and climatic changes in different atmospheric parameters on the Indian landmass and the surrounding sea and ocean body in

Arabian sea and Bay of Bengal thus making the study a much robust document for the policy makers. We also focused on the interaction and association of various meteorological parameters by examining the changes in their pattern with time; this is analysed in the Indian landmass at several locations and at three locations in the Arabian sea and Bay of Bengal each.

Sun-climate connection has been the most debated topic, which is helping to upgrade the understanding on the natural variability of climate and its atmospheric components vis-a-vis anthropogenic factors [3][44][45] . To elaborate this thought further, we need to investigate changes in temperature, wind, and relative humidity, and their association with El- Nino Southern Oscillation (ENSO) and sunspot numbers patterns etc. in the Indian region.

ENSO and Sun spot numbers are two such natural variations, which have the significant influence over atmospheric and meteorological parameters, which is selective and more prominent in different latitudes and altitudes[3][15]. ENSO is a coupled ocean and atmosphere phenomenon. It is associated with periodic warming in the sea surface temperatures of the Pacific Ocean which not only changes the temperature in ocean waters, sea level pressure but also adversely affects the monsoon in India[46][47]. These findings are displaying a complex interplay between meteorological parameters and ocean-atmosphere interaction. Therefore, ENSO is expected to control the meteorological parameters, wind patterns, and prominent convergence and divergence cells present in the troposphere, namely Walker circulation and Hadley circulation. There are studies which supports changes in the ocean and sea surface temperature of anthropogenic origin, while there are evidences of influence from the sun activity over a long period, i.e. a few solar cycles [29][3][33].

Sea Surface Temperature (SST) is the water temperature at the surface of ocean. SST plays a crucial role in earth's climate by influencing marine ecosystems and ENSO etc [48]. As per the WMO report of 2022, the SST, an indicator of changing climatic conditions, has shown an increasing trend in the Indian Ocean [4][49]. The overall surface ocean warming has been observed at a rate of 0.5ºC per decade in various oceanic areas including the Indian Ocean. This is almost thrice the rate of global surface ocean warming trends obtained by the WMO [4]. This report seems to be in good agreement with our results which point towards increasing temperature trends in the islands of Andamans and Lakshadweep, detailed analysis is given in this chapter.

Chapter 6, is the last chapter of the thesis which summarizes the results presented in each chapter sequentially along with an evolving sensitization of greater understanding on this new aspect of the Sun and lower atmosphere connection in the presence of large-scale oceanic phenomena of ENSO and rising temperature trend in the Arabian sea and Indian Ocean.

Future course of action is also proposed, which can prove a significant improvement in our understanding and set a new narrative for the policy makers and scientific community.

CHAPTER 2

DATA AND TECHNIQUES

2.1. Introduction

This chapter illustrates the procedure deployed for carrying out research over the Indian landmass and its isles in different domains[46][50]. It begins by describing the strategy and datatypes used for studying the impact of aerosols especially highlighting the particulate matter ($PM_{2.5}$) over North India. This study is diversified by taking into consideration the effects of solar radiation and relative humidity for the same region to decipher the results in an enhanced manner. Thereafter, the chapter proceeds with describing the data source and techniques employed for widening our research area from fewer locations of India to a larger portion of Indian landmass and its isles. In totality, this chapter deals with the types of data sets, the methodologies used and finally the approach used for analysis of these datasets in our research study.

2.2. Data Attributes

2.2.(a) ERA-5

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an independent intergovernmental organization providing operational medium-range and long-range weather forecasts located at United Kingdom. Its datasets are useful for carrying out atmospheric research and climate analysis on a global scale. This organization provides data for any selected location in GRIB, NETCDF formats which can be converted into CSV formats as per the usage of research.

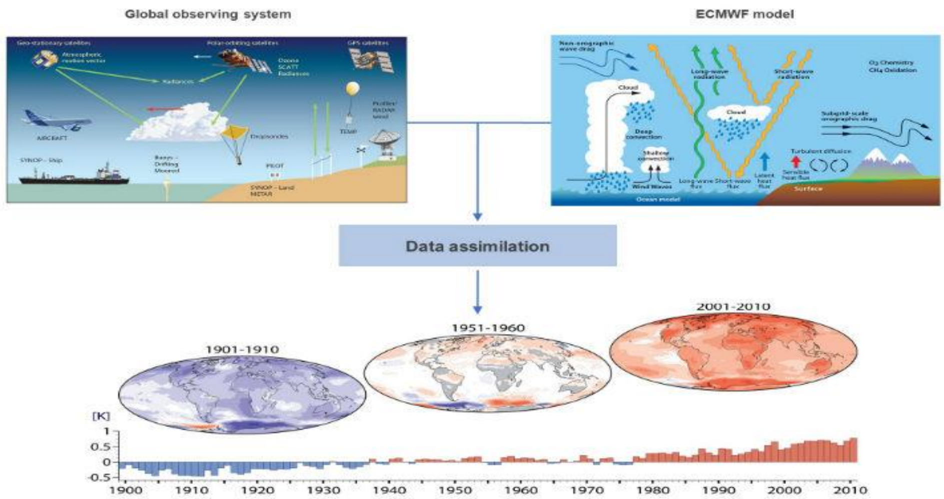


Figure 2.1: Schematic illustration of data assimilation process under ECMWF (https://www.ecmwf.int/en/about/media-centre/science-blog/2017/era5-new-reanalysis-weather-and-climate-data)

ECMWF has evolved with time in the sense that each generation of datasets offers a unique approach for carrying out atmospheric and climatic change research [Figure 2.1]. One of the upgraded datasets of this organization is the ERA5, which provides us the platform for global climate and weather-related research. This reanalysis has a set of models which use the observations and the re-creates them in the form of a globally complete dataset consistent with the basics of physics. Reanalysis uses observations from all sorts of resources including weather balloons, radiosonde and satellites after stringent quality checks [Figure 2.2].

ERA5, part of Copernicus Climate Change Services provides a higher spatial resolution of about 31 km grid than the earlier generations of reanalysis and resolves the atmosphere upto a height of 80 km using 137 levels. The hourly estimates of atmosphere-hydrosphere-lithosphere's climate variables can be obtained from this reanalysis. Moreover, this data is not only gridded but also has a projection of latitude-longitude grid with the high horizontal resolution of $0.25^o \times 0.25^o$. The vertical pressure coverage ranges from 1000 hPa to 1 hPa and temporal resolution is hourly based. These attributes listed above distinguish this generation of data from the prior ones and hence we deployed it in our thesis work.

Figure 2.2: Pictorial representation of the sources used for reanalyses by ECMWF (https://www.ecmwf.int/en/about/media-centre/focus/2020/fact-sheet-earth-system-data-assimilation)

We were highly motivated to use the reanalysis data in our research while studying the instances of particulate matter in indoor and outdoor environment over North India. The reason for the upliftment and stagnation of these aerosols could be linked to the atmospheric dynamics[51][52]. Thus, to further our research in exploring how pollution dispersal takes place, we made use of solar radiation and relative humidity variables, for Dwarka sub city located in South-west Delhi, from November 2018 to February 2019.

The Solar radiation data is the monthly averaged reanalysis by hour of day, with the accumulation period being 1 hour. This dataset is available in Jm^{-2} and it has been converted to Wm^{-2} to portray the intensity of solar radiation at a particular location. To change the unit, we divided the accumulated values by the accumulation period taken in seconds. Intensity helps in interpretation of the amount of energy received per unit area which is much more realistic to visualize.

The relative humidity is expressed in percentage and it is that value of water vapour pressure at which the air becomes saturated i.e. it cannot hold more moisture. At this particular value, the water vapour either starts to condense into liquid droplets or ice. There are different ways to calculate relative humidity based upon the temperature viz. for temperatures above 0º C, it is calculated for saturation over water. Whereas, when the temperature falls below -23º C, its calculated over ice. And, finally when the temperature ranges from -23º C to 0º C, it is calculated by interpolation between ice and water values with the help of a quadratic function.

Having taken the two climatic variables, we were able to deduce relationship between the dispersal of pollutants and the atmospheric dynamics for the considered time period. The data techniques used for understanding and plotting these variables is explained in the upcoming sections of this chapter. Along with these variables, we also obtained the data for zonal mean circulation including the Hadley cell values from 90º N to 90º S latitudinal range. The graph obtained was highlighted with a red dotted line to represent the area under study. Thus, using all these three datasets we were able to draw certain conclusions regarding the atmospheric behaviour in the context of pollutants.

Finally, we made use of the solar radiation and relative humidity data for a period from November 2018 to February 2019 at Dwarka (New Delhi) and compared it with the particulate matter over the region to understand the role of meteorology in dispersal of pollutants. The solar influence over the lower atmosphere dynamics in Delhi was studied with respect to the air quality and ultimately the health perspective arose from this study.

2.2.(b) CUPI

Particulate matter is usually the microscopic particles that are suspended in the air. These particles are so small that they are not usually visible to the naked eye, and this makes them more jeopardous as regards to human health and air quality. Thus, the study of particulates is an essential aspect of atmospheric research. In this work we used a Compact and Useful $PM_{2.5}$ Instrument (CUPI) to measure the $PM_{2.5}$ particles over Dwarka (New Delhi) [Figure 2.3]. It is a sensor compact in size and fitted with a data logger. This data logger records data over time in the internal storage which is later used for computational analysis.

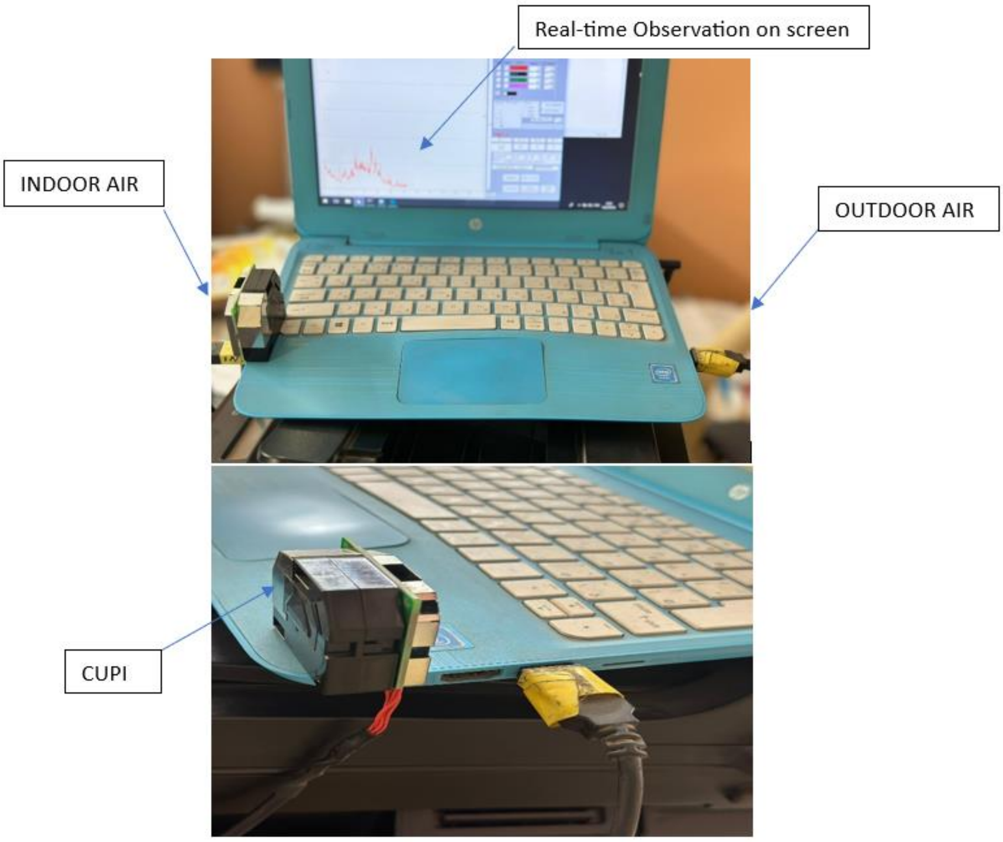


Figure 2.3: Compact and useful PM2.5 Instrument used in the study of atmospheric conditions over Dwarka, New Delhi for collecting particulate matter observations (https://doi.org/10.1007/s12647-023-00694-2)

This instrument evaluates the total volume of 2.5 μm or smaller size particles based on the scattered signals received from single particles. It does so by measuring the intensities of the signals received and the count of the scattered signal received by the sensor. The unit-to-unit variation of the sensor's sensitivity is less than 10% with a temporal resolution of less than 2 minutes. The precision of this sensor is somewhat less than 23%. In the making of this instrument, Polystyrene latex was used for calibration purpose. This latex was specifically chosen to be monodisperse i.e. it was characterised by particles of uniform size in a dispersed phase. This instrument has been widely used to carry out analysis of particulate matter in various areas across South-East and South Asia [53].

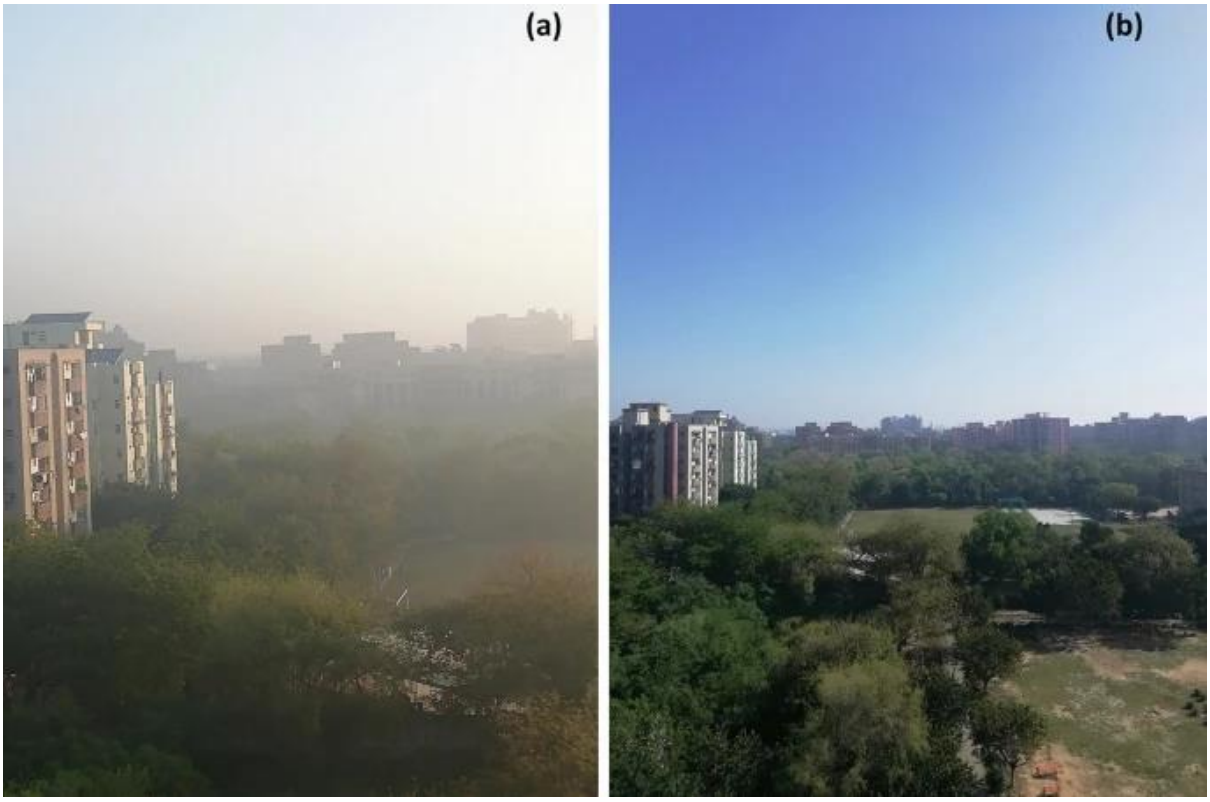


Figure 2.4: The real-time photograph of Dwarka site depicting the presence of haze in the early morning hours and its dispersal gradually as the day progresses (https://doi.org/10.1038/s41598-020-70179-8)

The atmospheric air in its natural state is termed as ambient air. The $PM_{2.5}$ levels must be measured in the presence of ambient air to have the exact readings of a location [Figure 2.4]. These levels are measured after multiplying a correction factor to the outputs of the Panasonic sensor. In order to calculate this correction factor, the ratio of the density of ambient particles and polystyrene latex was taken initially. However, due to the differences in the physical properties of the latex and ambient particles, correlation between particulate matter at a nearby location with the output of the sensor was taken. Thus, the correction factor came out to be 1.4 which was later used to get the final set of readings in this study. Some researchers have used a factor of 1.3 based upon their correlation as per the locations [53][54]. The major advantage of this sensor is because it detects particles of relatively lower size. Furthermore, to prevent excessive heating of the sensor, it is deployed with an air flow to allow its continuous usage without an external fan. This sensor also has louvre windows to mitigate any potential artifacts resulting from winds.

The readings from this device have been used in our study of indoor and outdoor environment over Delhi. The particulate matter readings were compared to other two variables viz. solar radiation and relative humidity. The sole reason to include these two variables in our study was to understand the role of atmosphere in the dispersal of air pollutants if any. As a result, we were able to obtain satisfying results that highlighted the significance of natural processes on the air quality. Along with these set of variables, we made also studied the tropical cell over the same region and analysed them.

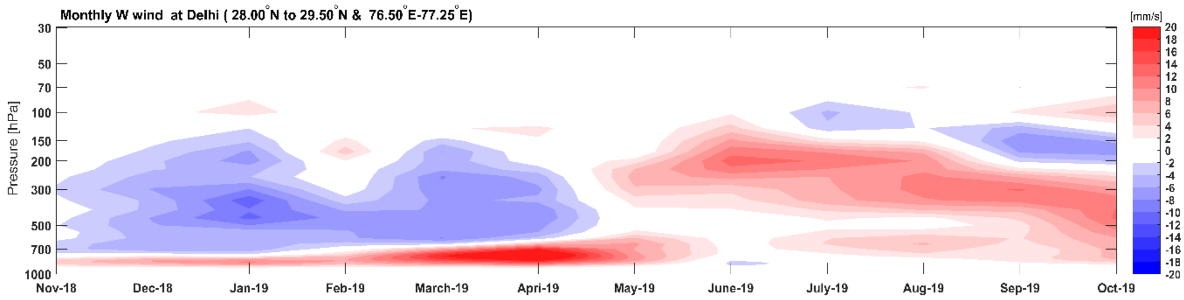


Figure 2.5: The monthly average vertical wind (W-wind) structure over Delhi for the time period (Nov-18 to Oct-19).

The meteorological variables, solar radiation, relative humidity, wind and Hadley cell were studied along with the observations of CUPI to gain insights over the atmospheric and anthropogenic barriers in the air quality of Dwarka [Figure 2.5].

2.2.(c) Royal Observatory of Belgium

Sun is the primary source of energy on Earth and thus it is important to study Sun and the activities occurring in it. The magnetic field of Sun reverses itself every 11 years approximately, this cycle is known as the solar cycle. During this cycle, the Sun attains peak of solar activity and then gradually fades towards a minimum signifying least solar activity. In going from minima to maxima, a lot of reactions takes place in the Sun such as solar flares and solar storms. These variations in the energy emitted from Sun have a profound impact on the Earth's atmosphere and eventually on various life forms. Hence, it is important to understand

Sun and its dynamics accordingly. Thus, studying the solar influence on our atmosphere was chosen to be the primary focus of this study.

For this, the data of the solar cycle in the form of solar sun spot numbers was obtained from one of the departments of the Royal Observatory of Belgium. This Observatory comprises of a total of four departments viz. Seismology, Planetology, Astronomy and Solar Physics. Of these, the Solar Physics department closely monitors Sun and its activities with the help of Solar Influences Data Analysis Center (SIDC) [Figure 2.6]. SIDC is also known as WDC-SILSO which abbreviates as World Data Center-Sunspot Index and Long-term Solar Observations. This body provides with all sorts of data related to the Sun and its dynamics including the monthly, daily, monthly smoothed values of the sun spots.

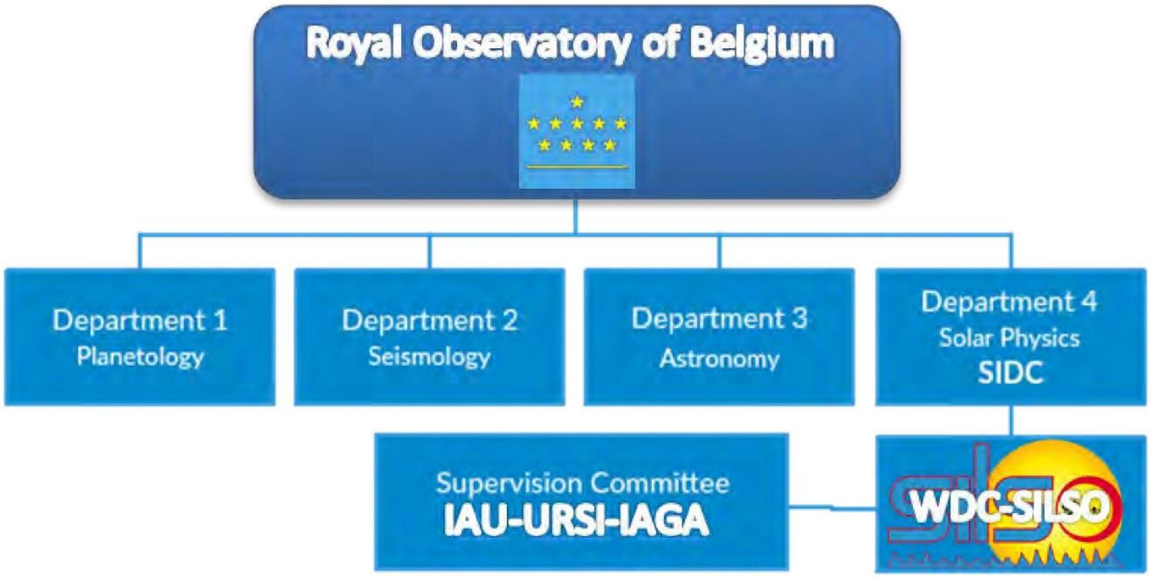


Figure 2.6: The Royal Observatory of Belgium departmental flowchart (https://www.sidc.be/SILSO/about)

The increment and decrement in the number of sun spots is a clear indication of solar activity. Sun spots are formed when the internal magnetic activity of Sun forces the radiation to emit from its surface, thereby creating a comparatively cooler region with respect to the surroundings. The increase in the solar sun spot numbers indicate excessive activity on the Sun's surface, this means that large amount of radiation is being emitted and thus it will in turn have a reasonable impact on Earth and its atmosphere. The emissions from Sun are known to influence radio communications, cause Auroras in Northern Hemisphere. In this study, we were keen to understand if the solar activities have an involvement in the meteorological processes happening in the lower atmosphere[55][56][57].

A little is known when it comes to understand the influence of solar activity in the region of Indian landmass and its isles. Thus, this became a motivation to proceed with this research study for India. We studied the solar cycle with respect to air pollutants, meteorological parameters and global circulation over the Indian region.

2.2.(d) MERRA-2

The meteorological datasets have been obtained from the Modern Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) of the Global modelling and Assimilation Office (GMAO). The Global Modelling and Assimilation Office (GMAO) is a unique organization that utilizes computer models and data assimilation techniques to enhance NASA's program of Earth Observations. The major focus of GMAO is the long-term model-based analyses of multiple datasets using a fixed assimilation system [Figure 2.7]. GMAO focusses on producing major Earth system Reanalysis covering atmosphere-biosphere-geosphere and hydrosphere.

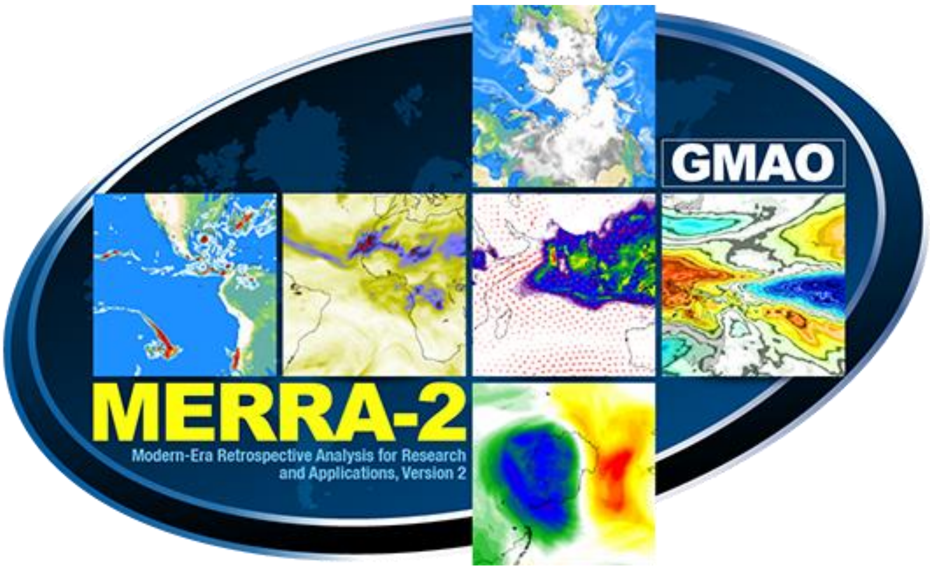


Figure 2.7: Pictorial representation of the types of reanalyses performed by MERRA-2 (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/)

The MERRA-2 datasets provide data as back as 1980s and continues to supply datasets close to real-time. Apart from the meteorological datasets, MERRA-2 also includes analysis of aerosols which have a profound impact on the circulations, using NASA observations of ozone and temperature (when available) and thus tries to represent the cryogenic processes. It makes use of the "Goddard Earth Observing System (GEOS)" family of models having a wide range of spatial scales. This organization also made use of the Earth Observing System (EOS) mission initially and later evolved to the current system of advanced observations.

GMAO primarily focusses on five major areas viz. Weather Analysis and Prediction, Seasonal-Decadal Analysis and Prediction, Reanalysis, Global Mesoscale Modelling and Observing System Science. Of these, our research focussed on the Reanalysis datasets for the Indian landmass and its isles and compared them to the solar irradiance datasets to derive our conclusions.

2.2.(e) Mapping tools

The maps used in this study have been obtained with the help of ArcMap 10.8 software which is a part of the ArcGIS software developed and maintained by Esri. ArcMap is a geographic information software which is widely used for creating maps, editing and analysing geospatial datasets [Figure 2.8]. We have used this software in a similar manner in studying the Indian landmass and its isles. The files for the region under study were obtained in the shapefile format from DIVA-GIS platform. This software not only edits, analyses but also provides data management. ArcMap also has the option of layout which allows one to design the maps as per the usage. In order to have a better visualization of the regions under study, the map of India has been used highlighting the locations under study.

2.3. Analysis Techniques

The purpose of this section is to explain the software used to explore the data and gain potential insights. The study began by taking particulate matter, solar radiation, relative humidity and Hadley cell datasets[58][59]. To gain the potential insights from these datasets we used the MATLAB software for graphical interpretation. MATLAB programming codes were run to create graphs of meteorological variables and statistical analysis was performed on them. The statistical analysis included linear fitting on the variables from which the slope was calculated and later used to generate bubble charts using MATLAB software. Apart from this, Excel software was also utilized to perform t-test for two sample means which highlighted the significance of the datasets under consideration with a confidence level of 95%. After the graphical and statistical procedure on the data, we moved on to creating a pictorial representation of the locations under study. For this, we made use of ArcMap 10.8 to portray our locations on the map of India. Thus, this software helped us in better interpretation of the data used for our research. Figure 2.9 represents the exact methodology and path used in accomplishing this research work.

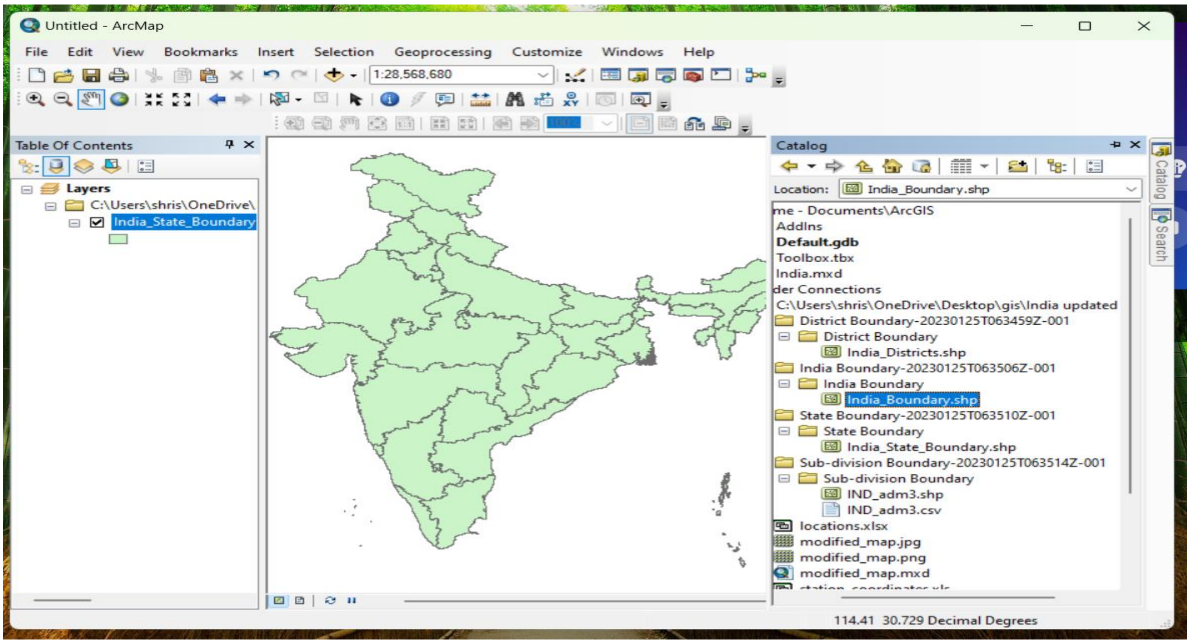


Figure 2.8: Visual representation of the ArcMap 10.8 software by Esri used to carry out our study on India.

In this chapter, we have provided a detailed description of instruments, Data derived, and the techniques. As one can visualise that reanalysis data is a state of art of technology inclusive of observations via radars, satellites, radiosonde and computer simulations etc. thus it presents a unique global feature of the atmospheric variables[60]. On the other hand, it is pertinent to mention here that solar irradiance and insolation intend to describe diurnal feature of incoming solar energy[61]. Whereas solar cycle is another feature of sun surface activity, which undergoes maxima to minima and have the capability of inducing changes on long period (~11 years) such as in cloud formation, water content, relative humidity etc. Thus, influence of sun in its different format (beginning from daily to 11 years) have variety of influences in our daily life (weather to climate), in the next chapter 3, daily variation of sun, wind, relative humidity, and temperature will be shown to examine deeply the pollutants both indoor and outdoor. Since, the role of pollutants is crucial in determining human health related aspects, hence the study shown in the upcoming chapter is of great importance from health perspective too.

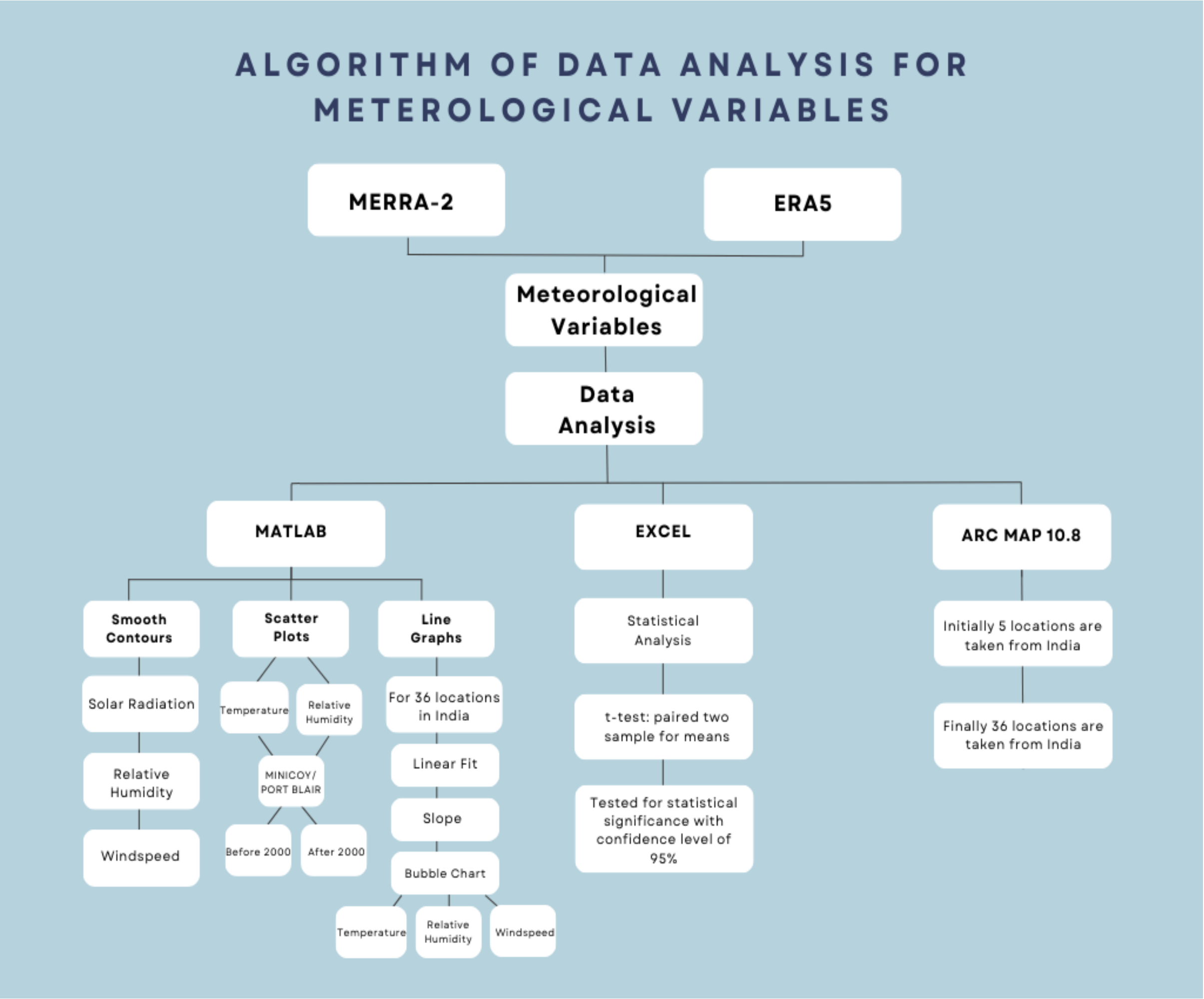


Figure 2.9: Algorithm of research plan to decipher datasets

CHAPTER 3

Solar irradiance and meteorological parameters influence on PM 2.5 observations of outdoor and indoor environment at Dwarka sub city, New Delhi

3.1. Introduction

The theme of the thesis focussed on the variation of meteorological parameters and their close association with solar insolation reaching on Earth on different time scales. All these parameters and solar insolation show a considerable change on a diurnal and seasonal basis. This particular chapter is confined mainly in studying and examining meteorological variables including particle pollution on a high temporal resolution (hourly avearged data shown in this chapter) in a particular day, benifiting us to present diurnal cycle with a difference from morning to night via peak of the solar insolation, which occurs sometime during late afternoon [30][62]. For enhancing understanding on the subject, a typical view graph is shown below, which gives a clean description of the solar irradiance measured in W/m^2, and the variation of several atmospheric variables including particulate matter ($PM_{2.5}$).

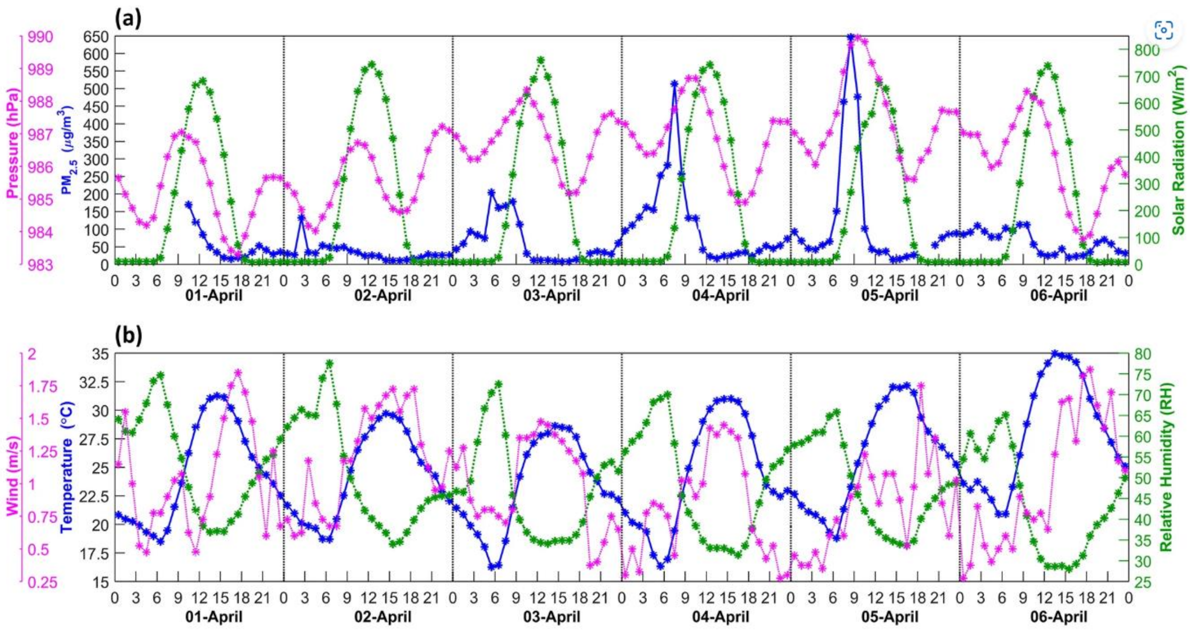


Figure 3.1: Hourly averaged $PM_{2.5}$ concentration as measured by CUPI at Dwarka in April,2020 (https://doi.org/10.1038/s41598-020-70179-8)

Eventually, the chapter is devoted to study variation of the concentration of pollutants both indoor and outdoor with influence of several meteorological variables including that of solar radiation[63][64][65]. At a later stage of this chapter, impact of large scale circulation i.e. Hadely Cell is also introduced to show the influence on dirunal and seasonal characterstics of the pollutants. The contents of this chapter are published in MAPAN-Journal of Metrology Society of India (Springer, 2023).

In the following chapter, a brief description of the particle pollution is presented. Particle pollution is an emerging area of concern as regards to human health in the present times[66][67][68]. The instances of high particulate pollution have become quite common in Delhi-NCR region, India, specially during winter period [36][69][70]. Air pollution over north India and more specifically over Delhi has attracted both public and scholastic group. Outdoor air pollution has detrimental health effects and is responsible for more than 4 million deaths every year globally[36] resulting in substantial global and regional decrements in life expectancy. India experiences high ambient air pollution, with an annual population-weighted $PM_{2.5}$ (particulate matter with diameter less than 2.5 μm) mean of 74 μg m^{-3}, and experiences the highest number of deaths[71]. Submicron aerosol composition in the world's most polluted megacity from ambient air pollution among all countries in the world, Delhi (population of about 28 million) is identified the world's most polluted megacity, with recent annual-average $PM_{2.5}$ concentrations of ∼ 140 μg m^{-3} [71][72][73].

Therefore, the ambient $PM_{2.5}$ exposure to the human being is quite large that affects our daily life. The sources of $PM_{2.5}$ are present both indoors and outdoors. Indoor activities such as cooking, frying, tobacco smoke, kerosene heaters etc produce pollutants. Since the size range of $PM_{2.5}$ is very small, thus it permits to pave way into the respiratory tract, thereby reaching the lungs. Even its short time exposure is capable of eye, nose, throat irritation, shortness of breath and many more such effects[74][75]. Prolonged exposure to $PM_{2.5}$ can prove hazardous as it can vary from showing mild symptoms to severe health conditions such as asthma. Hence, it is important to study $PM_{2.5}$ both indoor and outdoor, which is not done systematically partly due to the poor understanding that indoor air quality is better and safe. Indoor measurements of $PM_{2.5}$ is equally important and there is a need to provide the real time status of the air quality.

Anthropogenic emissions have been widely accepted as the dominant driver for $PM_{2.5}$ concentrations, whereas meteorological conditions also exert a strong influence on long-term $PM_{2.5}$ variations[76] [77][78]. Thus it is important to study $PM_{2.5}$ both indoors and outdoors. Influence of meteorological conditions on $PM_{2.5}$ concentrations are essential to understand its diurnal variability; in this regard solar radiation and relative humidity are analysed during winter to seek the influence on $PM_{2.5}$[79][80][81].

In this chapter, the concentration of $PM_{2.5}$ presented both indoor as well as outdoor using a Compact and Useful PM2.5 Instrument (CUPI) from Nov 2018 to Oct 2019. A high-time resolution data (~ 2 min interval) was recorded at Dwarka (West Delhi), New Delhi to investigate the difference in the concentration of ambient particulate matter outdoor as well as indoor. CUPI instrument records data at a very fine time scale [82][83][84].

3.2. Data used

$PM_{2.5}$ observations were taken at Dwarka (South-West Delhi), India using a Compact and Useful $PM_{2.5}$ Instrument (CUPI), which is a Panasonic sensor of small proportion including data logger. In order to ascertain the typical standards required for air quality measurements, this instrument has been duly tested and verified on behalf of Panasonic and deemed suitable for air environment monitoring. CUPI is capable of air quality measurements including HEMS (Home Energy management system) and BEMS (Building energy management system) [85]. The volume of $PM_{2.5}$ is estimated by this sensor in terms of the counts and intensities of scattered signals from single particles. This total volume once observed was then converted to mass concentration after multiplying by a factor of 1.4. This factor was determined and explained in earlier study by Nakayama et al., Dhaka et al. [76] in a recent study, during lockdown period, used this CUPI instrument and demonstrated its capability of taking observations at a fine time resolution under different environmental conditions.

The physical environment in the premise of CUPI is located on the first floor, which is about 4 m above the ground. During observations it was occupied by 2 members, with open window. The size of the room is 50 m^2. There was no kitchen usage during observations, however, it is the residential area wherein kitchen usage was common in all floors. During day a good ventilation provision of air flow was there based on the prevailing meteorological conditions [85]. The details of the instrument are given at Nakayama et al., [59][86]. For the sake brevity, we mention here the highlight of the CUPI instrument and data quality. Following is the instrument set up for the real time observations.

Instrument Set up at the observation site: An onsite measurement device "CUPI" is shown in the Figure 2.3 (Section 2.2.(b)). Upper panel depicts indoor device and for the measurement of outdoor air $PM_{2.5}$ concentration a USB cable is seen which is connected to the CUPI unit located outside the house in Dwarka sub city, New Delhi. Size of the CUPI can be visualized as it is placed on the corner of the laptop[87][88]. This is a compact size, having length 5.2 cm, width 4.5 cm, and the thickness being 2.2 cm.

3.2.(a) Data source, uncertainty, errors and novelty of the observations

Under high relative humidity conditions (>70%), the sensor has a tendency to overestimate the $PM_{2.5}$ mass concentrations compared to those measured by the standard instruments such as BAM instrument[54]. The CUPI instrument also tested in the Indian environment, and the device did not saturate even up to 800 µg/m^3 (measurement done during Diwali has shown the concentration close to 1000 µg/m^3).

The comparison of the CUPI measurement at Dwarka location with the standard instrument (BAM -1020 instrument) at US Embassy in New Delhi have shown that the observations are in good agreement. Data comparison with the BAM instrument is shown during Oct- Nov 2019.

This new device has a novelty because of its compact size and low power consumption. The power consumption of CUPI is about 0.4 W at 5 volts. It is easy to carry and install at any place as it requires minimum space. The life span of the CUPI in the most polluted environment is about nearly one year. Observations are quite reliable as mentioned above

Geographical location of the observation site is at Dwarka, New Delhi, which is the capital and a chief metropolitan city of India. It is situated between the latitude of 28°34′ N and the longitude of 77◦12′ E at an elevation of around 213.3 to 305.4 m above sea level. Atmospheric conditions of Delhi are subtropical and is characterized by a semiarid climate with summer (April–June), moderate rainfall (July–September), post–monsoon (October–November) and winter (December–February). Temperature of Delhi is characterized by a maximum of ~45–48 ◦C in June during the summer season and minimum of ~1–2° C in January during the winter season and the average rainfall is around 611 mm [89].

High resolution data of $PM_{2.5}$ were acquired using CUPI (one indoor and the other one outdoor), which were deployed to produce hourly and daily averaged data over a period from Nov 2018 to Oct 2019. Meteorological data were also used from the nearby central pollution control board (CPCB) and Delhi pollution control committee (DPCC) stations during this period. CPCB provides data quality assurance by following rigorous protocols for the sampling, analysis and calibration. Continuous ambient air quality monitoring (CAAQM) systems are used. Multipoint calibration using automatic dilution system for the calibration or/and auto calibration are in practice [59]. For the analysis of horizontal wind 'u and v' and vertical wind 'w', which is required to understand the large-scale convergence of winter season, the monthly mean ERA-5 reanalysis data for a period of 10 years from 2010 -2019 has been used. This is an improved dataset in comparison to earlier ones like ERA interim. Moreover, ERA 5 dataset surmounts the high-resolution topical analysis on 31 km horizontal resolution thereby permitting an evolution of weather systems.

3.3. Results and Discussion

3.3.(a) Diurnal variation of PM2.5 in outdoor and indoor environment during all seasons from Nov 2018 to Oct 2019

Hourly data of $PM_{2.5}$ acquired using CUPI for both outdoor and indoor environment is shown in Figure 3.2. Diurnal (00 Hrs to 24 Hrs) variation is quite evident; pollution remains quite dominant during winter season both for indoor as well as outdoor air. Concentration of $PM_{2.5}$ were found in the range of 100 – 600 µg m^{-3}, which maximizing during morning and late evenings. In the afternoon, diurnal cycle shows a decline. However, during winter when indoor and outdoor concentration is compared, significant difference is noted outdoor remains on higher side. In order to investigate the difference in the concentration, data is examined on a fine scale especially during winter. For this purpose, the difference in outdoor and indoor concentration of $PM_{2.5}$ is plotted in Figure 3.4. Upper panel shows diurnal variation of concentration of $PM_{2.5}$ throughout the year, while lower panel is focussed to show the difference during winter period, starting from Nov 2018 to Feb 2019. Owing to the fine scale data, we took the difference of indoor and outdoor daily averaged $PM_{2.5}$ concentration data to obtain fine scale view for winter season (see lower panel, Figure 3.4).

CUPI sensor-based air quality monitoring, installed at Dwarka station, revealed that diurnal variation in the indoor environment is missing and not prominent as seen in the outdoor environment. During high concentration period (Nov-Dec), indoor pollution remains less in the range of 100-200 µg m^{-3} in comparison to outdoor. Thus, the effect of meteorology (solar radiation, wind speed, and relative humidity etc.) in outdoor air pollution is much more influential than indoor environment. This is one of the key findings of this analysis. Another important finding is the intermittence presence (for about a week period) of low values of $PM_{2.5}$ (by an amount of 50-100 µg m^{-3}) in outdoor environment, which coincides with sunny days and fine weather conditions. Moreover, the 24-hour averaged graphs of both indoor and outdoor data along with the correlation coefficient between the two datasets have been incorporated for an increased comprehensibility of the comparison results[85]. The graph reflects a significant variation in the outside and inside data. The correlation coefficient (R_{xy})

between the two series is “0.71”, which suggests a high correlation as seen in time variation of PM2.5 as shown in Figure 3.3.

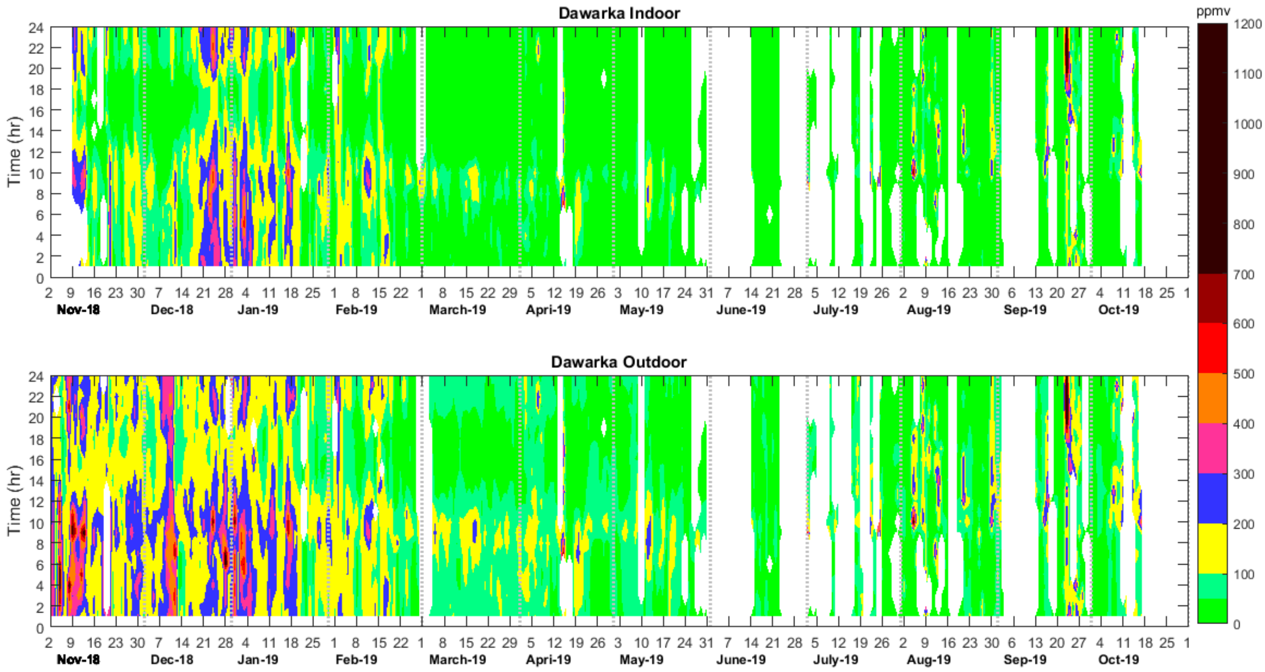


Figure 3.2: Hourly averaged $PM_{2.5}$ concentration from November 2018 till October 2019 over Dwarka, New Delhi showing both Indoor-outdoor Contour. Alongside scale depicts the colour code of the $PM_{2.5}$ concentration. On x-axis, year-long data is plotted, while on y-axis, data displayed from 00 Hrs to 24 Hrs each day.

Meteorological instruments, which are deployed by CPCB and DPCC, precisely measure with high accuracy and resolutions all the atmospheric parameters such as wind speed, wind direction, ambient temperature, relative humidity, solar radiation, and atmospheric pressure using state of the art technology. These processes involve automated transfer of data every 15 min [76]. CUPI is located in sector 4, Dwarka, which is at about 4 km away from DPCC Dwarka monitoring site.

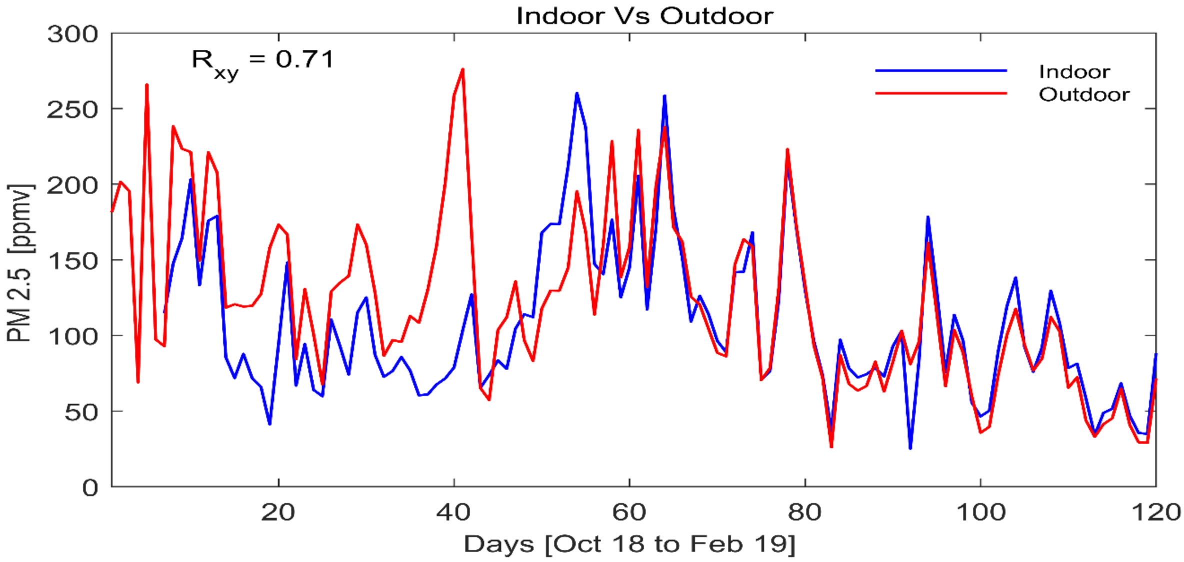


Figure 3.3: Correlation plot between the 24-hour averaged PM2.5 indoor and outdoor datasets highlighting a significant correlation of 0.71 for the period from Oct 2018 to Feb 2019.

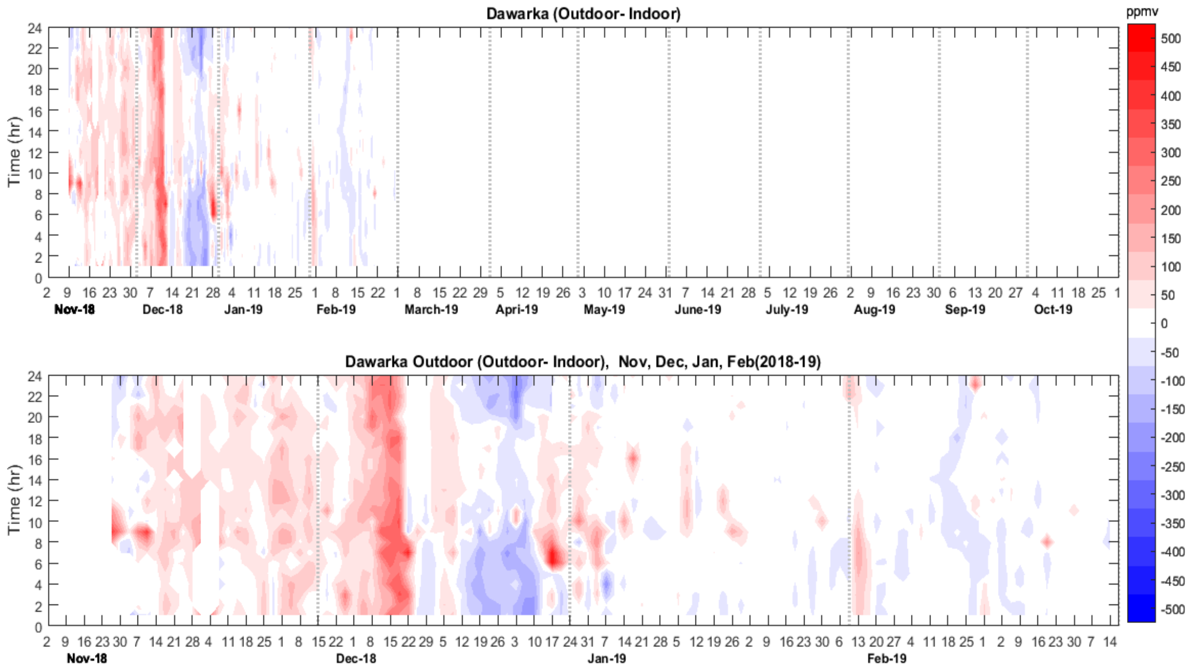


Figure 3.4: Difference of outdoor and indoor (outdoor – indoor) hourly averaged $PM_{2.5}$ concentration is shown from Nov 2018 to Oct 2019 over Dwarka, New Delhi showing both Indoor-outdoor Contour. In the bottom panel, scale is expanded (difference is highlighted during winter i.e., from Nov 2019 to Feb 2019).

3.3.(b) Diurnal variation of solar radiation and its structure from Nov 2018 to Oct 2019

Solar radiation, is one of the key parameters, which plays an important role in dispersing the pollutants[90][91][92]. High concentration of $PM_{2.5}$ has been observed during winter partly due to less reaching solar radiation on the ground. Figure 3.5 represents diurnal variation of solar radiation from Nov 2018 to Feb 2019, covering fairly a winter period. Late winter, during Jan and Feb 2019, solar radiation amounting ≥ 300 W/m^2 reaching on ground. Note that lower panel of Figure 3.4 shows not much difference to indoor and outdoor pollution. Dhaka et al. [76] have shown in the CUPI observations, during March and April 2020 (lockdown period), that solar radiation crossing 250 W/m^2 is sufficient to evaporate the tiny droplets of the morning prevalent haze. It is apparent that during Dec 2018, less solar radiation (≤ 250 W/m^2) were present hence not sufficient to disperse the pollutants. Such situation of lesser solar radiation favours more trapping of pollutants.

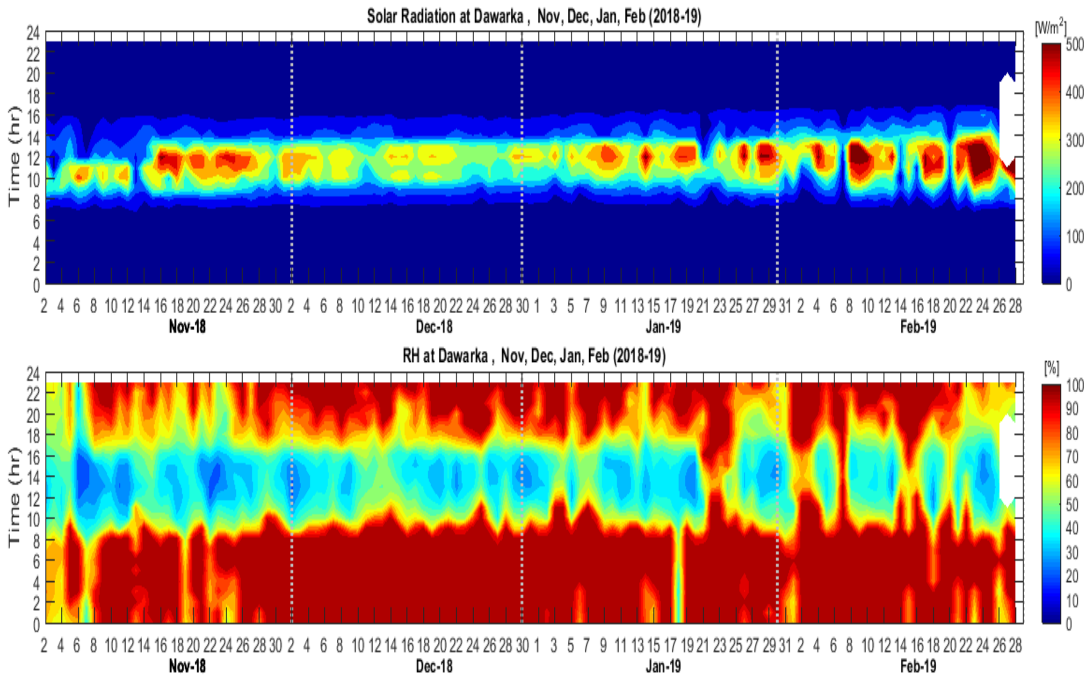


Figure 3.5: Diurnal variation of solar Radiation (upper panel) and relative humidity (lower panel) during winter (Nov-18 to Feb-19), a peak season of high $PM_{2.5}$ concentration.

Lower panel of Figure 3.5, shows that high relative humidity (≥ 70 %) is more susceptible to formation and retention of high concentration of $PM_{2.5}$. As soon as relative humidity declines after 10-11 am in the diurnal cycle during winter (that corresponds to increasing of solar radiation), the CUPI observations show less $PM_{2.5}$. Decrease in relative humidity (≤ 40-50 %) corresponds to 100-200 µg m^{-3} dip in the concentration (see Figure 3.2, upper panel). Thus, both solar radiation and relative humidity are the key atmospheric parameters, which play a significant role in the formation and dispersion of the pollutants during winter[93][94][95].

3.3.(c) Role of Hadley Cell in determining dynamics of atmosphere during winter in northern India

As mentioned above, there are meteorological factors, which prominently describes day to day weather conditions and temporal variation in the concentration of pollutants. Winter conditions in northern India experiences low wind speed, foggy environment, less solar insolation, high relative humidity, comparatively high atmospheric pressure, and low atmospheric boundary layer [36]; all these factors are favourable for developing high concentration of $PM_{2.5}$. Large scale motions including Hadley cell is also examined to check the convergence or divergence of the air mass so that one can understand the mechanism on a wider scale during winter in northern India. Monthly mean ERA-5 reanalysis data for a period of 10 years from 2010 -2019 has been used to generate zonally averaged wind from northern hemisphere to southern hemisphere to show meridional and vertical wind structure with altitude (pressure). Above mentioned features in wind are shown in Figure 3.6. Climatology of meridional and vertical wind is shown during Dec (winter) in the upper panel, while lower panel depicts the wind scenario during Aug (summer).

Convergence of air mass during winter seems prominent, this natural variability provides a way for high concentration of pollutants over northern Indian region. Red dotted vertical line represents location of Delhi, which corresponds to situation of downward wind. This is an additional feature of large-scale circulation, which creates downward motion and precisely unfavourable for dispersion of pollutants during winter season[96][97]. Air mass convergence shifts in the southern hemisphere around 20-25°S during Aug (lower panel), while there is an upward motion during summer in the northern hemisphere creating less accumulation of the pollutants.

Thus, large circulation is a mechanism which explains the tropospheric wind structure and movements which in turn acted as a tool for us to understand the stagnant atmospheric conditions prevailing over Delhi during winter [58].As seen from Figure 3.6, we may conclude that the rate of vertical dispersion is very slow and weak thus whatever movement happens it will be aligned horizontally.

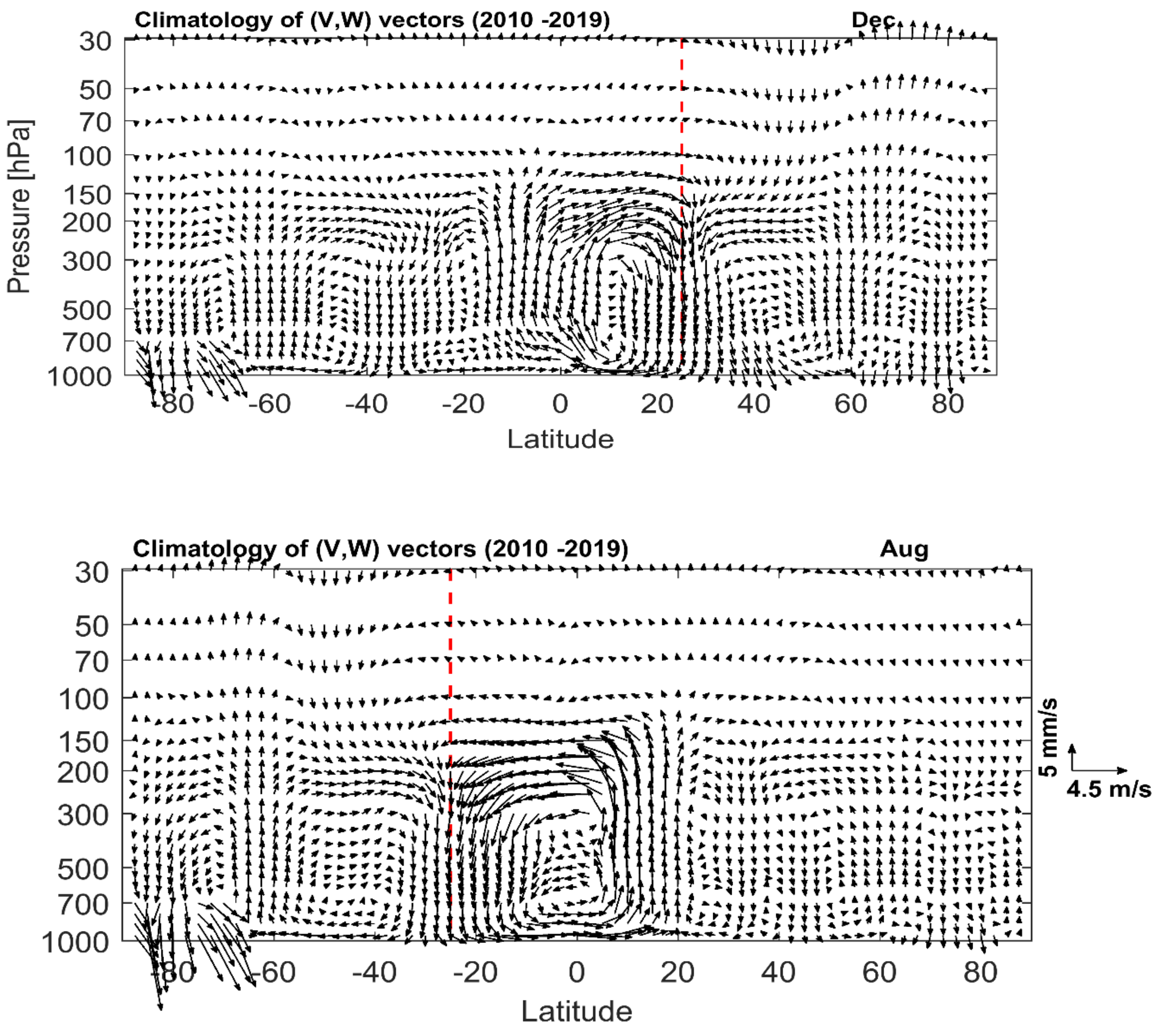


Figure 3.6: Representation of meridional and vertical wind **(**Hadley cell) for the month of December (upper panel) and August (lower panel). Wind vector (V, W) is shown from Northern pole to Southern pole from surface to 30 mb pressure level using ERA5 data. The vertical red dashed line is shown at the latitudinal position of Delhi in the upper panel. During winter, downward motions (convergence) are quite evident over Northern India which is a favourable condition for increasing pollutants.

3.3.(d) Vertical Wind patterns in determining the meteorological conditions

As burning and fog activities start terminating after December, the period after December corresponds to the little rise in the retention of indoor pollution concentration in comparison to the outdoor environment. The change in the meteorological conditions and the reduction in the transport from the North-West side of Delhi NCR contributes to this phenomenon. Therefore, there is a marked period when indoor pollution is little larger than outdoor environment.

Furthermore, it is pertinent to ascertain whether pollution levels started to decrease after mid-December and into January. This is noteworthy because pollution levels in Delhi typically remain stable during this period due to consistent emissions and meteorological conditions. Understanding any potential reasons for this decline would be significant. The abstract highlights that outdoor pollution experienced a rise from mid-November to mid-December. Investigating potential factors beyond solar radiation that may have contributed to this increase in pollution would be valuable. Meteorological conditions, such as a low dispersion rate and a shallow boundary layer height, have been identified as responsible for heightened pollution levels during December[59]. Additionally, heating activities have been recognized as a contributing factor to increased pollution during the winter months [98][26].

3.4. Summary and Concluding Remarks

Measurement of $PM_{2.5}$ is carried out simultaneously outdoors as well as indoors using a Compact and Useful $PM_{2.5}$ Instrument (CUPI) from Nov 2018 to Oct 2019. Following are the important findings of the indoor and outdoor environmental pollution.

(1) Year-long observations provide an opportunity to decipher that indoor $PM_{2.5}$ concentration increases significantly from mid-November 2018 to mid-December 2018. During this high concentration occurrence of $PM_{2.5}$, outdoor concentration was higher in the range of 100-200 $\mu g/m^3$ than indoor. Indoor pollution was less by 30-50 % in comparison to the outdoor environment.

(2) Analyses reveal that during a high pollution period, intermittently for a short period, outdoor $PM_{2.5}$ was less, which coincides with clear weather days suggesting that indoor pollution did not disperse due to a closed environment.

(3) Diurnal variation of $PM_{2.5}$ clearly shows high concentration stays until 12:00 noon in both indoor and outdoor environments, which reduces in the afternoon and again picks up in the evening.

(4) Diurnal variation of solar radiation showed a consistent increase from 9 am to 2 pm, while relative humidity declined considerably from 10 am to 4 pm (local time); these two factors correspond to less concentration in both indoor and outdoor environments. However, there is no significant difference between outdoor and indoor concentration during summer and monsoon season.

(5) As seen during Dec 2018, less solar radiation ($\leq$ 250 W/m^2) were present hence not sufficient to disperse the pollutants. Such situation of lesser solar radiation favours more

trapping of pollutants. On the other hand, high relative humidity (≥ 70 %) is more susceptible to formation and retention of high concentration of $PM_{2.5}$.

(6) During winter, convergence of air mass of (Hadley cell) taking place during winter in the northern India, thus showing a downward motion creating a condition of less dispersion of the pollutants [Figure 2.5 of Chapter 2]. This is the additional large scale circulation feature, in addition to weak wind, low solar radiation, high relative humidity, and lower atmospheric boundary layer.

3.5 Motivation for the next chapters

Having done a detailed analysis on the particle pollution and its association with meteorological variables on a different time frame including sun diurnal variability. Now, it is to be noted that Sun passes under different time cycles, and the most prominent one is of ~11year solar cycle. This cycle is described using sun spot numbers, which increases during solar maxima period along with increased intensity of solar flares and more ejections of charged particles. Recent studies suggest a link between solar activity and cloud formation [3][99][100]. Thus, solar variability may change the Earth's climate by modulating atmospheric dynamics. Though, it is quite complex to decipher the exact mechanism that links solar cycle and atmosphere; and solar cycle and clouds. We need further investigation to predict the future climate trend.

In the next chapter 4, we present 40 years of data of sun spot numbers as a measure of solar activity and the expected influence on meteorological variables are shown. Since, solar radiation depends on latitudinal position, altitude, day and season, therefore it is expected that solar influence may differ at different places.

Our next chapter is focussed on Indian region, which is covered by ocean body in the southern most part, Arabian sea in the west side and Bay of Bengal in the east side. Central Indian region has a huge landmass, and in the north, it is covered by the mountains. Due to varying topography, uniform influence of solar cycle on atmosphere and clouds may not be possible from climate point of view. Oceanic region including Indian isles needs examination of ENSO on atmospheric temperature, wind, pressure, and relative humidity. This would be helpful to understand and decipher the influence of solar cycle versus ENSO on different variables. Results are shown in the upcoming chapters.

CHAPTER 4

Solar cycle influence on wind, temperature, and surface pressure during Jan 1981- Dec 2021 over Indian region

4.1. Introduction

A solar cycle linkage is investigated on wind, temperature and surface pressure over a period of 1981 to 2021 using The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) data. Sunspot data were obtained from the Royal Observatory of Belgium (solar cycles 21 to early 25). It is determined from the analysis that solar cycle intensity decreased gradually in the last four cycles; wind data at six stations over India showed a consistent decrease in the wind speed by an amount of 0.3 to 0.6 m/s, on average 0.5 m/s. A strong association is evident between the solar cycle and wind variability while approaching closer to the equator from northern tropics; wind speed declined more clearly at latitudes around 10^0N. This consistent decline assumes a strong significance during winter in northern India i.e., the climatic trend is unfavourable for dispersing the pollutants and will have an adverse impact on air quality. On the other hand, temperature and pressure data showed a climatic increasing trend (~0.9^0C and ~1.5 - 2.0 mb) most prominently seen from 2000 to 2021 over the tropical region; which became slightly weak in extra tropical region (Delhi). It is found that solar cycle intensity and variability influenced significantly the windspeed (positive correlation ~ 0.5, with 95% confidence level). Temperature and pressure data did not show a significant relationship with sunspot numbers. These findings provide important inputs to the policy makers to take steps how the change in meteorological variables is going to impact the air quality in urban cities, which is the key for the sustainable development. The content of this study is under revision in the Journal of the Indian Society of Remote Sensing (Springer) (2024).

In the recent decades, it has been a serious concern to investigate the linkages of solar cycle influence on different atmospheric parameters mainly focused in the troposphere [15][28][29]. Kumar et al. (2018) have investigated the influences of the solar cycle on temperature using radio occultation measurements by COSMIC/FORMASAT-3 satellite covering fairly large region of the tropical belt from 2007 to 2015. Though, it has been quite challenging to detect the signal due to presence of various atmospheric oscillations such as seasonal, annual, quasi-biennial, an El Niño southern oscillations (ENSO) in the troposphere and lower stratosphere [80][34]. A consistent rise (1.5^0C) in the interannual variation of temperature was observed along with minimum to a peak in the solar cycle. However, it was an averaged feature using huge data set in the tropics, though influence of solar cycle remains dissimilar in different regions. In the earlier related studies, Dhaka et al. (2010) over Indian region, solar cycle influence was shown in temperature, using radiosonde data, in the upper tropospheric region (at 100 mb pressure level) with a magnitude of ~ 2-3^{0}C, which was prominent near 10^{0}N only, and no relation was seen over Delhi and Kolkata stations.

In the past studies, 11-year solar cycle signal was also shown in zonal wind fields. However, this signal was examined in the subtropical lower mesosphere and upper stratosphere. A strong positive zonal wind response of solar cycle, in the ERA-40 regression, was seen. This signal has been shown to come predominantly in each hemisphere by Crooks et al. (2005) ; Frame et al. (2010) and Hood et al. (1993), using rocket-sonde and NCEP data, have also shown lower mesospheric sub-tropical jet response in zonal wind anomaly near winter solstice. Such studies are missing in the lower troposphere, which seems to be much more important in the current scenario of changing climate.

There has been serious concern about the decreasing intensity of the peaks of solar cycle; sunspot numbers are on decline in the last 3-4 consecutive solar cycles (solar cycle 21, 22, 23, and 24). Therefore, it is important to examine the solar cycle influences on the meteorological parameters. Recent study by Castro et al. (2022) over the Peru region, using 5 stations in Mantaro valley, have emphasized that solar cycle effect could not be seen in temperature data, rather they concluded that anthropogenic factors dominated and were responsible for the warming. Thus, the solar cycle's direct impact on temperature on Earth's surface is not uniform.

In this chapter, we mainly focused on the climatic trend in wind speed variability on a time scale covering a few solar cycles (~ 11-year periodicity) over Indian region covering from tropical latitudes down to equatorial region. Additionally, temperature and pressure data were also analysed over the same period. Sun linkages with the lower atmosphere is apparent in the form of a natural variability of various parameters [40][35][14][3]. For the sake of brevity, we provide in the following some scientific evidences of connection between sun and lower atmosphere.

The dynamics of energy emissions from the sun and its varying magnetic field sets it aside as the fundamental source of energy for Earth. The amount of energy that we receive from the Sun just outside the Earth's atmosphere is defined as the total solar irradiance containing every possible solar wavelength [39]. Past studies have shown that the sunspots correlate with the solar radiation[39][40]. The concentrations of solar magnetic fields occurring at the photosphere are known as sunspots. These are identified by an umbra dark zone in the centre having a vertical field and surrounded by penumbra with a horizontal field [31]. Sun activity varies over a period of solar cycle, having a periodicity of nearly 11 years, and sunspot number gives us a quantitative description of the sun's energy [41]. During the Small Ice Age period no sunspots were observed, in the wake of sunspots absence, there has been a suspicion that the solar cycle has an influence on Earth's climate[42].

Furthermore, sun is the main source of energy on Earth's surface, thus it is liable to influence Earth even by a small fluctuation [43][3]. Hence, in this chapter we aim to study the influence of solar cycle on meteorological parameters over the Indian region. In a companion paper[3], solar influence showed its long-term influence on cloud formation by changing the regional circulation. It is therefore apparent to examine the solar cycle influence in the basic meteorological parameters, though it is complex and latitude dependent[40].

The main concern of the study is to contemplate about the decrease in wind speed over Indian mega cities for the last 41 years (1981-2021), and its link with the solar cycle as a natural variability. Wind speed plays a dominant role in the dispersion of the pollutants and hence its long-term change would surely be affecting air quality of the region[36]. Decrease in wind speed show an immediate impact on worsening the air quality especially during winter. Chetna et al. (2023) have shown the indication of decline in wind speed at Income Tax Office (ITO) station, New Delhi during 2007-2021, and this is supposed to be one the reason of adverse impact on non-dispersal of pollutants. This has raised a curiosity to examine the reasons for a consistent decline in wind speed and its possible association with decrease in the sunspot numbers. It is therefore, necessary to examine the reason for this decline in wind speed. We have investigated and present the results by looking at the natural variability of sunspot numbers (varying intensity of solar cycle) and the impact on meteorological (especially wind speed variability) parameters in the Indian region. Analysis over a period of 1981-2021 is presented in this chapter.

4.2. Data Methodology

Data for sunspot numbers, version 2, were taken from the world data centre for sunspot index and long-term solar observations (WDC-SILSO) from the Royal observatory of Belgium, Brussels. Both monthly and annual sunspot data was obtained from the Sunspot Index and Long-term Solar Observations (SILSO). Further we analysed solar cycles from 1981 to 2021 covering last phase of solar cycle 21 (1981-1986), three complete cycles 22 (1986-1996), 23 (1996-2008), 24 (2008-2019) and the starting phase of cycle 25 (2019-2030).

MERRA-2 reanalysis data were used for wind and temperature (2m above surface), and pressure. For the meteorological variables (wind, temperature and pressure) monthly and annual data were obtained for 6 stations over Indian region (Table 4.1) from NASA power data access platform for a period of 41 years. Data were obtained from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER) Project funded through the NASA Earth Science/Applied Science Program. Data are of version 2.0.0 accessed on 2022/11/24 and 2023/01/15. Spatial resolution of data on the latitude and longitude sections remained 0.5×0.625^{o}. Web link of the data on public domain is as follows: https://power.larc.nasa.gov/data-access-viewer/

Analysis has been performed for the behaviour of these meteorological variables and sunspots. The Excel software, MATLAB and GIS platforms are used to compute the required parameters and presentations. Using the Excel software, statistical analysis was performed to obtain both Pearson and Spearman correlation for the meteorological parameters and sunspots of all the six stations. Furthermore, we also performed the t-test for two samples mean using a level of significance of $\alpha=0.05$ portraying confidence level of 95%. The basic fitting tools and codes were applied using MATLAB to obtain linear fitting and graphs between sunspots and meteorological variables. The Geographic Information System (GIS) was used to represent all six stations on a map (Figure 4.1).

In the realm of solar cycle analysis, understanding the intricate relationship between variables under study is of great importance. To accomplish this, we have utilized two robust statistical tools, specifically the Pearson and Spearman correlation coefficients using Excel software. These methods help us to uncover the linear and monotonic relationship between the variables and thus to draw specific conclusions. The Pearson method measures linear relationship between two continuous variables by using the covariance between the variables and dividing it by the product of their standard deviations. Whereas, Spearman method is helpful to understand the strength and direction of monotonic (increasing or decreasing) relation among the variables. It ranks the data first and then calculates the Pearson coefficient to get the final results instead of using the actual data. We made use of both methods to make a robust statement as both results support each other.

4.3. Results and Discussion

Sunspot number and meteorological variables are analysed over Indian region covering from tropical belt down to equatorial region. As mentioned above the main objective of the analysis remains to correlate solar cycle activity on meteorological variables, especially to examine the influences of solar cycle on wind speed, which is less studied in comparison to temperature and other parameters[101][102][103]. Since the influence of sunspot numbers is non-uniform over the globe, therefore, in this study, it is aimed to scan it from the northern region down to southern region of India, which essentially covers tropical belt and equatorial region. Six stations are selected, which envisages four mega cities (Delhi, Kolkata, Mumbai, Chennai) and two medium size cities i.e., Kochi and Trivandrum. These locations are shown with detail in Figure 4.1; Delhi station is a representative of the inland; while others represent coastal region. Table 4.1 provides details of the latitude and longitude of the stations along with the time period of the analysis.

Table 4.1: Time period of data and locations of the stations over Indian region:

Station	Latitude N	Longitude E	Time Period
Delhi	28.62	77.22	1981-2021
Kolkata	22.56	88.36	1981-2021
Mumbai	18.92	72.82	1981-2021
Chennai	13.08	80.27	1981-2021
Kochi	9.93	76.27	1981-2021
Trivandrum	8.46	76.95	1981-2021

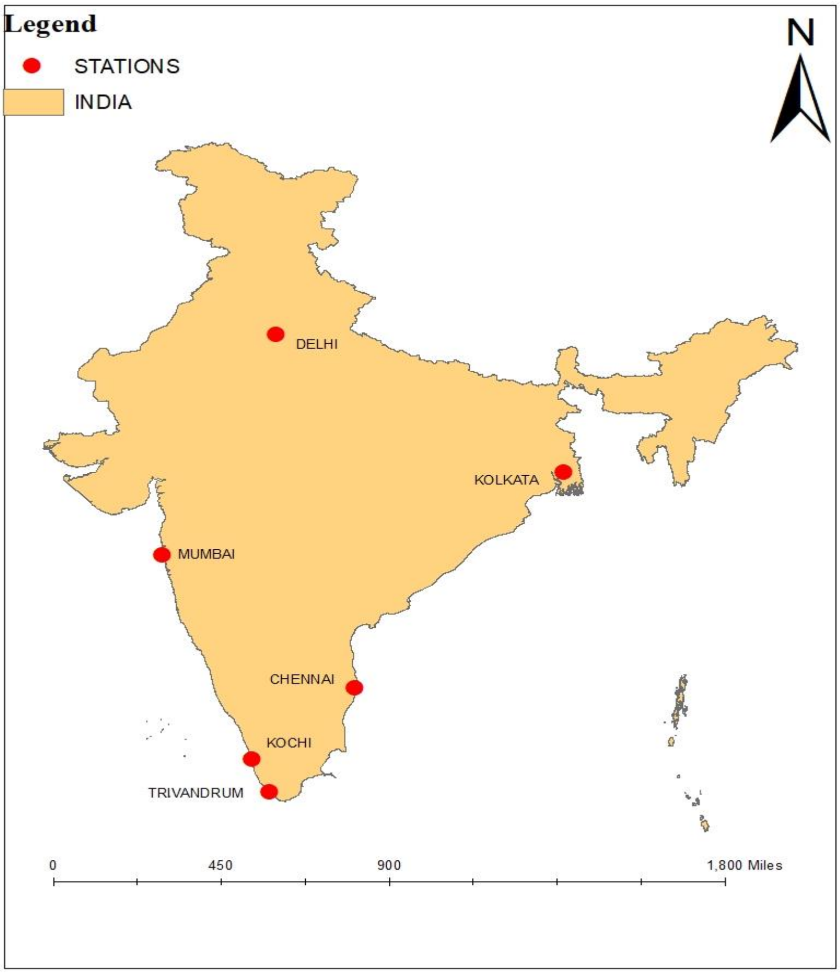


Figure 4.1: Outline of Indian map showing the locations of the stations Delhi, Kolkata, Mumbai, Chennai, Kochi, and Trivandrum. Data length and latitudes and longitudes are shown in table1.

4.3.(a) Sunspot numbers and windspeed

Wind speed (m/s) and sunspot numbers are analysed, and plotted over a period of 4 decades, that covered latter half of the solar cycle 21, full solar cycles of 22, 23, 24, and then very early phase of solar cycle 25. In Figure 4.2, for the sake of brevity, we are showing sunspot numbers and wind speed data together over two stations (Kolkata and Chennai) facing Bay of Bengal side and one station (Trivandrum) facing the Arabian Sea side. Solar cycle and wind data are shown over rest of the stations (see Annexure A).

A clear downward linear trend is evident over all stations. In general, on average ~ 0.4 m/s wind speed decreased over the period of observations. Though decline in wind speed at

Trivandrum is clearer from year 2000 onwards until 2021. Solar cycle (sunspot numbers) association is seen in the long-term variation of wind speed, which is more visible towards equatorial region[104][105][106]. For instance, Chennai and Trivandrum wind speed variability showed a close association along with solar cycle. In order to examine the correlation between the sunspot numbers and wind speed, statistical analysis is performed as mentioned in the data analyses. Correlation coefficient 'r' and coefficient of determination 'R^2' were calculated and shown below in Table 4.2.

Since there is a decline in sunspot numbers; solar cycle is showing a clear climatic downward trend; each successive cycle is less intense. Linear trend in both parameters is almost similar, rather solar cycle is more rapidly decreasing in comparison to wind speed. Computed correlation coefficients are significant, as we obtained 'p' value for each of them with the level of significance (α) 0.05. We obtained 'p' value less than 0.01, which points to statistically significant data set. One can see that spearman correction coefficient is nearly 0.5 on stations which are latitudinally located below 15^0N.

Times series contains many quasi-periodic fluctuations, which are primarily on seasonal, annual, ENSO time scale (~ 2-5 years), and longer solar cycle time scale. Power spectra using Fast Fourier transform (FFT) was deployed to detect dominant signals in sunspot numbers and wind data. This is performed to check the consistency of the predominant signal with period of about 11 years in wind data that most likely correspond to a solar cycle signal. FFT derived power spectra are shown at two stations (Chennai and Trivandrum). A dominant peak corresponds to a frequency of 8×10^{-3} month^{-1} (~ 11 years signal) is detected in wind data at Chennai (Figure 4.3) and Trivandrum (Figure 4.4) stations. This peak corresponds to a known solar cycle dominant frequency of 8×10^{-3} month^{-1} in sunspot numbers data shown in the upper panels of Figure 4.3 and 4.4. Besides this broad peak the common dominant frequencies are also noticed that coincides to sub- periods such as 1.5 to 4 years (5×10^{-2} to 2×10^{-2} month^{-1}).

Further, in order to examine the impact of urbanization, land use, and global warming etc on wind data vis-à-vis solar cycle, we have used data at a station "Car Nicobar" (located in Andaman and Nicobar Islands), which is located far from the main land. As shown in annexure B, wind and solar cycle seems following each other as shown on main land stations. There is a decline in wind speed on a station that can be considered away from high rise building and urbanization[107][108]. This further strengthen our findings of solar cycle induced change in the wind fluctuations (solar-climate connection).

Earlier results shown on association of solar cycle and temperature data using radiosonde data in the upper troposphere (at 100 hPa) by Dhaka et al., (2010) confirmed that correlation coefficient was maximum at Trivandrum; suggesting the maximum influence of solar cycle around this latitude over Indian subcontinent[109][110]. Solar radiance data maximizes on both sides of the equator maximizing near 10-15^0 latitudes (Chun et al., 2007; Kumar et al., 2017). Even in the case of wind speed data, maximum correlation coefficient with solar cycle was found over Chennai and Trivandrum re-confirming the significant influence of solar derived dynamics.

Table 4.2: Correlation coefficient 'r' between sunspot numbers and wind speed, values shown are significant at 95% (α =0.05) confidence level.

Stations	**Pearson correlation coefficient**	**Spearman correlation Coefficient**	**R^2**
Kolkata	0.31	0.35	0.19
Chennai	0.45	0.49	0.20
Trivandrum	0.46	0.49	0.21

Note that wind speed data at all stations (Figure 4.5) showed a consistent decrease over a period of 4 decades with a little slow and distinct change of linear trend at Mumbai station, which is facing the Arabian sea. Quasi-periodic fluctuations in the wind data are mainly the imprints of El Nino Southern Oscillation (ENSO) (Dhaka et al., 2010; Kumar et al. 2023). Kumar et al., (2023) highlighted that solar cycle – climate connection is operating via change in the regional circulation, thereby it may affect the wind speed pattern in the region[111][112]. These fluctuations may have effect on the linear trends as well. It is important to mention here that value of spearman coefficient (Table 4.2) is medium and not very high, though these are statistically significant values, reaffirming the robustness of the relationship.

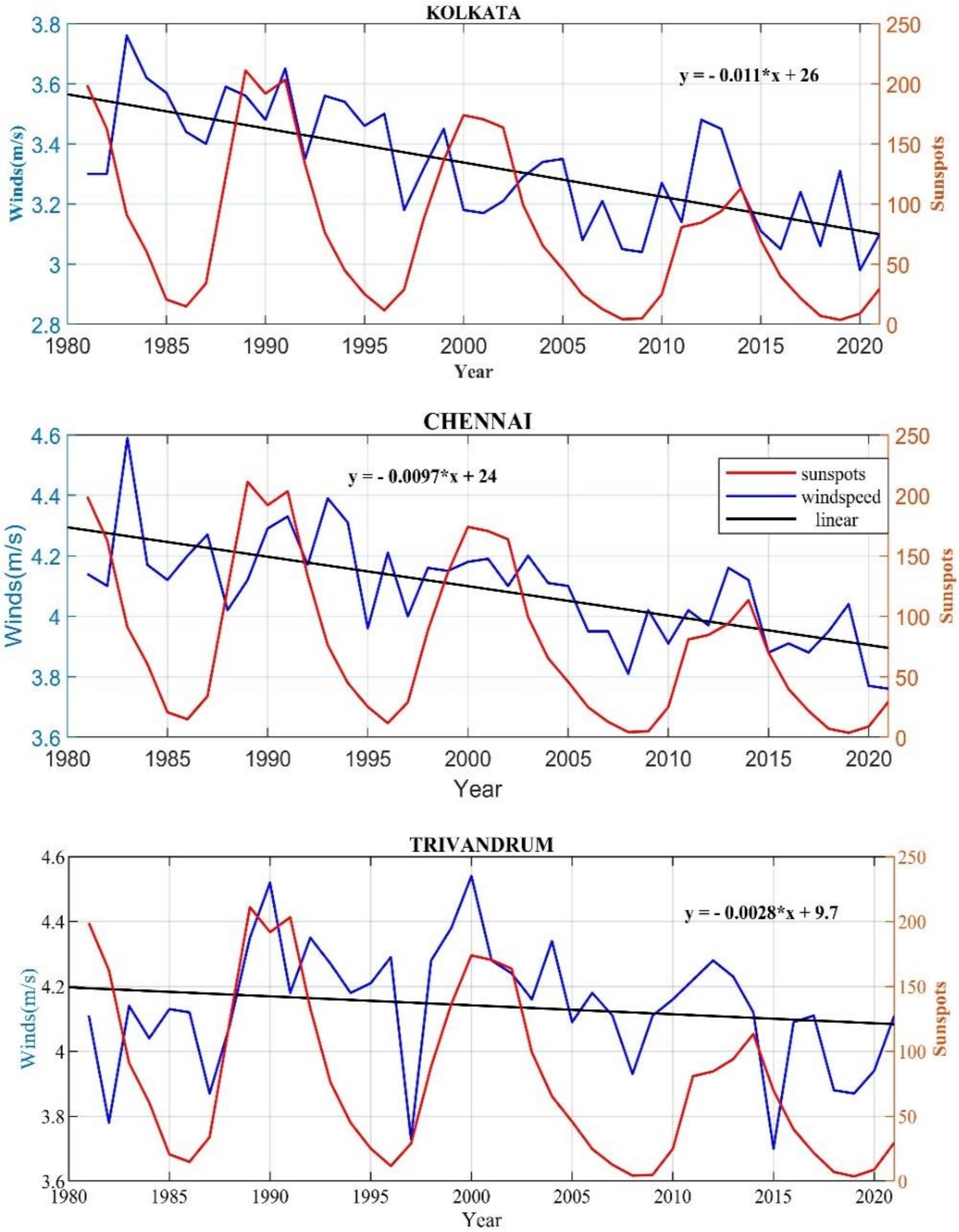


Figure 4.2: Yearly averaged sunspot numbers(red) and windspeed (blue) from 1981-2021 at the three stations in the tropical and equatorial belt in Indian region. The linear trend of sunspot number is shown in black line with a formulation representing a least square fit.

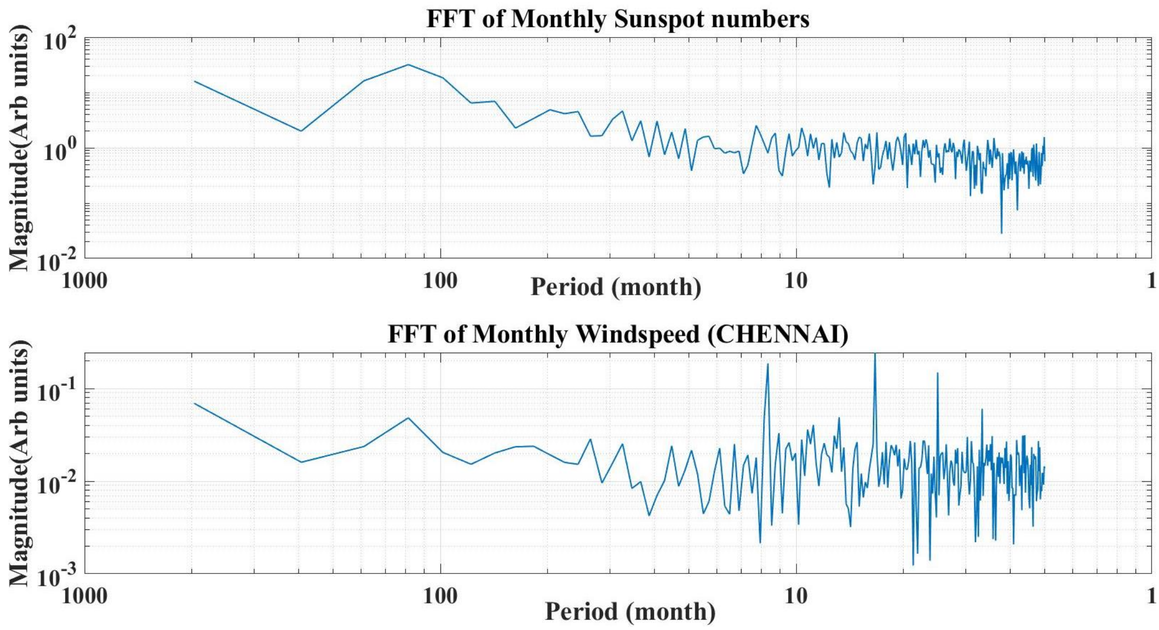


Figure 4.3: Power spectra using Fast Fourier transform (FFT) is shown on Chennai station using monthly sunspot and wind data. Upper panel (lower panel) shows different dominant frequencies (represents in periods for convenience) in sunspot (wind data); a broad peak corresponds to ~ 11 years (frequency 8×10^{-3}) and several other sub periods (corresponds to annual and semi-annual periods) are also seen.

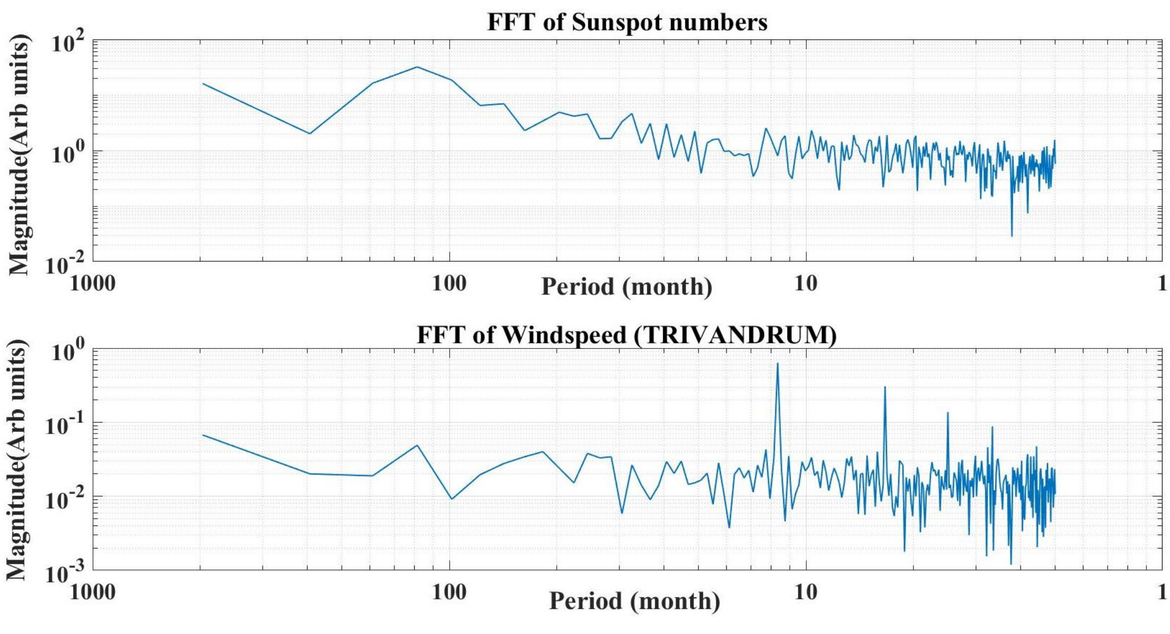


Figure 4.4: Same as Figure 4.3 but for Trivandrum station.

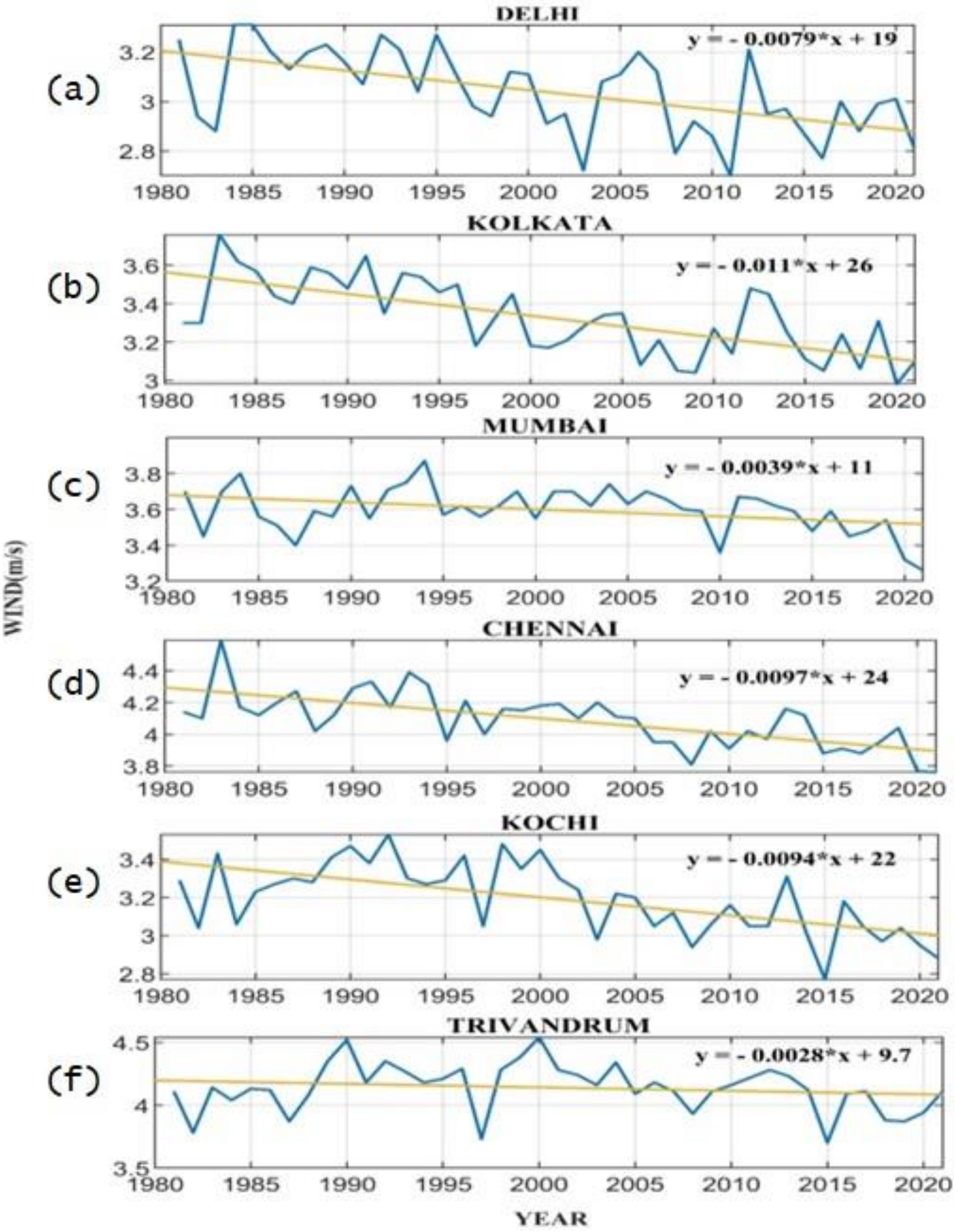


Figure 4.5: Yearly time series of the wind speed (m/s) at 6 stations over India from northern to southern regions, arranged from 28.62^0N to 8.46^0N. Linear trend is shown in yellow line with formulation representing a least square fit.

4.3.(b) Sunspot numbers and temperature

Temperature and sunspot numbers are plotted with linear trendline for all the six stations as shown in Figure 4.6. A clear upward trend is evident for 4 stations, whereas for Delhi and Chennai, a downward trend is evident. Despite the downward trend in these two stations, analysis shows very low values of correlation coefficient which seems to be insignificant. The overall trend observed in temperature variables point towards an inverse relationship with sunspot numbers (Table 4.3). The low values of ‘p’, showing high confidence level, t values are also high.

Wind data directly correlated with solar radiation rather than temperature. Rise in temperature noted at 4 stations do not show relationship with solar cycle rather suggests that anthropogenic or rise in CO_2 could be the dominant factors[31][113][114]. Natural variability of solar cycle is not affecting the ground temperature (2 m above surface) directly as seen in wind data.

The insignificant correlation, as shown in table 4.3, is similar to a recent study conducted for the valley region of Peru implying that the trends obtained for temperature are not due to solar influence only [31].

4.3.(c) Sunspot numbers and pressure

Further, analysis carried out with surface pressure, another meteorological variable. We have examined the behaviour of pressure with sunspot numbers for the period 1981-2021 and shown in Figure 4.7. Results suggest the climatic trends are slightly increasing on Delhi, Kolkata and Chennai. Correlation coefficient between sunspot numbers and pressure data (Table 4.4) show small values (near zero at Mumbai and Chennai, and fluctuating at other stations). Chetna et al, (2023), using radiosonde data, showed similar increasing linear trend in pressure over Delhi, which eventually associated with the decrease in the height of planetary boundary layer, which is unfavourable for the dispersion of the pollutants[115][116][117]. However, Kochi and Trivandrum stations show a deceasing linear trend, which is different than shown for Delhi and Kolkata, Chennai being on the transition latitude. Statistically, ‘r’ is very small. Note, that climatic linear trends in temperature and pressure follow the basic principle at all stations; showing inclination of low temperature corresponds to high pressure and vice-versa.

Table 4.3: Correlation coefficient 'r' between sunspot numbers and temperature are shown over 6 stations ranging from 28.6^0 N to 8.5^{0}N latitude range

Stations	**Pearson coefficient**	**Spearman coefficient**	**R^2**	**p-value**
Delhi	0.12	0.16	0.02	3.41752E-06
Kolkata	-0.07	-0.09	0.01	3.80764E-06
Mumbai	-0.26	-0.27	0.07	4.81862E-06
Chennai	0.01	0.01	0.00	7.02137E-06
Kochi	-0.13	-0.08	0.02	5.73356E-06
Trivandrum	-0.17	-0.12	0.03	5.13517E-06

Table 4.4: Correlation coefficient 'r' between sunspot numbers and pressure are shown over 6 stations ranging from 28.6^0 N to 8.5^{0}N latitude range

Stations	**Pearson coefficient**	**Spearman coefficient**	**R^2**	**p-value**
DELHI	-0.21	-0.15	0.0448	6.05948E-48
KOLKATA	-0.17	-0.11	0.0296	2.18416E-48
MUMBAI	0.05	0.09	0.0028	3.02804E-48
CHENNAI	-0.08	-0.03	0.0065	2.49115E-48
KOCHI	0.07	0.14	0.0046	2.28225E-48
TRIVANDRUM	0.06	0.14	0.004	2.76574E-48

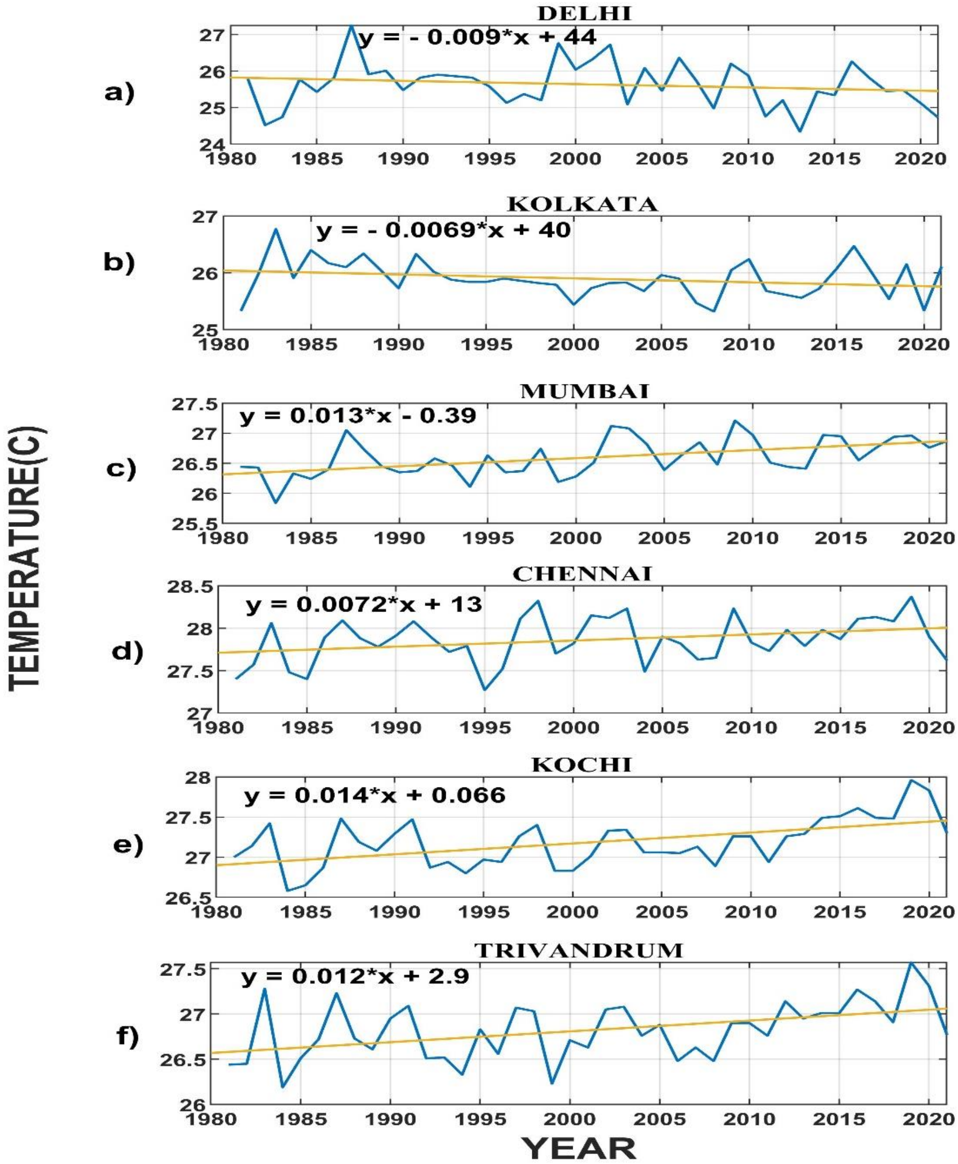


Figure 4.6: Yearly time series of the temperature at 6 stations over India from northern to southern regions, arranged from 28.62^{0}N to 8.46^{0}N. Linear trend is shown in yellow line with formulation representing a least square fit.

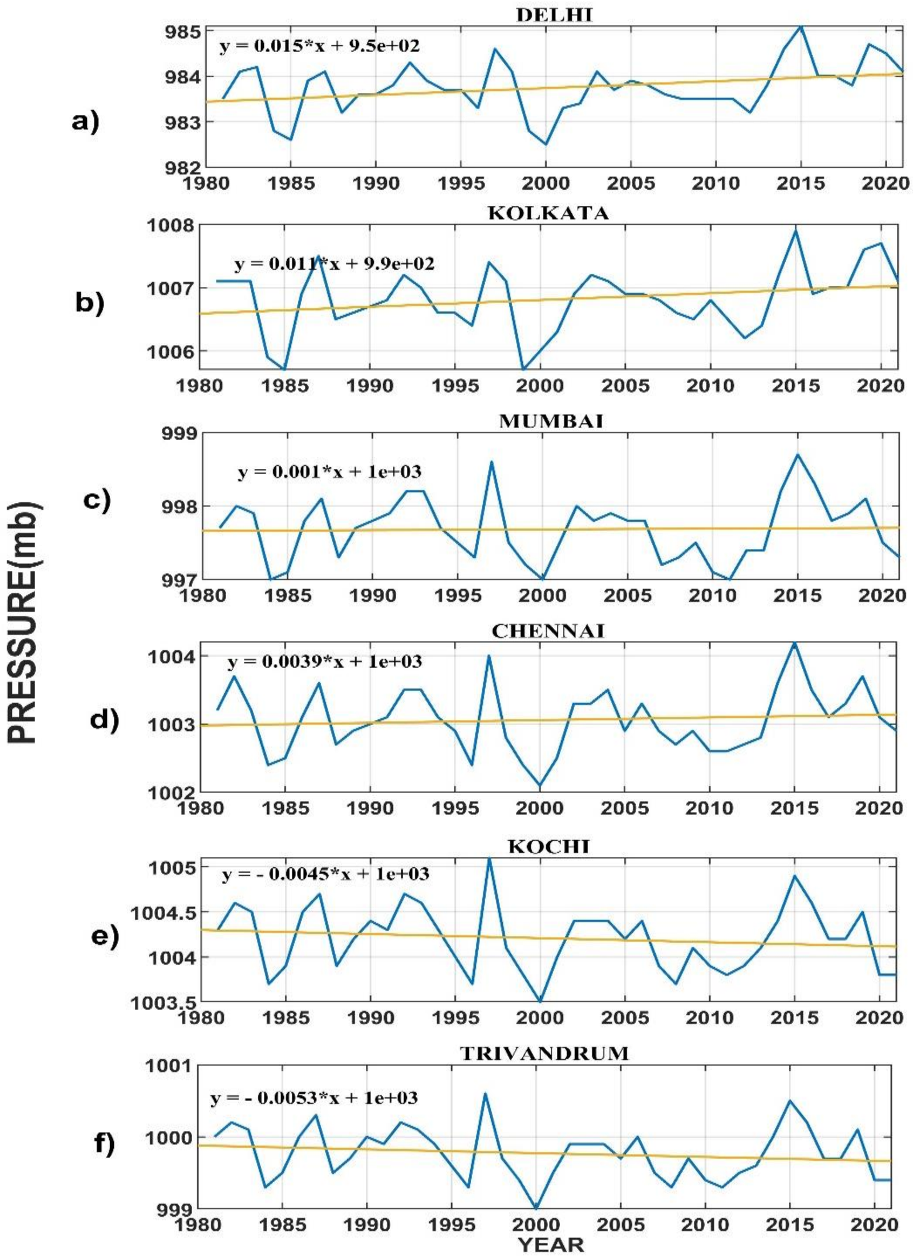


Figure 4.7: Yearly time series of pressure at 6 stations over India from northern to southern regions, arranged from 28.62^{0}N to 8.46^{0}N. Linear trend is shown in yellow line with formulation representing a least square fit.

4.4. Summary and Concluding Remarks

We examined solar cycle influence on meteorological parameters highlighting mainly wind speed data as a consequence of natural variability in sunspot numbers. Results are presented in association with sunspot numbers, which represent varying intensity of solar cycle. Decreasing climatic linear trends in wind speed data showed a positive correlation with the consistently deceasing intensity in the peak of solar cycle. Data used in this study is from 1981 to 2021, which is fairly representing nearly 4 solar cycles. Positive correlation coefficient 'r' of ~ 0.5 with 95% confidence level, is a robust indication of solar radiation influence on wind in the lower atmosphere over Indian region.

Power spectra using FFT has identified a broad peak in wind field corresponds to a dominant frequency 8×10^{-3} $month^{-1}$ (~ 11 years signal). This is similar to in sunspot numbers data (a well-known ~ 11-year solar cycle). We consider this analysis a preliminary step to detect solar activities signal on wind field on the ground level. This needs further investigation at different regions of the globe.

However, we could not detect similar features in temperature and pressure; one obvious reason seems that numerically a change in wind speed remains high (5 -12%) over a period of 4 decades while it is not so prominent in pressure (~0.04 %) and temperature (1.0 -1.8 %). Consequently, we did not decipher convincing and significant positive/ negative correlation of pressure and temperature with solar cycle suggesting that natural solar variability did not show influence on all meteorological variables rather other climatic factors such as anthropogenic activities seem dominating entities.

On the other hand, temperature and pressure for the six stations, did not show convincing and significant positive/ negative correlation with solar cycle suggesting that natural solar variability not directly influencing all meteorological variables rather other climatic factors such as anthropogenic activities are more dominating entities.

Based on the findings of previous studies[41] [3][36], as mentioned in the text, we are moving one step ahead to examine and ascertain the solar influence on wind speed in different longitude sectors. Our analysis and results suggest that solar cycle influence is not uniform rather it shows latitudinal dependence. Solar cycle influence even on cloud cover (via modifying regional circulation) on different altitudes is itself strong evidence of the natural solar-climate connection [3].

In this chapter, we are not separating the influence by the ambience conditions such as land use and land surface, seasonal cycle of monsoon and other anthropogenic conditions. There is a possibility, that these factors could be influencing partly. In order to examine this point and the impact of urbanization, land use, etc. on wind speed vis-à-vis solar cycle, we have used data at a station "Car Nicobar" (located in Andaman and Nicobar Islands), which is located far from the main land. As seen in annexure B, wind speed and solar cycle seems following each other as shown on main land stations. There is a decline in wind speed on a station that can be considered away from high rise building and urbanization. This further strengthen our findings of solar cycle induced change in the wind fluctuations (solar-climate connection). It is important to mention here that to increase the confidence level of our analysis of wind data obtained from MERRA-2, we compared this with the radiosonde data at two stations Kochi and Delhi (detailed comparison is shown in Annexure C).

Our objective was to examine the natural variability of solar insolation on the atmospheric parameters. Since it is a complex system to decipher each component, therefore we confined ourselves to the solar variability component and its modulation and link to the atmospheric parameters in this study. Further expansion of the work is required to answer the unexplored connection of natural versus anthropogenic contributions.

Annexure A

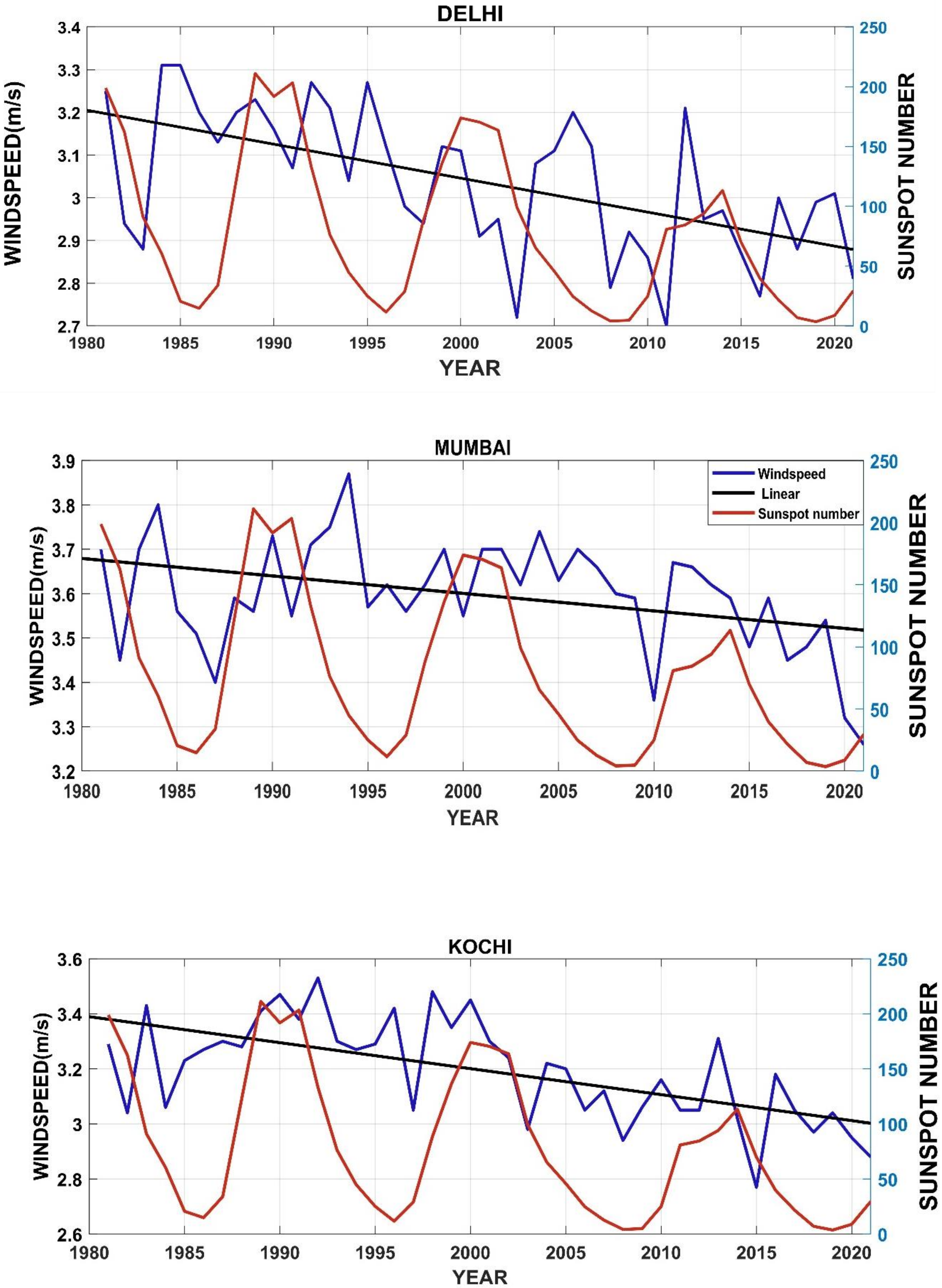


Figure 4.8: **Solar cycle and wind speed variation from 1981 to 2021 at Delhi (top panel), Mumbai (middle panel), and Kochi (lower panel).**

Annexure B

Impact of urbanisation, monsoonal activity, land use, and global warming etc. can affect wind speed. In order to eliminate these factors, we have selected a station Car Nicobar (located in Andaman and Nicobar Islands) to verify this fact; graph shown below. Surprisingly, solar cycle and wind speed data is similar to the observed on the main land stations in the tropical regions. Thus, this proved to be a major motivation for us to further our research on macroscopic domain for Indian landmass and its isles. Therefore, result at Andaman and Nicobar Islands is strengthening our results of sun – climate connection via wind speed variation. (Correlation coefficient between solar cycle and wind speed data is "0.4")

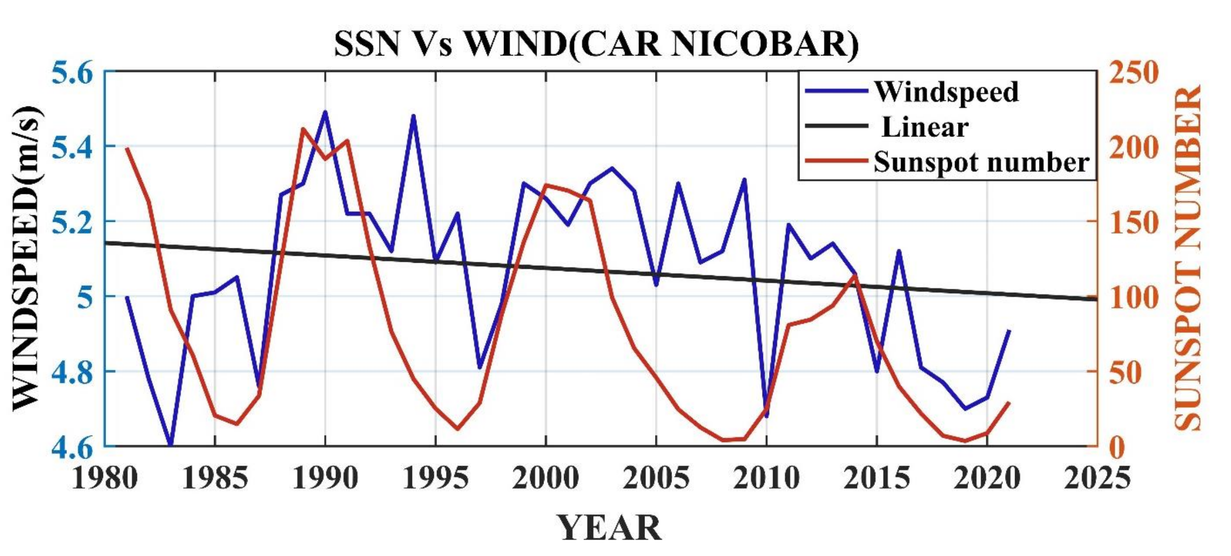


Figure 4.9: Solar sun spot number versus windspeed over Andaman and Nicobar Island.

Annexure C

Comparison of wind data obtained from MERRA-2 with the radiosonde observations over Kochi and Delhi stations.

To examine the consistency of wind data obtained from MERRA-2, radiosonde data are plotted in the bottom panels over Kochi (9.93º N, 76.26º E) – a tropical station and over Delhi (28.70º, 77.10ºE) an extratropical station. Annually averaged wind data from radiosondes at 1000 mb pressure level is used to analyse the trend; graph clearly show a decreasing trend. However, radiosonde data were available only for a limited period over Kochi (2000-2011) and Delhi Station (2007-2023). There is minor difference in the magnitude between MERRA-2 and radiosonde wind data too. It is noted that MERRA-2 data is used at 10 m, while radiosonde data is taken at a fixed pressure level of 1000 mb. Results from two data sets are in good agreement.

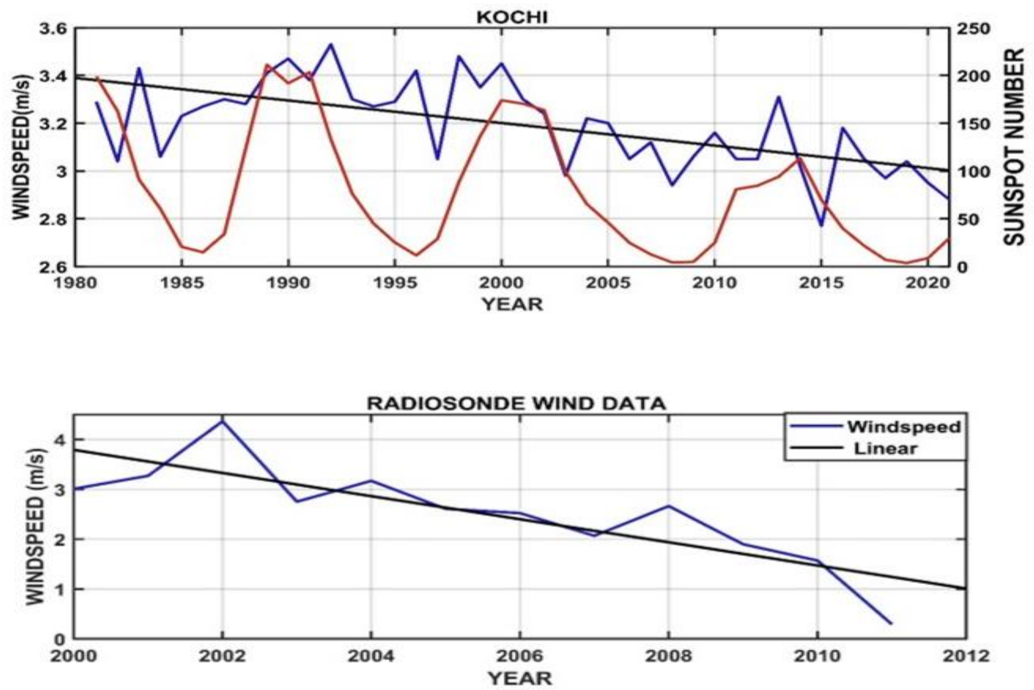
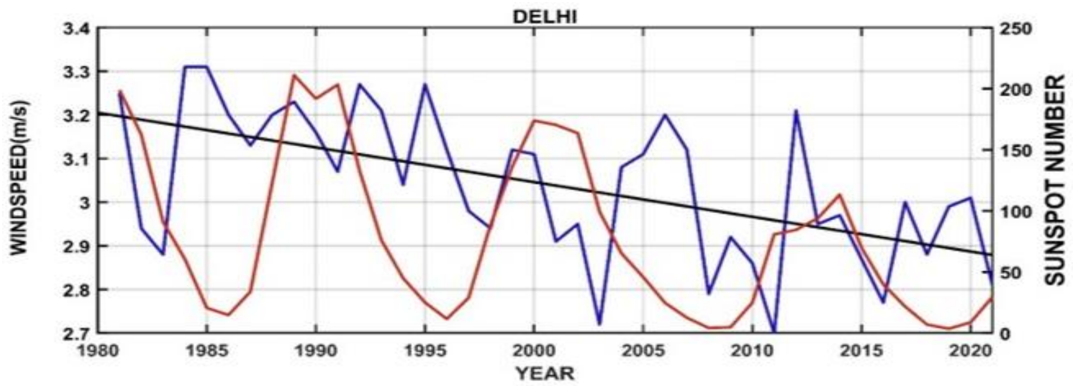


Figure 4.10: Wind data obtained from MERRA-2 and sunspot number are plotted in the upper panel. While wind from radiosonde is shown in the bottom panel from 2000 to 2011 over Kochi (9.93º N, 76.26ºE) – a tropical station. Decreasing trends in both



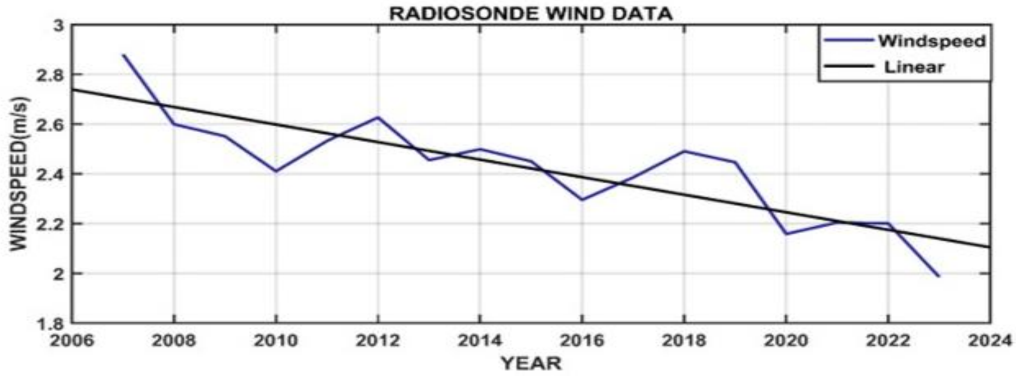


Figure 4.11: Wind data obtained from MERRA-2 and sunspot number are plotted in the upper panel. While radiosonde data are shown in the bottom panel from 2006 to 2023 over Delhi (28.70º, 77.10ºE) – a tropical station.

CHAPTER 5

Climatic trends in temperature, relative humidity, and windspeed over Indian landmass and isle in Andaman Nicobar and Lakshadweep during Jan 1981- Dec 2021

5.1. Introduction

An analysis is performed to examine trends in temperature, relative humidity, wind speed over the Indian landmass and in the isles of Lakshadweep (Arabian sea side) and Andaman and Nicobar (Bay of Bengal side) over the last 4 decades (from 1981 to 2021). MERRA-2 data deployed for revealing the large-scale fluctuations and linear trends in these parameters covering 36 locations (30 locations located over landmass and 3 each in the Arabian sea side and in the Bay of Bengal side). Surface temperature (2 m above ground) data showed a linear rise, which is more prominent after 2000, both in the Arabian side and the Bay of Bengal. Over this period, temperature increased ~ 0.7- 0.8ºC on both sides of Indian landmass. About two third locations (24 locations) in the study showed increase in temperature. However, relative humidity data on all island locations exhibited a decrease (prominent during 2000-2021). Wind speed, in general, showed larger magnitude over Andaman and Nicobar Islands (~ 5.0 m/s yearly averaged) in comparison to Arabian sea (~ 4.0 m/s) and landmass (~ 2.2 m/s). On the other hand, solar cycle (sun spot numbers) and wind speed reflects a weak positive correlation coefficient (< ~ 0.40) but statistically significant while no consequential correlation found between solar cycle and relative humidity. Detailed analysis suggests that relative humidity decreased both over landmass and islands during 2000-2021. Interestingly, surface temperature increased more rapidly between latitudes 7.03ºN and 12.91ºN after 2000. Rise in temperature and long period fluctuations (> 2-3 years) in the lower latitudes (< 15ºN) showed a strong association with ENSO signal suggesting invigorated atmosphere ocean interaction. This study has been published in MAPAN-Journal of Metrology Society of India (MAPAN-JMSI) https://doi.org/10.1007/s12647-024-00743-4 (2024).

Climatic changes and its manifestations cannot be expected to remain uniform throughout the planet, though climate change is happening globally. Due to lack of observational data, there is a mysterious representation when it comes to studying the climate at a regional scale[33]. On the other hand, at a global scale we find relatively sufficient data and ongoing research for the climatic domain. Therefore, we need to understand the climatic changes at the regional scale so that the administration and government policies be ready for future disaster management.

Indian subcontinent shows a very complex dynamics of the atmosphere-hydrosphere-lithosphere-cryosphere system[33]. Recently, it has been discussed that the regional climatic changes in the past decades have been influenced by anthropogenic factors along with the other natural process[29]. It is felt necessary to understand the climatic regimes and their changing behavioural patterns over Indian region as well as globally [3][48]. The uniqueness of the topography of India supports diverse climatic zones, flora and fauna and micro climatic areas. The World Meteorological Organization (referred to as WMO from now onwards) is a specialized agency for promoting international cooperation on atmospheric science, geophysics and climatology. With the increased frequency of weather extremes and expeditious climate change, it becomes even more important to revisit the meteorological parameters affecting the climatic trends in the Indian landmass and its surrounding isles[4].

The WMO report on 'State of Climate in Asia 2022' clearly points to the fact that Asia is warming faster than the global average. This requires deep analysis at several locations in Asia[4][49]. In the present study, we intend to decipher the trends and climatic changes in different atmospheric parameters on the Indian landmass and the surrounding sea and ocean body. We also focused on the interaction and association of various meteorological parameters by examining the changes in their pattern with time; this is analysed in the Indian landmass at several locations and at three locations in the Arabian sea and Bay of Bengal each.

Sun-climate connection has been the most debated topic, which is helping to upgrade the understanding on the natural variability of climate and its atmospheric components vis-a-vis anthropogenic factors[3][45][44]. To elaborate this thought further, we need to investigate changes in temperature, wind, and relative humidity, and their association with El- Nino Southern Oscillation (ENSO) and sunspot numbers patterns etc. in the Indian region.

ENSO and Sunspot numbers are two such natural variations, which have the significant influence over atmospheric and meteorological parameters, which is selective and more prominent in different latitudes and altitudes[15]. ENSO is a coupled ocean and atmosphere phenomenon. It is associated with periodic warming in the sea surface temperatures of the Pacific Ocean which not only changes the temperature in ocean waters, sea level pressure but also adversely affects the monsoon in India[118][47]. These findings are displaying a complex interplay between meteorological parameters and ocean-atmosphere interaction. Therefore, ENSO is expected to control the meteorological parameters, wind patterns, and prominent convergence and divergence cells present in the troposphere, namely Walker circulation and Hadley circulation. There are studies which supports changes in the ocean and sea surface temperature of anthropogenic origin, while there are evidences of influence from the sun activity over a long period, i.e. a few solar cycles[33][28][15][29][3].

Sea Surface Temperature (referred to as SST hereinafter) is the water temperature at the surface of ocean. SST plays a crucial role in earth's climate by influencing marine ecosystems and ENSO etc[48]. As per the WMO report of 2022, the SST, an indicator of changing climatic conditions, has shown an increasing trend in the Indian Ocean[4]. The overall surface ocean warming has been observed at a rate of 0.5ºC per decade in various oceanic areas including the Indian Ocean. This is almost thrice the rate of global surface ocean warming trends obtained by the WMO [4]. This report seems to be in good agreement with our results which point towards increasing temperature trends in the islands of Andamans and Lakshadweep, this would be shown in the result section.

Solar sunspot numbers, which is an indication and measure of the sun activity such as variation in its intense magnetic field and emission of strong solar flares etc., are known to influence cloud formation, temperature, and regional circulation.[119][106]. A brief description of physics of sunspot numbers is discussed by[98] . Keeping in view the above description, we analysed MERRA-2 data involving meteorological parameters such as wind speed, temperature, and relative humidity at 36 locations. In the section 2, we present data and methodology, and the location of the locations; section 3 describes results and discussion; and in the last section 4, concluding remarks are given.

5.2. Data Methodology

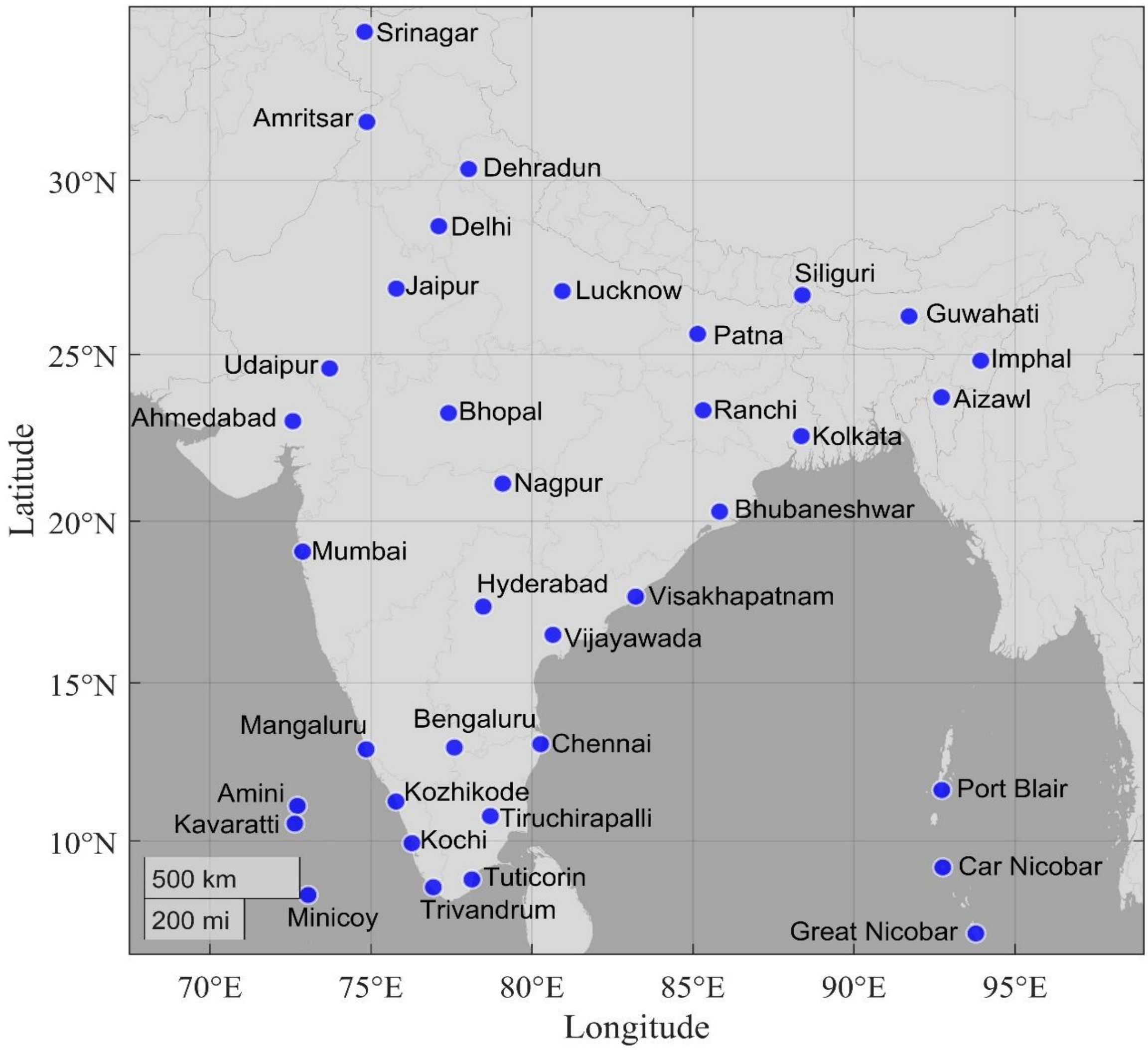


Figure 5.1: Outline of Indian map showing the location of all the stations. Data of latitude and longitudes are shown in Table 5.1.

The Modern-Era Retrospective analysis for Research and Applications (MERRA-2) is a NASA atmospheric reanalysis data for the satellite era using the Goddard Earth Observing System Model with its Atmospheric Data Assimilation System (ADAS). The MERRA-2 project focuses on historical climate analyses for a broad range of weather and climate time scales and places the NASA EOS suite of observations in a climate context. Reanalysis data is of great importance with metrological contents. Our current study makes use of MERRA-2 reanalyses integrated satellite-based data over Indian landmass and its Islands which has been extracted from the NASA power access library under the POWER project. This project provides both solar as well as meteorological datasets from NASA research for multiple needs such as agricultural, and renewable energy etc. We utilized the Power Single Point from this project which requires the latitudinal and longitudinal positions of the place to be studied. Using this we obtained datasets of wind, temperature and relative humidity for 30 locations situated over Indian landmass and 06 locations situated over the islands of Lakshadweep and Andaman and Nicobar for the purpose of our study. The slope of temperature obtained for all locations is represented as SlopeTemp and this column has been multiplied by a factor of 100 to increase the visualisation in the bubble chart for the corresponding locations (Table 5.1). The time period for our data is from 1981 to 2021 and the spatial resolution on the latitude and longitude sections remained 0.5º×0.625º. (Web link of the data on public domain is as follows: https://power.larc.nasa.gov/data-access-viewer/).

The latitudinal and longitudinal extent of this work is from 37º6´N to 8º4´ N and 68º7´ to 97º25´E, which includes major portion of Indian landmass and the islands of Lakshadweep and Andaman and Nicobar (Figure 5.1). Location of all sites are depicted on the Indian map in Figure 5.1. Yearly average data of temperature, relative humidity, wind speed, sunspot numbers and ENSO were prepared during the period 1981-2021.

In addition, data for solar sunspot numbers and ENSO were used for analysing the association with other meteorological parameters. The solar sunspot number data was retrieved from the world data centre of the Royal Observatory of Belgium. Sunspot index and Long-term Solar Observations (SILSO) was used in accessing the annual sunspot number (SSN) data for our research purpose [31]. The analysis makes use of SSN ranging from the year 1981 till 2021, thereby taking into consideration past four decades data. The true nature of the climatic impact on any meteorological data can be revealed with more accuracy provided we have sufficiently large datasets; therefore, in this chapter, we used 40 years data. ENSO data was accessed from the National Oceanic and Atmospheric Administration (NOAA) from 1981 till 2021.

In order to study the climatic trends over 36 locations, we made use of MATLAB and excel software. Analysis also includes the usage of bubble maps for providing a greater insight into the meteorological variables. These bubble charts have been prepared using MATLAB software, which are, filled bubbles displaying our data on a map. The size and colour of these bubbles help in better interpretation of the dataset. Using the Excel software, we calculated correlation coefficient for temperature and ENSO, and SSN and windspeed in order to examine the linkage between these variables [47][120][121][122] . Additionally, the t-test was performed revealing that analysis results are statistically significant with "α" being 0.05 depicting a confidence level of 95%.

5.3. Results and Discussion

5.3.(a) Time series analysis of temperature over Arabian sea, Indian landmass, and Bay of Bengal

One of the main objectives of this analysis is to determine the trends and long-term fluctuations in temperature over Andaman and Nicobar Islands, landmass, and Arabian sea (Lakshadweep). In order to examine the salient features associated with long term fluctuations, time series of annually averaged data is shown over different regions in Figure 5.2. Diverse features are seen in the northern and mid Indian region (Figure 5.2(a)) about the trend and behaviour of temperature variability during 2000-2021 in comparison to other regions. In the annexure A (Figure 5.9 and Figure 5.7), one can notice that significant changes occurred in temperature variation over several locations after year 2000. During 1981-2000, no significant warming occurred.

In Figure 5.2, we have shown four sections which depicts (a) North and mid Indian region, (b) Indian Coastal region, (c) Lakshadweep, and (d) Andaman and Nicobar during 2000-2021. Rise in temperature is prominent and linearly increasing from year 2000 onwards in Arabian sea, Andaman and Nicobar, and coastal and tropical locations over Indian landmass (warming ~ 0.8ºC). In the north and mid region (Delhi, Jaipur, and Bhopal), a slight decline in temperature is seen (cooling ~ 0.5ºC). Interestingly, large scale fluctuations (3-5 years' time scale) in the time series are noticed at all locations, these are corresponding to ENSO signals.

Table 5.1: Details of Locations over Indian landmass and its isles

Location	Lat	Long	SlopeTemp	SLOPE(C3×100) values multiplied by a factor of 100
Srinagar	34.0837	74.7973	0.0098	0.98
Amritsar	31.634	74.8723	-0.0026	-0.26
Delhi	28.7041	77.1025	-0.0086	-0.86
Dehradun	30.3165	78.0322	0.0027	0.27
Jaipur	26.9124	75.7873	-0.0028	-0.28
Udaipur	24.5854	73.7125	0.0000017	0.00017
Ahmedabad	23.0225	72.5714	-0.0096	-0.96
Lucknow	26.8467	80.9462	-0.013	-1.3
Patna	25.5941	85.1376	-0.0047	-0.47
Siliguri	26.7271	88.3953	-0.0036	-0.36
Guwahati	26.1158	91.7086	0.013	1.3
Imphal	24.817	93.9368	0.0075	0.75
Aizawl	23.7307	92.7173	-0.017	-1.7
Kolkata	22.5726	88.3639	-0.0069	-0.69
Bhubaneshwar	20.2961	85.8245	-0.0096	-0.96
Bhopal	23.2599	77.4126	0.005	0.5
Ranchi	23.3441	85.3096	-0.0014	-0.14
Mumbai	19.076	72.8777	0.013	1.3
Mangaluru	12.9141	74.856	0.013	1.3
Kozhikode	11.2588	75.7804	0.014	1.4
Kochi	9.9312	76.2673	0.014	1.4
Trivandrum	8.5241	76.9366	0.012	1.2
Tuticorin	8.7642	78.1348	0.033	3.3
Tiruchirappalli	10.7905	78.7047	0.0034	0.34
Chennai	13.0827	80.2707	0.0072	0.72
Vijayawada	16.5062	80.648	-0.00055	-0.055
Visakhapatnam	17.6868	83.2185	0.0039	0.39
Hyderabad	17.385	78.4867	0.0052	0.52
Bengaluru	12.9716	77.5946	0.0085	0.85
Nagpur	21.1458	79.0882	-0.0033	-0.33
Amini	11.1142	72.7204	0.022	2.2
Kavaratti	10.5593	72.6358	0.022	2.2
Minicoy	8.274	73.0496	0.02	2
Port Blair	11.6234	92.7265	0.02	2
Car Nicobar	9.1573	92.7581	0.019	1.9
Great Nicobar	7.0346	93.7842	0.017	1.7

ENSO signatures in the temperature variation are quite strong over Andaman and Nicobar, slightly weaker in Arabians sea, nevertheless present over land region too.

Dhaka et al., (2010) have shown strong ENSO event's influence on temperature in 1991 (a peak was observed in temperature data) over Trivandrum and Cochin, which is an indicative of a close association of both the parameters.

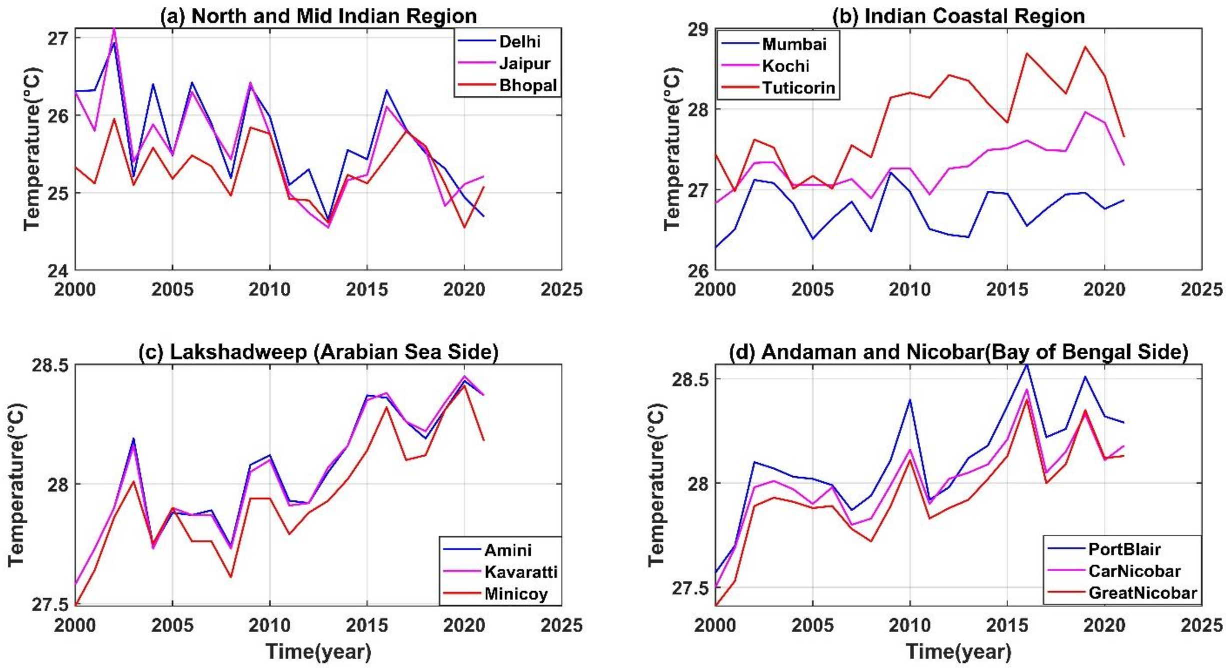


Figure 5.2: Times series of the annually averaged temperature data over (a) North and mid Indian region, (b) Indian Coastal region, (c) Lakshadweep, and (d) Andaman and Nicobar during 2000-2021. Rise in temperature is prominent and linearly increasing from year 2000 onwards. In the north and mid region (Delhi, Jaipur, and Bhopal), a slight decline in temperature is seen; while in the coastal and landmass region (Mumbai Kochi, and Tuticorin), and the stations located in Arabian sea and Bay of Bengal show a clear rise in temperature.

5.3.(b) Warming/ cooling analysis at 36 stations over Indian landmass and adjoint islands

As mentioned above, there is a diverse effect of temperature variability over Indian region; stations located in north and mid India experience a slight cooling while warming signals are obtained at other locations, which are more prominent below 20ºN. Since there are large number of locations, therefore presenting time series at all locations would be a very crowded scenario; thus, we have presented the warming and cooling quantitatively using a unique method of showing the value of slope fitted linearly in the time series of temperature data. Larger slope denotes warming (which is shown in the form of a red and orange bubble). MATLAB software has been used to visualise data in the form of bubbles over 36 locations spread in the landmass, Arabian Sea and Bay of Bengal.

The bubble chart shown in Figure 5.3 represents slope of linearly fitted temperature data post year 2000. This chart helped us in data visualization in a holistic way across different geographic locations over Indian landmass and its islands. In Figure 5.3, larger bubbles represent higher values and smaller ones show lower values of slopes. We have considered our datasets in three sections viz. red colour points to a high slope (slope values are from 1.64 to 3.31 ~ from 58.62° to 73.18°), orange colour to a medium slope (-0.03 to 1.64 ~ from -1.71° to 58.62°) and the yellow colour point towards low slope values (-1.7 to -0.03 ~ from -59.53° to -1.71°). Positive values of the slopes denote warming and the negative one's cooling.

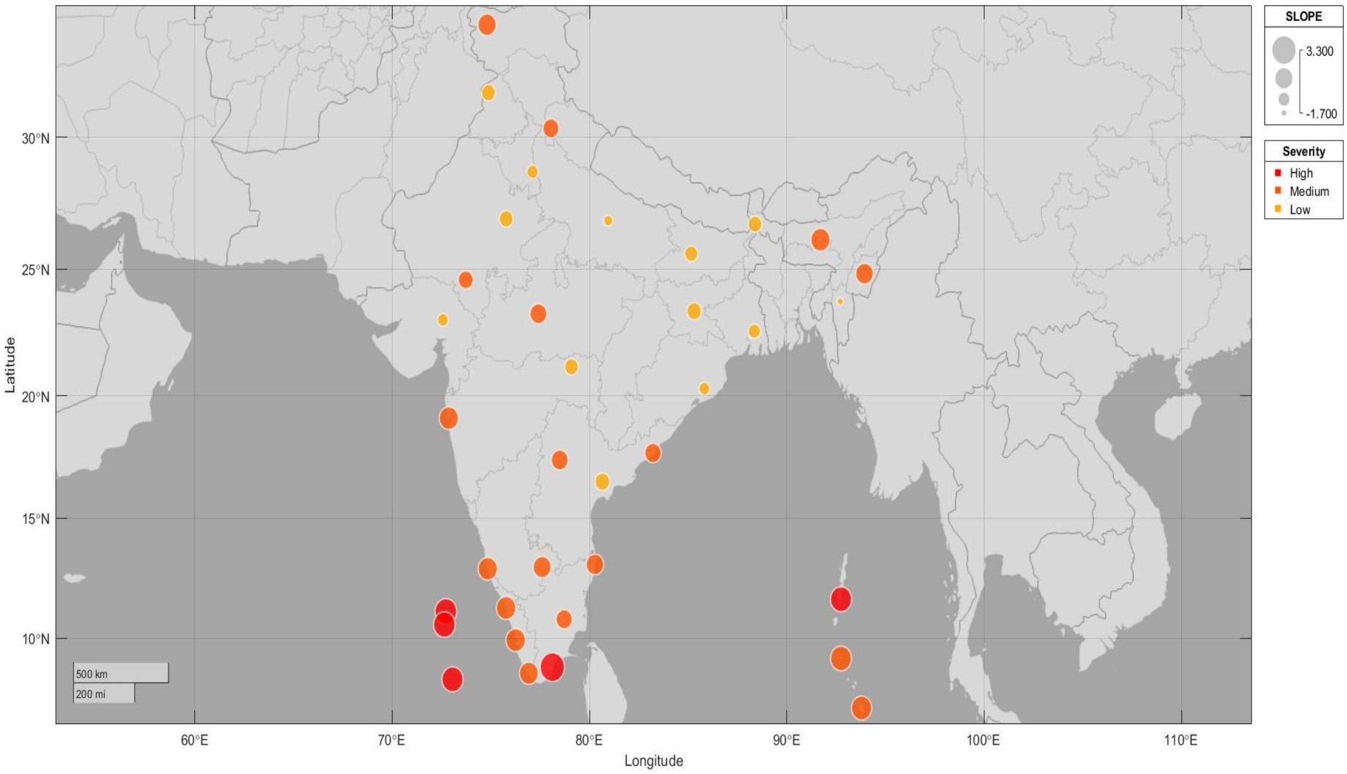


Figure 5.3: A bubble chart illustrating the linearly fitted temperature trends across 36 locations, spanning the Indian landmass, the Arabian Sea (Lakshadweep), and the Bay of Bengal (Andaman and Nicobar Islands), for the period 1981 to 2021. Positive slopes represent an increase in temperature, while negative slopes indicate a decrease. The color scale is used to differentiate temperature trends, with yellow signifying a decline or minimal change (slight cooling or neutral trend), and red and orange indicating a rise in temperature (warming).

This type of representation has been effective in identifying the warming hotspots and also to identify the regional variations across India. Conclusively, one can discern from Figure 5.3 that about 21 locations showed a warming, mostly located in the Arabian sea and Andaman and Nicobar, and tropical Indian region (< 20° N).

5.3.(c) Relative humidity at Indian landmass and adjoint islands

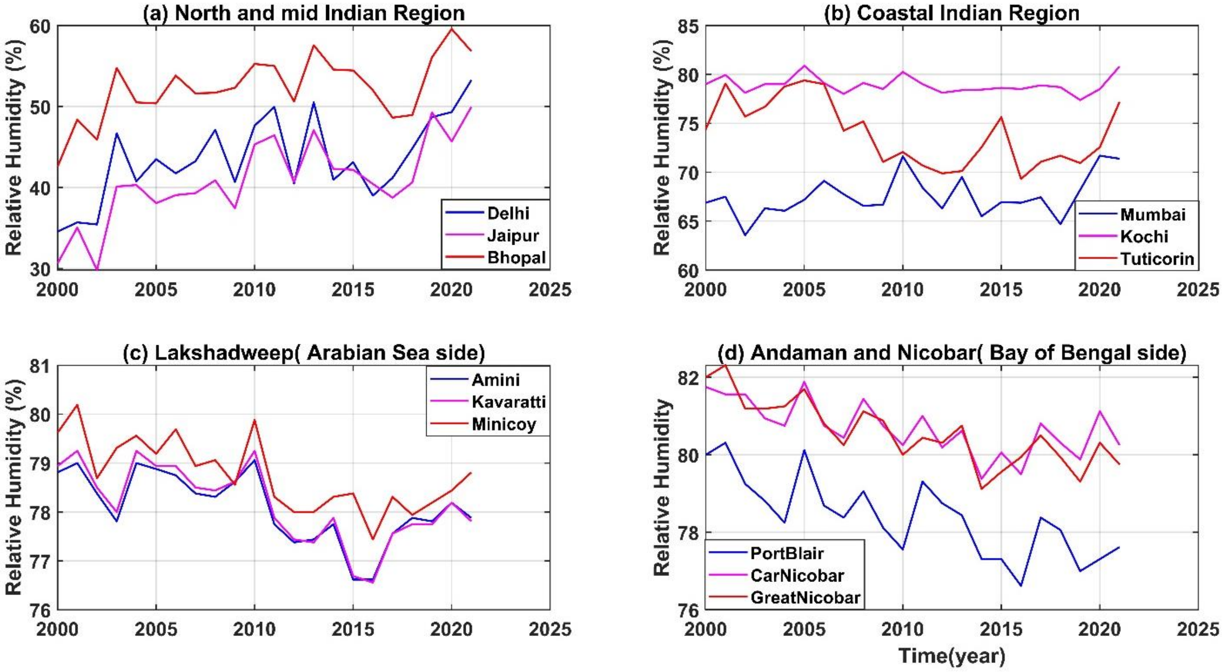


Figure 5.4: Same as Figure 5.2 but for relative humidity.

In Figure 5.4, we have shown four sections which depicts relative humidity for (a) North and mid Indian region, (b) Indian Coastal region, (c) Lakshadweep, and (d) Andaman and Nicobar during 2000-2021. Decline (rise) in relative humidity (temperature) noted which is decreasing (increasing) from year 2000 onwards in Arabian sea, Andaman and Nicobar, and coastal and tropical locations over Indian landmass. In the north and mid region (Delhi, Jaipur, and Bhopal), a slight rise in relative humidity (decline in temperature) is seen, which is nearly 10 percent over 2 decades. This is interesting to note that rise in relative humidity is accompanied by cooling in temperature (~ 0.5°C) over this period in north and mid region. This is in good agreement with ideal conditions of atmospheric parameters. Further, it is seen that large scale fluctuations (3-5 years' time scale of ENSO) in the time series are noticed more prominently in the Arabian sea and Bay of Bengal. However, the decline is clearly seen in the relative humidity, which is less in magnitude (~ 2 percent). It is important to mention here that during 1981 to 2000 the trends are totally different than obtained post 2000 to 2021 (See Figure 5.10). Scenario of two decades of post 2000 (2000-2021) are showing contrast behaviour in both the parameters i.e., temperature and relative humidity (Figure 5.9).

5.3.(d) Winds at Indian landmass and adjoint islands

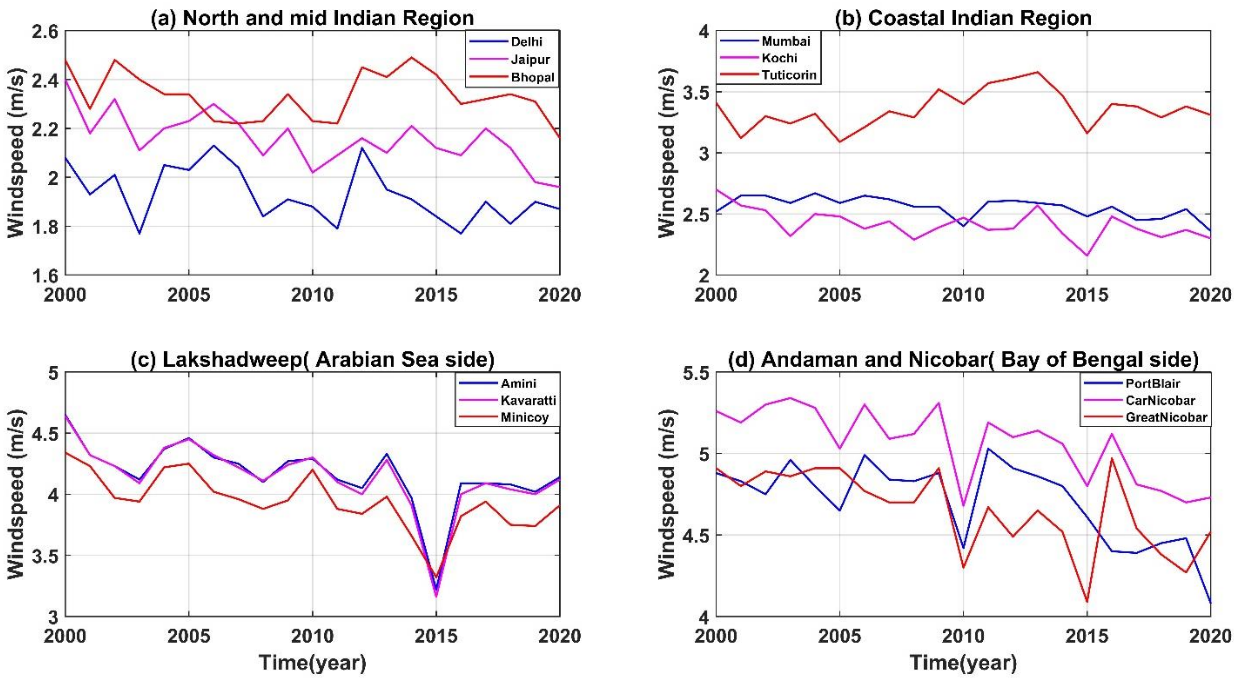


Figure 5.5: Same as Figure 5.2 but for windspeed

In Figure 5.5, winds variations are shown. Description is given in four sections which are focussed on (a) North and mid Indian region, (b) Indian Coastal region, (c) Lakshadweep, and (d) Andaman and Nicobar during 2000-2021. Consistent decline (~ 0.5 m/s) is noted in all sections from 2000 onwards in the Arabian sea, Andaman and Nicobar, and coastal and tropical locations over Indian landmass. In the north and mid region (Delhi, Jaipur, and Bhopal), winds blown at a speed of roughly half than the Arabian and Andaman and Nicobar Islands.

This is interesting to note that winds in coastal region (shown in Fig 5.5(b)) do not show any significant change over two decades. Further, it is seen that large scale fluctuations (3-5 years' time scale of ENSO) in the time series are noticed more prominently in the Arabian sea and Bay of Bengal. It is important to mention here that during 1981 to 2000 the trends are totally different than obtained post 2000 to 2021 (Figure 5.6 & 5.7 IN ANNEXURE). Scenario of two decades of (2000-2021) are showing a link with (Figure 5.6 & 5.7) solar cycle, there is a decline in wind speed with decreasing sun spot numbers in all locations of Arabian Sea and Andaman Nicobar. However, solar cycle (~ 11-year cycle) does not conform with temperature in this period, temperature increased rapidly post 2000, a clear sign of global warming in the Indian Ocean. Rather, changes in temperature are coinciding with ENSO signal.

5.4. Summary and Concluding Remarks

An analysis is performed to examine trends in temperature, relative humidity, wind speed trends over the Indian landmass and in the isles of Lakshadweep and Andaman and Nicobar over the last 4 decades (from 1981 to 2021).

MERRA-2 data deployed over 36 locations (30 located over landmass) while 3 locations each on the Arabian sea side as well as on the Bay of Bengal side. Coverage of large number of locations enabled us to provide a comprehensive picture of the change in meteorological parameters with solar cycle influence and ENSO signal. Results in terms of trends are more clear post 2000, making study a meaningful document from climatic point of view. Following are the highlights and concluding remarks of the results:

(1) Temperature showed a linear rise, which is more prominent after 2000, in the Arabian side as well as in the Bay of Bengal. Over the period (2000-2021), temperature increased about 0.7- 0.8ºC on both sides of Indian landmass. About 2/3 locations in the study showed increase in temperature. Rise in temperature is clearer towards lower latitude (< 15ºN) region.

(2) Relative humidity data on all island locations showed a decrease (prominent during 2000-2021). These findings are displaying a complex interplay between meteorological parameters. A clear rising trend in temperature during 2000-2021 may reduce the relative humidity and hence the decreasing trend is observed. It is evident that warm air can possess more water vapor (moisture) than cold air, so with the same amount of absolute/specific humidity, airmass will possess a higher (lower) relative humidity for cold (warm) airmass. In our results we have shown that temperature is linearly

increasing thus pointing towards warmer air which eventually led to lower relative humidity, our analysis confirms this finding.

(3) Quasi-periodic fluctuations in temperature (which is linearly rising) closely relates with the ENSO parameter (correlation coefficient ‘r’ using 6 locations spread over Arabian sea and Andaman and Nicobar ranged from ~ 0.20 to 0.34; which is statistically significant and larger towards Andaman Islands). The value of ‘r’ increased considerably (> 0.5) during 2000-2021, confirming rapid increase in temperature along with ENSO linear rise with synchronized quasi-periodic fluctuations.

(4) Wind speed, in general, showed larger magnitude over Andaman and Nicobar Islands (~ 5.0 m/s yearly averaged) in comparison to Arabian sea (~ 4.0 m/s) and also over landmass (~ 2.2 m/s).

(5) Solar cycle (sun spot numbers) and wind speed reflects a weak positive correlation coefficient (< ~ 0.40) though it is statistically significant while no consequential correlation found between solar cycle and relative humidity.

(6) Detailed analysis suggests that relative humidity decreased over landmass as well islands during 2000-2021, temperature increased more rapidly between latitudes 7.03ºN and 12.91ºN post 2000 in comparison to other stations located above 15ºN.

(7) Increase in temperature in the lower latitudes (< 15ºN) seems thoroughly controlled by the ENSO signal.

ANNEXURE

5.4.(a) Solar sunspot numbers and wind

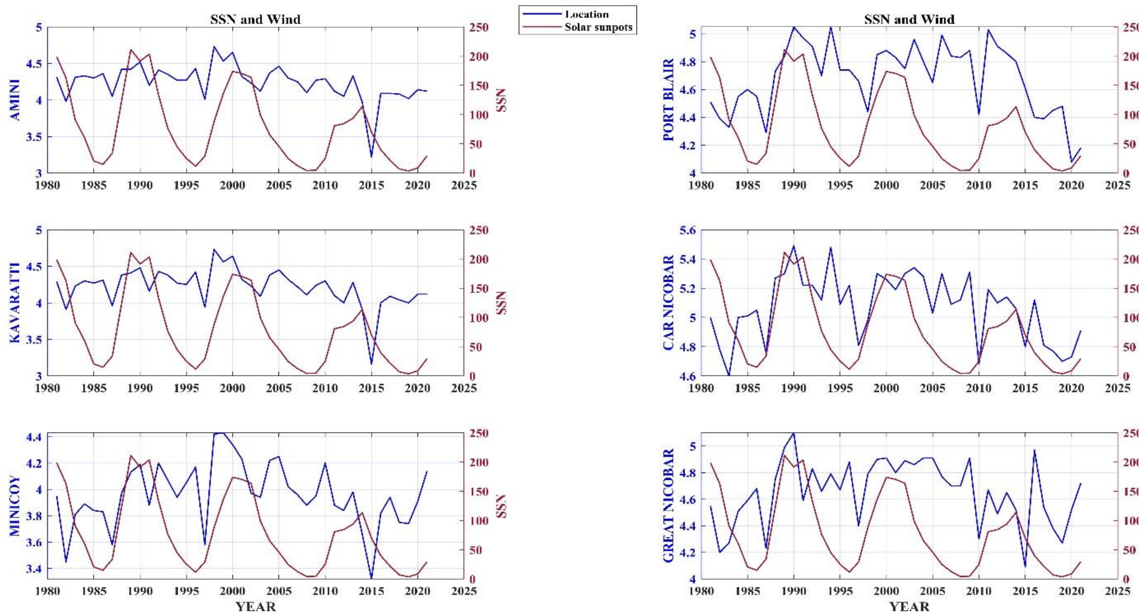


Figure 5.6: Solar sun spot cycle and wind variability over Arabian sea and Andaman and Nicobar.

5.4.(b) El-Nino Southern Oscillation Phenomenon and Temperature

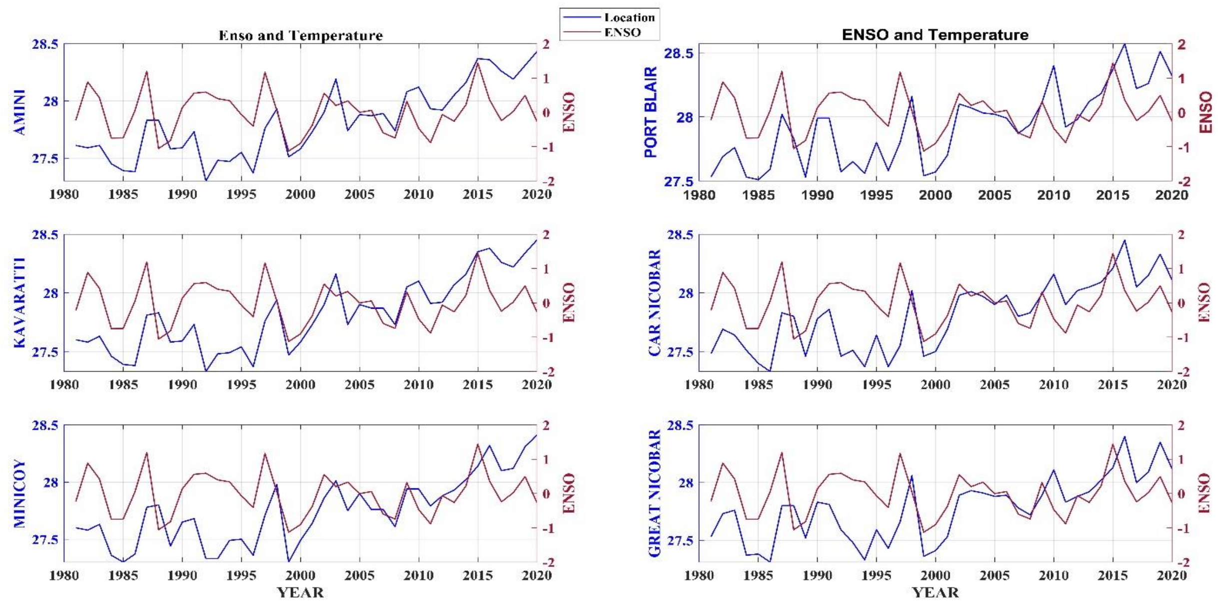


Figure 5.7: ENSO and Temperature variation

5.4.(c) Solar sunspot numbers and temperature

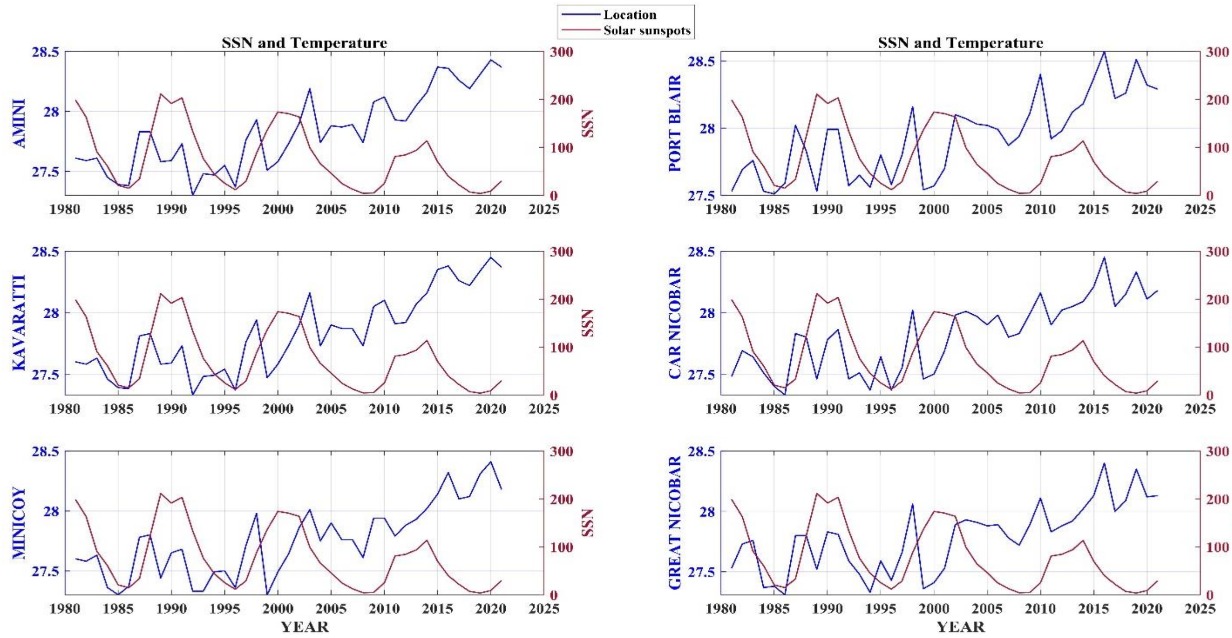


Figure 5.8: Solar sun spot numbers and temperature variability during 1981-2021.

5.4.(d) Temperature and Relative Humidity in two different time frames; one is from 1981 to 2000 and the second from 2000 to 2021.

1)**Temperature**

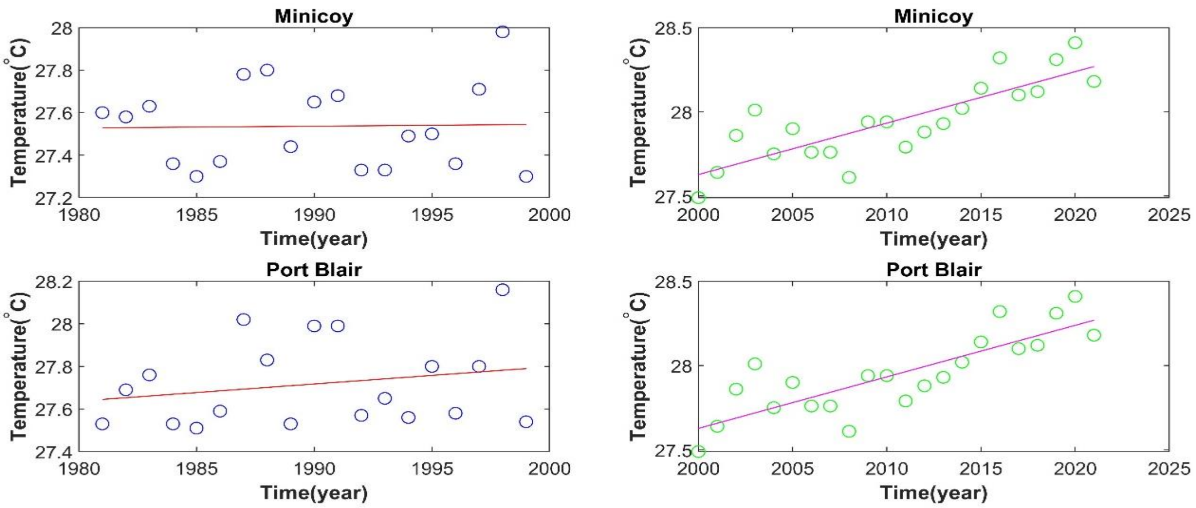


Figure 5.9: Linear fit and slope is shown in temperature over a) Minicoy (top panel), b) over Port Blair (lower panel). Left panels denote the time period from 1981 to 2000, and the right panel from the year 2000 to 2021. Two distinct slopes are clearly seen. Increasing trend in temperature is evident after year 2000. About 0.7°C rise in temperature noted after 2000 over Minicoy and Port Blair.

2)**Relative Humidity**

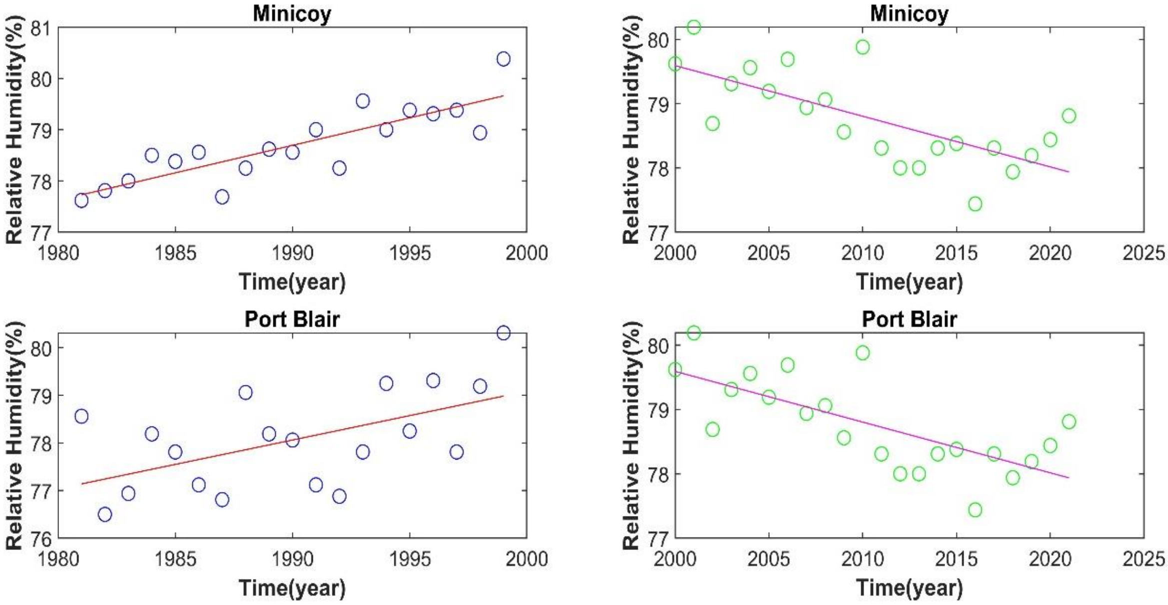


Figure 5.10: Linear fit and slope is shown in relative humidity over a) Minicoy (top panel), b) over Port Blair (lower panel). Left panels denote the time period from 1981 to 2000, and the right panel from the year 2000 to 2021. Two distinct slopes are clearly seen before and after 2000. Increasing trend in relative humidity is evident from 1981 to 2000; after a clear decline noticed beyond 2000. About 1.5% decline in relative humidity noticed beyond 2000 over Minicoy and Port Blair.

CHAPTER 6

SUMMARY AND FUTURE TERMINOLOGY

In conclusion, this thesis "Solar Influence on meteorological parameters in the lower atmosphere" has explored the intricate relationship between Sun and the meteorological parameters for the Indian region. The Sun and its activities on a macro time period have been extensively studied both for Indian landmass and the islands in its territory. It began with the study of particulate pollution over North India and its possible connection with Sun and the meteorological parameters. Further, it paved its way towards the study of Indian meteorology and the impacts of Sun on it. Our research was divided into three specific areas viz. solar insolation and particle pollution linkage, secondly, it aimed to focus on understanding the influence of Sun on meteorology for six stations over India. Finally, we aimed to study solar and meteorology linkage over a major portion of India including its islands. The study leaves us with the conclusions that Sun activity and metrology do have an intricate relationship when it comes to Indian landmass and its isles. It is seen that the windspeed has a good correlation with the sun spot numbers, whereas the temperature has an inverse nature for major portion of India. This leaves us with the conclusion that though Sun is our primary energy source, yet, not all meteorological parameters are solely influenced by it. They are dependent on other parameters too including anthropogenic ones and latitudinal positions and many more. The results obtained from our research leave us with a number of questions which further increase our curiosity to continue our study of India.

The future goals of my research include the following:

- The study of black carbon, particulate matter and Sun activity together. Furthermore, I aim to find out the probable impacts black carbon, particulate matter has on health. To bring out the health perspective with the study of aerosols will be an outstanding approach to bring our research closer to society which is the end goal.
- While this research has shed light on key aspects of solar-atmospheric interactions, it also acknowledges the limitations inherent in such investigations. As an evolving step, we will focus our research efforts on refining methodologies, expanding data and exploring the long-term implications of solar variability on regional and global climate systems.
- To extend my work in the field of Remote Sensing and its applications. Remote sensing is an emerging field which provides us better insights in monitoring environment,

pollution and habitat loss with better visualization. We wish to apply remote sensing for Indian subcontinent so as to study various key aspects.

- To extend my work towards studying ocean-atmosphere dynamics specifically for Indian Ocean.

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4. V. Kumar[1], S. K. Dhaka[1*], V. Panwar[1], Narendra Singh[2], A. S. Rao[3], **Shristy Malik[3]** and S. Yoden[4], **"Detection of solar cycle signal in the tropospheric temperature using COSMIC data", Current Science, Volume 115(2018). (I.F.=1.169)**

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