The effect of different meteorological factors on the concentrations of air pollutants.

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Abstract

The concentration of harmful air pollutants is increasing and one of the reasons is meteorological factors. It is necessary to identify how much influence factors like wind speed, atmospheric pressure, temperatures, and humidity have on the spread of air pollutants. Here we review studies that show a correlation between meteorological factors and synthesize how such factors influence the concentration of harmful air pollutants. In most cases, we saw a negative correlation between air pollutant concentrations and meteorological factors, with some exceptions: ozone increased as temperature increased, and atmospheric pressure increases caused an increase in most pollutants. Different regions and seasons change the meteorology which affects the concentration of pollutants. For instance, in mountainous terrain, the increase in altitude leads to a lower pollutant concentration than the base of the mountain. It is critical to understand how meteorology impacts air pollutant concentration as climate change increases.

Keywords Air Pollution · Pollutant Concentration · Meteorology · Spatial Variation · Temporal Variation · Climate Change · Correlation

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Introduction

The predominant contributor to pollutants in developed and industrialized nations arises from the burning of fossil fuels for various purposes such as generating electricity, industrial operations, transportation, and heating buildings. Fossil fuels have accounted for 80% of the world's total energy consumption (Ilten & Selici, 2008). The rise in the global population, coupled with the growth of industries and cities and the proliferation of motor vehicles, has resulted in a heightened need for energy. Over the past century, there has been a consistent increase in the creation and utilization of both sustainable and finite energy sources. Air quality is frequently assessed by monitoring several standard pollutants, namely sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), and particulate matter ($PM_{2.5}$ and PM_{10}), with the numbers denoting the particle size upper limits in microns (µm) (Hu et al., 2021). These pollutants can cause a range of health implications, including elevating the incidence of cardiovascular and respiratory ailments, as well as diabetes and hypertension. Pollutants can also contribute to dementia and increase the risk of abortion during pregnancy (Zhang et al., 2017). They are also linked to psychiatric issues, mental health concerns, premature mortality, and memory function, and can hamper cognitive capabilities, and diminish life expectancy. In more severe cases, a decrease in urban residents' sense of happiness, a reduction in the potential for solar power generation, and substantial economic losses (Liu et al., 2020).

Air pollution, defined by the World Health Organization (WHO) as the presence of contaminating chemicals and physical, or biological agents altering the natural characteristics of the atmosphere, is a complex issue influenced by various factors. Among these, meteorological elements such as temperature, wind speed, humidity, precipitation, and air pressure play a crucial role in shaping weather patterns and atmospheric conditions. As determinants of the atmosphere's state, these factors contribute to the concentrations of air pollutants. When substances are released into the air, they transform into pollutants when their concentrations exceed specific thresholds. It's important to note that these thresholds can be surpassed not only due to increased emissions but also as a result of prevailing meteorological conditions. The key distinction lies in the controllability of emissions versus meteorological conditions; emissions can be regulated when they exceed acceptable limits, while meteorological conditions remain beyond our control. Consequently, any effective strategy to control air pollution must consider meteorological factors, recognizing their inevitable influence on the formulation of such plans (Pérez et al., 2020).

This paper seeks to answer how meteorological factors influence the concentrations of air pollutants throughout the world. We will begin this review by discussing the correlations between the meteorological factors and the air pollutants in question. Later to move into the difference was noticed in different regions and with the seasonal fluctuation.

Section 1: Correlations observed between meteorological factors and air pollutants.

Air quality is directly influenced by the interaction of meteorological factors that impact the dispersion transformation and removal of pollutants in the atmosphere (Yan et al., 2016).

1.1 Temperature

Temperature is a meteorological factor that influences the dispersion of air pollutants. Notably, it influences pollutants that are of great harm to the human population: Ozone(O_3), Particulate Matter(PM_x), and Nitrogen Dioxide(NO_2) (Kalisa et al., 2018). As the temperature rises, the Kinetic Energy in gas molecules increases which leads to the expansion of air, ultimately leading to an increase in pollutant distribution. However, an increase in temperature can also lead to thermal inversions, which is a phenomenon where a layer of air that is warmer than the air directly below it traps the cooler air (Trinh et al., 2019). Since the pollutants are being generated but not spread through the air, the concentration of those pollutants elevates in that inversion. A team in China found that the concentration of SO_2 decreased by 0.85 $\mu g/m^3$ for every 1 °C increase in the average temperature. The O_3 concentration increased by 2.63 $\mu g/m^3$ for every 1 °C increase in the average temperature (Liu et al., 2020) They also found that the 2018 8-hour concentration of Ozone was 92.15 $\mu g/m^3$, and the average concentration of SO_2 was 14.4 $\mu g/m^3$.

1.2 Humidity

Humidity is defined as the amount of water vapor in the air. Low humidity decreases the stomatal uptake of air pollutants. Stomatal uptake is a process where the stomata of a plant take in CO_2 and O_3, effectively removing it from the environment. A decrease in stomatal uptake means that trees close their stomata and limit the amount of air pollutants they take in. Additionally, low humidity leads to dry deposition (Jacob & Winner, 2009). Dry deposition is when gas and particulate matter fall from the atmosphere directly to Earth (*World Meteorological Organization*, n.d.). In other words, dry deposition is the process of pollutants being absorbed into the Earth's surface. On the other hand, a higher humidity does the exact opposite. Higher humidity leads to wet deposition, which is when the gasses mix with the substantial amount of water in the air and are in the rain, snow, or fog elsewhere (*World Meteorological Organization*, n.d.). This means that the pollution will spread through natural means like rain and snow due to high humidity. A team in Hong Kong was studying the effect of humidity and seasons on air pollution and found that air pollution increased on days with low humidity (Qiu et al., 2013).

1.3 Wind Speed

Wind refers to the natural flow of air from zones of high to low atmospheric pressure, resulting from the rotation of the earth and the sun's uneven heating of the earth's surface (*Wind*, n.d.). Wind has a major influence on meteorological conditions, influencing storm formation, temperature, and more. A higher wind speed will improve the dispersion of pollutants concentration (Coccia, 2021) and reduce the concentration in the area where the pollutants originate. On the other hand, a lower wind speed will lead to pollutant accumulation, increasing the concentration. The same team in China found that the concentration of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 decreased by 0.16, 0.22, 0.12, and 0.12 $\mu g/m^3$ for every 1 m/s increase in average wind speed, respectively. They also found that in 2018 the average concentration of $PM_{2.5}$ and PM_{10}were 40.96 $\mu g/m^3$ and 74.78 $\mu g/m^3$ respectively. (Liu et al., 2020).

1.4 Atmospheric Pressure

Atmospheric pressure is the amount of pressure exerted by molecules of gas in the atmosphere on objects that are on Earth's surface (Brown et al., 2006). Atmospheric Pressure plays a key role in the dispersion of air pollutants. As the air moves downward, it becomes warmer and traps cooler air underneath it (Atmospheric Inversions, Gale). This phenomenon is known as an Atmospheric Inversion, and because air is trapped beneath, all of the pollutants released become more concentrated in the area. However, with lower atmospheric pressure, vertical mixing increases and increases the dispersion of gas pollutants and decreases the concentration in the area.

1.5 Precipitation

Precipitation is any form of water that falls from the atmosphere to Earth (National Oceanic and Atmospheric Administration). The influence of precipitation on air pollutant concentration is through wet deposition, which decreases the concentration in the area of origin and increases elsewhere through rain, snow, or fog. In other terms, precipitation will carry any pollutants that are dissolvable and take them somewhere else (National Weather Service). A team in India explored the air pollutant conditions in Kolkata and Siliguri. They found that the concentration of air pollutants, especially $PM_{2.5}$ and PM_{10}, peaked after the monsoon season (Biswas et al., 2020).

	Ozone	Particulate Matter (PM)	Sulfur Dioxide	Nitrogen Dioxide	Carbon Monoxide
Temperature	Positive Correlation	Mostly Negative Correlation	Negative Correlation	Negative Correlation	Negative Correlation
Humidity	Weak Correlation	Mostly Positive Correlation	Weak Correlation	Negative Correlation	Negative Correlation
Wind Speed	Mostly Negative Correlation	Mostly Negative Correlation	Negative Correlation		Negative Correlation
Precipitation	Weak Correlation	Negative Correlation	Negative Correlation	Negative Correlation	Negative Correlation
Atmospheric Pressure		Positive Correlation	Positive Correlation	Positive Correlation	Positive Correlation

Table 1 - This table shows the different correlations between the meteorological factors and pollutant concentrations. A positive correlation means that when the meteorological factor is high and concentration is also high. A negative correlation would mean that when one is high the other is low. A weak correlation would represent that there exists a very small correlation that is variable. So it could be slightly positive or slightly negative.

Data from Hu et al., 2021, Jacob & Winner, 2009, and Ilten & Selici, 2008.

Section 2: Spatial Variability

2.1 Urban vs Rural

An Urban region is a city or town - that includes residential, commercial, and other land uses - with a population of 2,500 to 50,000+ people (*Urban Areas*, n.d.). Rural regions have lower populations and are located outside of cities, and often have undeveloped land, farmland, or forest (*Rural Areas*, n.d.).

Examples of urban areas include New York City, Beijing, Los Angeles, and London. Rural examples are Hamlets, villages, and small settlements with fewer than 2,500 people (*USDA ERS - What Is Rural?*, n.d.). The impact that an urban area has on meteorological factors and pollutant concentration is significantly different from the impact of a rural area. One of the most profound effects is an increase in temperature in the urbanized city compared to the temperature of its rural surroundings. The phenomenon is called the UHI (urban heat island) effect and leads to a general decrease in pollutant concentration except for Ozone (Qian et al., 2022). Urban areas also have a higher sensible heat flux, which means more heat is transferred from the city's surface to the atmosphere, ultimately raising the temperature. Additionally, due to the larger amount of buildings and other rough elements, the wind speed is generally reduced as it nears urbanized cities and goes through them. Due to the increased buildings and sensible heat flux, there exists a stronger vertical mixing between the ground and 1-2 km up and entrainment. Furthermore, there is a lack of vegetation in urban regions which leads to lower evaporation and water vapor; coupled with the higher temperature results in low humidity (Qian et al., 2022). Furthermore, the UHI creates a discrepancy in the boundary layer (a dome with a radius of 1-2 km from the ground), leading to increased precipitation around downwind areas (Qian et al., 2022).

Still, the production of pollutants in urban areas outweighs the distribution effect of the temperature so the concentration increases. A lower wind speed, lower precipitation, and lower humidity all further increase the concentration; the stronger vertical mixing is the only other factor that decreases the concentration in an urban area (Qian et al., 2022; Neisi et al., 2018). In rural areas, due to higher wind speeds and less production of pollutants the concentration of air pollutants is lower than in urban areas (Qian et al., 2022; Zeleňáková et al., 2015).

2.2 Coastal vs Inland

Coastal environments are complex regions where terrestrial and offshore atmospheres interact, and atmospheric conditions along coasts can be influenced by offshore winds and currents as well as continental weather conditions. Coastal meteorology refers to the study of atmospheric conditions within 100 km from a coastline (*Coastal Meteorology - Rogers - 1995 - Reviews of Geophysics - Wiley Online Library*, n.d.). Coastal regions are closer to the water. There exist complex interactions between the 2 distinct atmospheres of the water and coast, which results in land-sea breeze, coastal atmospheric fronts, coastal ocean currents, and upwelling, as well as heavy precipitation and runoff (Rogers, 1995). As you progress further inland, away from water, the higher the temperature (*Coastal-Inland Distributions of Summer Air Temperature and Precipitation in Northern Alaska: Arctic and Alpine Research: Vol 12, No 4*, n.d.). A land-sea breeze occurs when there is a significant difference between the temperature of the coastal land and the ocean. The cooler/warmer air from the ocean goes to the land and warmer/cooler air from the land goes to the ocean. This will lead to a greater diffusion of pollutant concentration and also a greater concentration on the land. This phenomenon is demonstrated by Darby et al., 2007 as they say that the sea breeze sent ozone from the coast to inland, increasing the concentration inland. Sang & Shon, 2008 also demonstrated that the sea breeze results in a significantly higher concentration of ozone at a coastal city than an inland city. Additionally, the NO_2 concentration was slightly lower in the coastal region. Coastal Atmospheric Fronts are boundaries that separate the different air temperatures of the land and the ocean, which further adds to the effect of the sea breeze. Thus, the increase in temperature going inland results in a larger concentration of pollutants.

2.3 Mountainous Territory

Mountains are defined as a landform that rises at least 1,000 feet (300 meters) above the surrounding area, and is characterized with steep slopes, sharp ridges, and a summit. The pollutant concentration is lower at higher altitudes and higher at lower altitudes (Meire et al., 2012). Aside from the higher altitudes mountains act as large land masses which act as a barrier for air flow at lower altitudes (Reiter, 1982). Additionally, it is known that temperature at mountains can drop considerably which leads to snow and absorbs a lot of the air pollutants in the air. Putting these meteorological factors together, it can be deduced that with the decrease in temperature, decrease in wind speed at the base, increased snowfall, and lower atmospheric pressure which also leads to a higher wind speed at the top of the mountain, there is a lower concentration of pollutants in mountains. Another study found that surrounding mountains restrict the dispersion of air pollutants (Allen et al., 2009), indicating that areas at the base of the mountain have a larger pollutant concentration than at the peak.

Section 3: Temporal Variability

Air pollutant concentration varies throughout the day and even throughout the year. These fluctuations were further studied and a trend of the pollutant concentration arose. The differences between annual and seasonal variability are the result of random moments of pollutant fluctuations. In general, the annual variation reflects the variation throughout the seasons.

3.1 Seasonal & Annual

In Guangzhou, China the change in pollution through the year was measured using the API, Air Quality Index which tracks how clean or polluted the air is by taking into account 5 different air pollutants: Ground-level Ozone, Particle Pollution (also known as Particulate Matter), Carbon Monoxide, Sulfur Dioxide, and Nitrogen Dioxide. Each of these pollutants have a standard, set by the government, that each recording is measured against (US Department of Commerce, n.d.-a). In Guangzhou, the API has a prominent peak in December and 2 smaller peaks in October and March and dips to the lowest in June and increases until December. This pattern can have more variance with random short-term air pollution episodes (Li et al., 2014). A similar trend was observed by a team studying the relationship in Istanbul. They believe the reason for this trend can be explained by the mixing height. Mixing height is the volume of vertical space in which surface pollutants are diluted in (Schäfer et al., 2006). The mixing height is temperature dependent with highs in the summer and lows in the winter (Unal et al., 2011). During the summer, the heat from the sun causes the pollutants and air near the surface to increase in kinetic energy and move upwards leading to a higher Mixing height. In winter, the colder temperatures make the air at the surface less prone to move upward and the pollutants don't rise readily resulting in a lower mixing height and higher pollutant concentration on the surface.

Section 4: Effect of Climate Change on Pollutant Concentration

Climate Change is the long-lasting shift in the weather (Nations, n.d.). Human-induced climate change led to more frequent extreme weather events, like drought, heat waves, and large storms. The vast amount of Greenhouse houses produced leads to increases in temperature, over the last 200 years the temperature has risen 1.1 degrees Celsius. Climate change also profoundly impacts various meteorological factors and in turn the concentration of air pollutants. Furthermore, air pollutants can stay in the atmosphere for tens to hundreds of years after their release impacts future generations as well (US EPA, 2015a).

4.1 The Meteorological Changes

On a global scale, the temperature has risen by an average of 0.17ºC per decade since the 1960s. This increase in temperature is due to an increase in the concentration of greenhouse gasses. (US EPA, 2015b). Extreme highs and lows have increased in frequency, duration, and intensity. For example, going from 2 to 6 heatwaves a year, averaging 4 days in duration, and 2.3 ºF above the local threshold (US EPA, 2021a).

Global precipitation has increased with an average rate of 0.04 inches per decade. However, in the US the average rate is increasing by 0.2 inches per decade. Precipitation on the East Coast has increased by about 30% while the West has stayed relatively the same. (US EPA, 2016c). In recent times, the frequency of an extreme increase in precipitation during a single day has increased(US EPA, 2016b) and is one of the factors for the increase in average precipitation. The frequency of flooding corresponds to the frequency of precipitation (US EPA, 2016d).

With the rising temperatures, evaporation increases, and the increase in evaporation leads to an increase in moisture content in the atmosphere. Therefore, a rise in temperature will mean a rise in humidity. Additionally, contrary to common belief a 100% relative humidity does not mean precipitation is guaranteed to occur (US Department of Commerce, n.d.-b) but in most cases it does.

GCMs (Global Climate Models) from around the globe found that climate change is expected to increase the near-surface wind speed in the Northern Hemisphere, which includes places such as Canada, Siberia, Russia, and tropical and subtropical regions in Africa, as well as Central and South America. On the other hand, Greenland, southern Europe, China, India, southern Australia, and large regions of the west coast of South America are expected to have a decrease in near-surface wind speed. (Eichelberger et al., 2008).

Utilizing the Global Historical Climatology Network in numerous parts of the world, a team found that the sea-level atmospheric pressure has been decreasing. They relate this finding to the current change in climate and narrow it to the effects of wind speed change in circulation patterns, and increase in humidity (Howells & Katz, 2019).

4.2 The Effect on Air Pollution

The increase in temperature will result in an increase in O_3 concentration but a decrease in PM, SO_2, NO_2, and CO. The increase in precipitation will result in a decrease in PM, SO_2, NO_2, and CO. The increase in humidity will result in an increase in PM but a decrease in NO_2, and CO. The increase in surface wind speed will result in a decrease in O_3, PM, SO_2, and CO but the decrease in surface wind speed will increase.O_3, PM, SO_2, and CO. The decrease in atmospheric pressure will result in a decrease in PM, SO_2, NO_2, and CO.

4.6 Case Study - United States

In this section we will look at the US and how meteorological variables are expected to change from 2009 to 2050 and the impact it will have on the air pollutants.

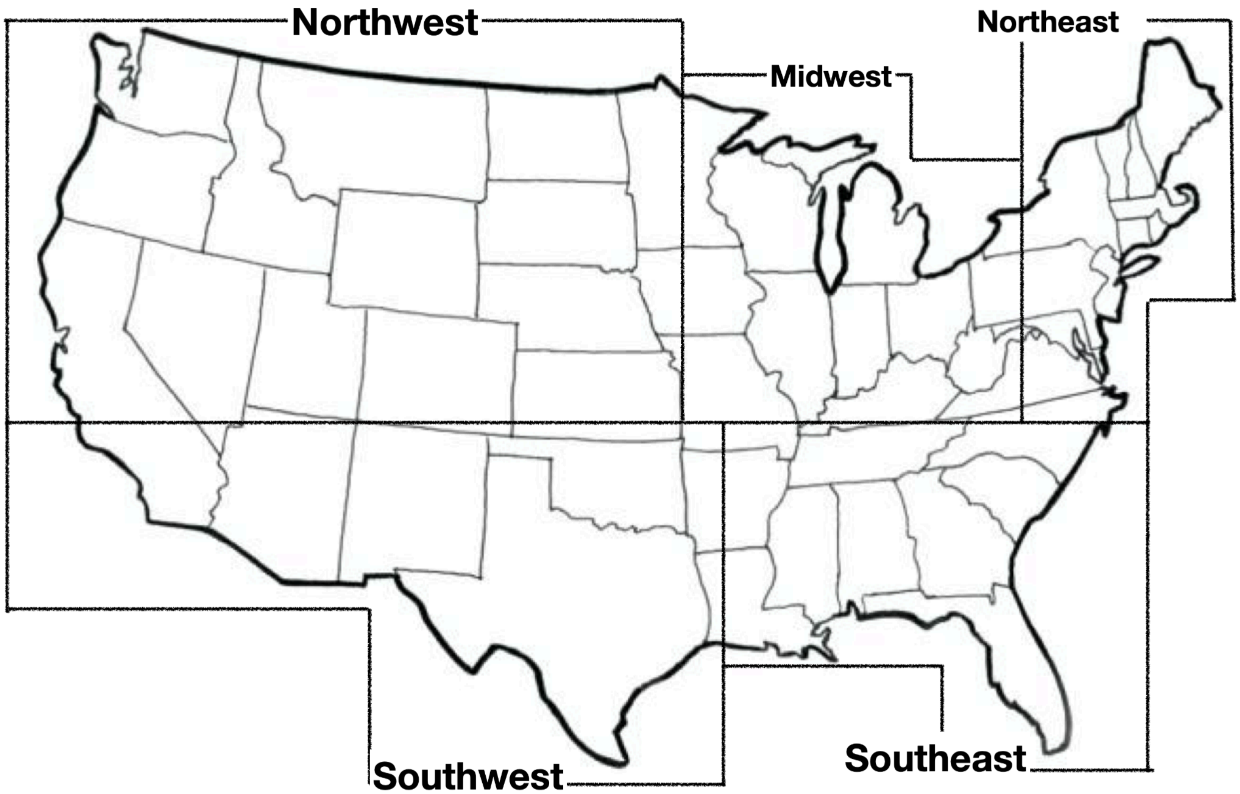

Figure 1 - This is a map of the United States of America with the referenced regions shown.

4.6.1 Precipitation

In January the precipitation will increase everywhere in the US, the most substantial being an 85% increase in the Northwest, the smallest being 2% in the South West, 63% in the Midwest, 73% in the Northeast, and 26% in the Southeast. In July, there will be an increase in precipitation in the northwest by 22%, in the Midwest by 13%, and in the southeast by 88%. As well as decreases in the Northeast by 40% and Southwest by 26% (Dawson et al., 2009). Large increases in precipitation would lead to a decrease in pollutant concentration and a decrease in precipitation would lead to an increase in concentration.(Table 1).

4.6.2 Wind Speed

During July there will be a consistent wind speed decrease throughout all of the contiguous states, the highest being 27% and the average being 15.2% (Dawson et al., 2009). However, in January there will be a slight increase in the Northwest and Midwest with an average of 9%, and a decrease everywhere else with an average of 5.7% (Dawson et al., 2009). Additionally, another experiment using GCMs (Global Climate Models) shows an increase in the annual mean surface wind speed in a broad swath from the 5 Great Lakes to Texas. As well as a decrease in wind speed between the West and the Eastern border. They also coincide with the changes in surface-level wind speed from summer to winter (Eichelberger et al., 2008). These findings indicate that there will be both an increase and decrease in pollutant levels in the US depending on the area (Table 1).

4.6.3 Humidity

In both January and July there will be an increase in humidity, with the average increase in January being 4.7% and an average decrease of 4.5% in the Northwest and Southwest. In July, there will be a 1% decrease in the Northeast and an average increase of 26.3% in the remaining regions. The general increase in Humidity will lead to a decrease in pollutant concentration except for $PM_{2.5}$ (Table 1).

4.6.4 Temperature

Consistent with the work done in the previous section the temperature in both January and July will generally increase but in January there will be a 2.5% decrease in the Southwest. However, the overarching increase throughout the contiguous states will lead to decreased pollutant concentration except for Ozone (Table 1).

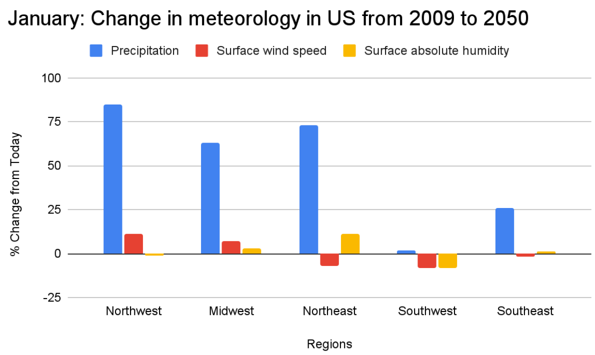

Figure 2 - The bar graph at the right shows the change in percentage from 2009 to 2050 of meteorological factors in 5 different regions in the US during January.

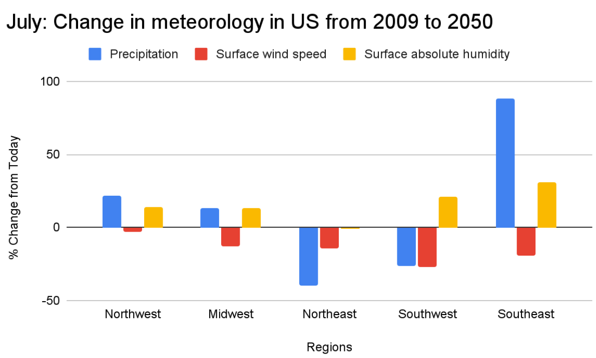

Figure 3 - The bar graph at the right shows the change in percentage from 2009 to 2050 of meteorological factors in 5 different regions in the US during July.

Surface Temperature

	January	July
Northwest	-0.3 K	1.1 K
Midwest	0.7 K	1.2 K
Northeast	1.9 K	1.0 K
Southwest	-2.5 K	-0.4 K
Southeast	-0.3K	0.9 K

Table 2 - The table above shows the change in Kelvin of the temperature from 2009 to 2050 in 5 different regions of the US in January and in July.

(Dawson et al., 2009)

Results & Discussion

Air pollution poses a large risk to many countries and it is crucial to understand how weather patterns of a particular region can influence the concentration of air pollutants. Wind speed is negatively correlated with all the pollutants except for NO_2 (no significant data found); precipitation is negatively correlated with all pollutants but there is a weak correlation with O_3; atmospheric pressure is positively correlated with all pollutants except O_3 because no data was found; humidity has a weak correlation with O_3 and SO_2, a negative correlation with NO_2 and CO, and a weak correlation with PM; and the temperature has a positive correlation with O_3, mostly negative correlation with PM, and a negative correlation with SO_2, NO_2, and CO. Differences in measurements in different parts of the world can be attributed to variation in conditions of each site. Urban areas differ from rural areas in higher temperatures, lower wind speed, stronger vertical mixing, less vegetation, and increased vehicular pollution, contributing to a higher pollutant concentration. Coastal regions differ from inland regions in lower temperatures, a land-sea breeze, atmospheric fronts, and heavy precipitation. Inland pollutant concentrations were generally higher, the reason being a higher temperature. However, the land-sea breeze can either increase or decrease the pollutant concentration. In mountainous terrain, the higher you measure the lower the concentration of pollutants. Additionally, the difference in measurement can be traced to different times during the year. Winter times have higher than average pollutant concentrations and summer times are below average. Mixing height is temperature dependent and the smaller mixing height in winter means higher measured pollutant levels and the opposite is true for summer. Over the next 10-20 years, these meteorological factors will change due to climate change. All meteorological factors except atmospheric pressure will increase, and the frequency of extreme weather events and the duration of these events will also increase. The increase in temperature, humidity, wind speed, and precipitation will lead to a general decrease in pollutant concentration (negative correlation). The decrease in atmospheric pressure will also result in a decreased pollutant concentration (positive correlation). Future research into the impacts of meteorology on air pollution could focus on incorporating additional meteorological factors and air pollutants. Additionally, researchers should obtain information on what happens when multiple spatial variations occur, such as an urban coastal city or an urban city in the mountains.

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