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# ENVIRONMENTAL FACTORS THAT INFLUENCE THE GEOGRAPHY OF YEMEN LEADING TO DUST AND SAND STORMS - A CASE STUDY

**Wadie Ahmed Mokbel Ghalib[1], Almoliki Mohammed Mansoor[2], Sajan Chimmikuttanda Ponnappa[3]***

[1]Taiz University, Faculty of Medical and Health Sciences, Laboratories department, Taiz, Yemen
[2]Taiz University, Faculty of Art, Geography Department, Taiz, Yemen
[3]R and D, Chemistry, VerdeEn Chemicals Pvt. Ltd,
D-11, UPSIDC Industrial Area, Masoorie-Gulawati Road, Hapur District, Uttar Pradesh, India-201015
Tel.: +90 (542) 3032275 ORCiD ID: 0000-0002-5759-1089
*Corresponding author, e-mail: sajan.saj@rediff.com

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**Abstract**

In Yemen, the dust storm is a common phenomenon severely affecting the economy and health. Yemen is located in a semi-desert desert area, where dust and sand storms occur all year round, however they are the most common at summer (from June until the end of September). Coastal areas (Hajjah, Hoddeidah, Taiz, Lahg, Aden, Abyan, Shabwah and Hadramout) and desert areas (Marib and Al Jowf) are affected by dust and sandstorms almost all year round. The western and central governorates of Yemen are mountainous regions, but influenced by dust too. Dust storms in Yemen have an impact on humans, animals, plants and all environmental ecosystems. In this article, we attempted to understand the possible relationship between environmental parameters such as wind temperature, and precipitation, which influence the development of dust and sand storms in and around Yemen. Statistical analysis such as descriptive statistics, T-test, ANOVA one-way test, Tukey test, Levene test, and Correlation test were performed. The statistical analysis confirms that there is a significant correlation between wind, temperature and precipitation at 0.01 and 0.05 levels. The results further depict that environmental factors play a vital role in the formation of dust and sand storm. The results obtained are encouraging and further research will be conducted based on technological evidence.

**Keywords:** dust storms, desert, wind, temperature, atmospheric pressure, Yemen

## INTRODUCTION

Sandstorms and dust storms are caused by strong high winds, which erode sand and sandy soils from arid and semi-arid environments and release them into the atmosphere (Goudie, 1988). The atmospheric dust is an integral part of the earth's atmosphere that has a direct impact on air quality and climate (Yin et al., 2002). Dust storms are frequent natural phenomenon in desert areas (Goudie & Middleton, 2001; Rezazadeh et al., 2013). Strong winds move dust and sand from the deserts and surrounding areas over long distances, triggering these incidents (Pye, 1987; Knippertz et al., 2007). The Northern Hemisphere is home to the world's largest dust source regions. They are found in North Africa, the Middle East, East Asia, and North America and are known as the "dust belt." In contrast, the Southern Hemisphere has less land; dust sources are found in Australia, South America, and South Africa and they are smaller in scale (Miguel, 2017). Dust storms have been widespread in the Favonian (west wind), Saharan, and Arabian regions. Dust storms that originate in the Gobi and Taklimakan deserts are only found in East Asia (Southern Mongolia and Northern China). However, prevailing winds bring the aerosols eastward, passing through China, Korea, Japan, and the North Pacific on their way to the Hawaiian Islands and the Western United States (Orlovsky et al., 2013). Rarely, significant concentrations of dust can be carried as far as the Western United States. Dust storm, originating in the Sahara region, travel through Western Sahara, Tunisia, Algeria, Morocco, West Africa, Sudan, Somalia, Ethiopia, the Canary Islands, the Mediterranean coast of Malaga-Alicante, etc. In case of Arabian dust storms, dust is blown from the deserts of Egypt, Saudi Arabia, Iran, Iraq, and Pakistan and from the surrounding areas into the Arabian Sea, the Red Sea and the Arabian Gulf (Pease et al., 1988). Dust storms affect the majority of the Middle East, in addition to the African Sahara region (Barnum et al., 2004; Rezazadeh et al., 2013; Furman, 2016).

The Arabian Peninsula is well-known for being one of the world's most prolific sources of dust storms (Fig. 1; Luo et al., 2004; Prospero et al., 2012). The Arabian Peninsula's large dunes, the deserts, the geologically diverse terrain with little rainfall, and sparse vegetation cover are the main sources that evoke dust in the air (A1-Sanad et al., 1993; Shepherd et al., 2016). On average, in every year Yemen has one to five dust storms with a visibility of less than 1 km (Middleton, 1986). Location, topography and climatic conditions are the key factors that caused sand and dust storms in Yemen. Dust storms have a serious impact on health, infrastructure, economy, agriculture, etc. As the

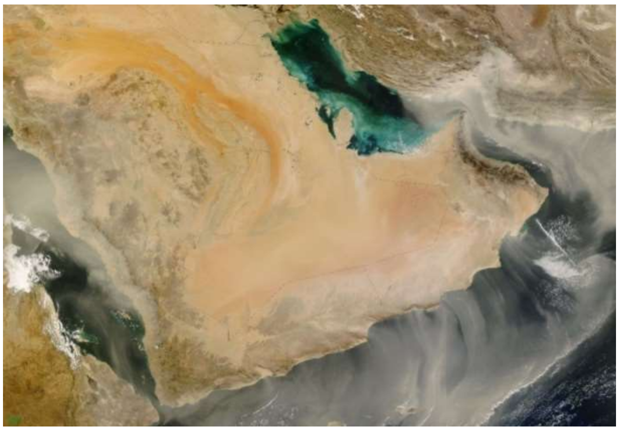

*Fig. 1* Satellite image showing the dust storms over the Republic of Yemen and the Middle East (MODIS image taken by Tera/Aqua satellite, 2008)

dust storm is a meteorological phenomenon, it is impossible to eliminate it (Middleton, 2001). However, by understanding the environmental factors that lead to duststorms, we can minimise their environmental impact.

In this study, we have aimed (1) to understand the interaction of environmental factors that play key role in the development of dust and sandstorms; and (2) to highlight their impact on human health and the Yemeni environment including merits and demerits. In addition, (3) we are proposing possible measures to be taken by the authorities to mitigate the impact of the dust and sand storms on the region of Yemen.

## STUDY AREA

*The geography of Yemen*

The Republic of Yemen between 12ºN and 19ºN is located in a tropical region and has all the general characteristics of the tropical region concerning the climate and its geographical determinants, except for local differences. Within a tropical climate zone Yemen is situated in a desert to the semi-desert region (Country Profile: Yemen, 2008). It is within the orbital zone of deserts extending from the east coast of the Atlantic Ocean to Morocco and, Mauritania, and further to the east of the Arabian Peninsula and continues to Iran. This expansion of deserts has a serious impact on the dust and dust storms in large parts of the Republic of Yemen. Yemen is located in the southwestern part of the Asian continent and the south of the Arabian Peninsula (Cullen, 2005). This geographical location is close to the continent of Africa. Saudi Arabia borders Yemen in the north, and the two countries share Rub' Al Khali, one of the world's driest deserts, and a major source of dust in the Arabian Peninsula. The south of the country is surrounded by water bodies. The impact of the Arabian Sea and the Indian Ocean on the territory of Yemen differs from the impact of the northern and eastern continents. Based on the geography of Yemen, there are variations in environmental factors, such as atmospheric pressure, wind and temperature, which cause dust or sandstorms in the territory of the Republic of Yemen.

*The topography*

The territory of Yemen is divided into two distinct topographical regions from the point of the dust and sand storms (Fig. 2). The first region is the hotspot for dust and sand storms, while the second represents the environment where dust and sand storms occur. The first region includes the west, south, and south-east coastal plains, as well as the Rub' Al Khali desert, and this large area is a source of dust and sand storms. Meanwhile, dust and sandstorms are coming in from the outside of Yemen's geographical borders too. The second region includes the Western highlands, Hadramout plateau, and interior basins. Due to the wide distance between the source and the receiving location, this region is mostly affected by dust rather than sand storms.

*The climate*

Yemen's climate can be characterized as a subtropical dry, hot desert climate with little annual precipitation. Yemen's summer lasts from June to September. In the summer, the temperature is high (40°C), and the amount of rainfall is very limited. The winter is colder, while the spring and autumn are mild. Rain usually appears in the spring, but only on rare occasions. In the dry periods the hot winds known as Shamal carry dust, and blow in the spring and summer (i.e. between March and August). The most important factor in the occurrence, transfer, and spread of dust and sand storms is the climate. The formation of dust and dust storms is directly related to various climate elements such as heat, rain, wind conditions, pressure, humidity, and solar radiation. It spreads as the drought worsens, causing temperature changes, changes in wind speed, and changes in wind direction (Climate Change Profile: Yemen, 2018). The driving force behind all aspects of climate is atmospheric pressure. Winds are created by differences in atmospheric pressure in different areas or layers of the upper atmosphere. The wind is one of the most important outputs for determining atmospheric pressure differences on the ground or in the upper atmosphere layers. It is also one of the most powerful factors in the movement of dust and sand storms. During the study of dust, it is necessary to analyze the wind moment because the wind is the energy that carries and spreads the dust by its direction (Rafferty, 2011). Seasonal variations in atmospheric pressure and winds result in the formation of various types of wind and breeze, such as:

*Local wind* is produced by a change in local air pressure. Atmospheric depressions are formed as a result of these winds. West and south of Yemen there are water bodies while highlands and lowlands of different natural terrain areas characterize the land of the country. The land surface is more exposed to sunlight triggering a frequent local and seasonal breeze known as land and sea breeze (Allaby & Garratt, 2007; Winter et al., 2020). The key factors

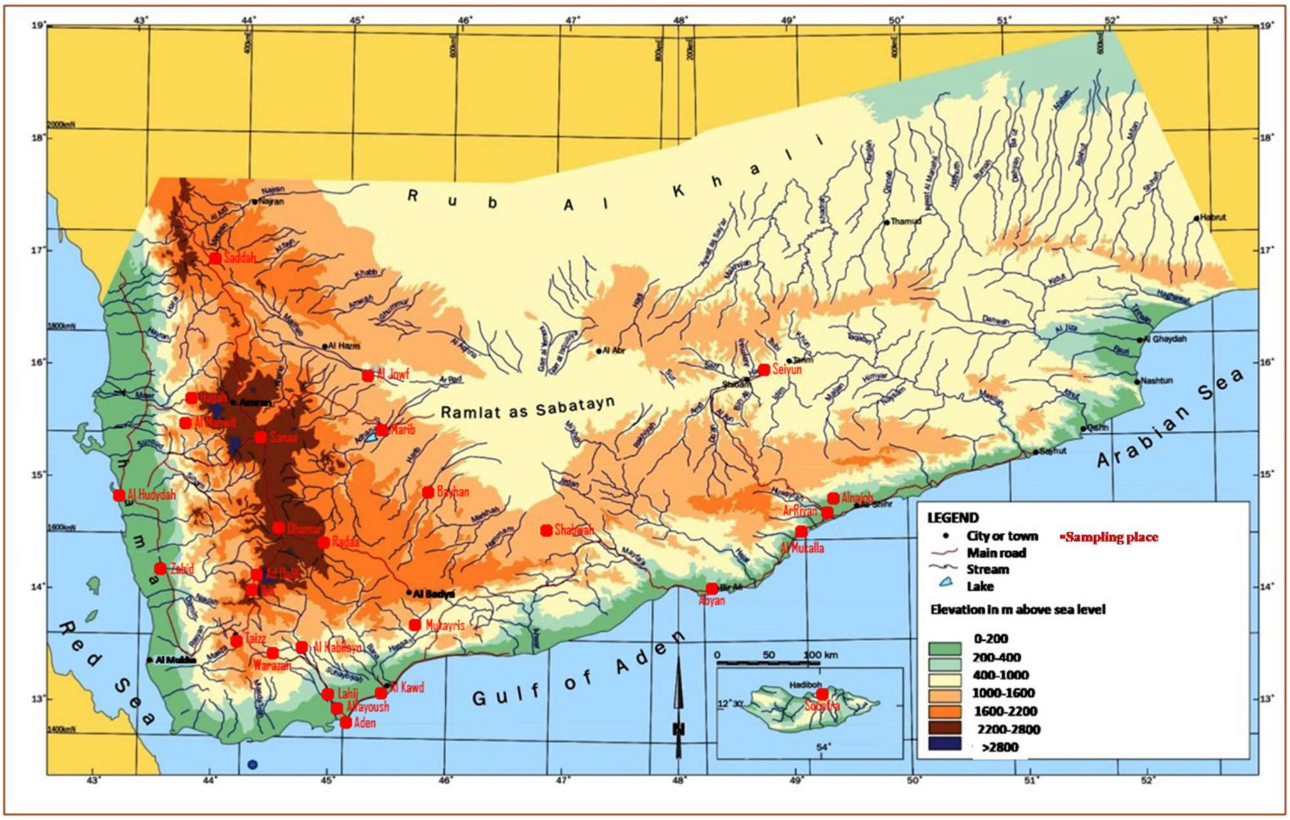


*Fig. 2* Topographical map of the Republic of Yemen

driving the land and sea breeze are variations in temperature and air pressure between dry land and the adjacent water bodies. In case of land breeze the land cools faster than the sea, allowing the air in contact with it to cool. This causes air to sink over the land, allowing sea air to replace it at a high level. The land breeze is a low-level flow of cool air from the land to the sea (Allaby & Garratt, 2007; Davis et al., 2019).

*Sea breeze* forms when the wind blows from the sea to the land throughout the day. The frequency of the sea breeze is determined by a variety of factors. This involves the area and level of the water, the temperature difference between land and water, the prevailing winds, the coastal topography up to 15-50 km from the coastline areas, and the prevailing wind direction of more than 100 km, all of which contribute to high relative humidity and supporting temperatures in coastal areas. The temperature of the coastal areas directly affects human comfort in the summer by altering the effect of the sea breeze on the Yemeni coast, resulting in temperature variations influencing air pressure and wind direction (Allaby & Garratt, 2007; Crowther et al., 2019; Davis et al., 2019). The blowing wind, the extension of the coastal area, and the natural mountain barriers all influence the sea breeze reaching the west and southern coasts. In the summer, the sea breeze has the greatest effect on the west coast, reaching up to 80 kilometres with a maximum wind speed of 7 m/s. The effect of the sea breeze on the southern coast approaches 80-100 km/h. This is due to the regressive strength of the pressure, the lack of a winding coast, and the lack of mountain barriers to alleviate the high summer heat. In winter, the sea breeze is weak compared to summer due to high pressure, which replaces the low pressure that blocked the flow of sea breeze to long-distance inside the coast, where its impact on the west coast between 40-60 km/h with a maximum speed of 3.5 m/s.

The *valley* and *mountain breeze* blows in places with a lot of topographical contrast. During the day, temperatures rise at the bottom of valleys, causing depressions and the air rises, causing its density to drop and the air to rise upwards the mountain peaks in the form of upwards foot winds known as valley breezes. These valley breezes are the persistent winds that bring warm air upwards, assisting in the growth of numerous trees. The self-cooling mechanism happens as air travels upwards, allowing water vapor to condense and form fog. Furthermore, some cumulus clouds form over the high mountain peaks when the air humidity is higher and the altitude is higher. The interaction of the air with the foot of the mountain in low-lying areas or restricted areas between mountainous areas during the night induces rapid heat loss by radiation, resulting in cold air in the surrounding. If the temperature decreases, the density of the air rises, causing cold air to slide down in the form of soot winds, which pass down into the depressions and are known as mountain breezes (Baumbach & Vogt, 1999; Allaby & Garratt, 2007). This decreases the temperature and, on rare occasions, causes frosts in the winter, resulting in crop losses in Kaa al Hakl, Jahran, Ma'abar, and Ka'a Amran. As a result, farmers cover certain fields to shield them from frost.

*Fohen winds* are warm and dry. By compressing when they land on the mountain slopes, these winds gain heat on their own (Gaffin, 2007). Because of the mountains and depressions in Yemen, this is a natural air phenomenon. The central depression arises in the valley of Al Jowf. It's also caused by a difference in air pressure at the foot of the mountains that developed as a result of temperature variations (Gaffin, 2007). The temperature difference in the mountains is determined by the level of the area exposed to sunlight. The high-pressure winds result in travel into the hills, leaving the depressions, and the air above the depressions increases, allowing the temperature to rise. Another reason in its development is that when humid winds hit the mountains, they rise on the mountain slopes, forming clouds and precipitation. They land on the other side of the slopes (the rain-shadowed foothills), where their temperature rises spontaneously due to compression during their landing beneath the feet of mountain slopes. Plants and crops benefit from these winds because they speed up the start of the growing season. (Sweeney et al., 2010; Iizumi & Ramankutty, 2015).

The *Al Ghawbah* is a local name for wind in Aden, Lahg, and their surrounding areas. In the summer, these winds, along with the southwestern winds, are caused by thermal depressions and dust-laden winds. The geography of an area surrounded by sand is the primary cause of dust-laden wind, which causes obstructed vision, and blocked sunlight. With a speed of 40-60 km/h and a frequency of 18-21 per day, they cause environmental and human disasters. Summer and autumn are the seasons when these winds blow, and they usually come from the north and west.

The warm (*Al-Kawi*) winds blow from the interior desert areas of the Rub' Al Khali (the Empty Quarter) desert in the summer and spring. To reach the coastal areas, the thermal depressions move south to the Aden Gulf and the Arabian Sea. These are hot winds that cause an increase in air temperatures or a dusty drying of agricultural land. They are common in Aden, Lahg, Shabwah, Bayhan, and in other northern governorates.

## MATERIALS AND METHODS

Wind, temperature, and precipitation data were gathered from 28 stations located throughout the county (Fig. 2). For each parameter, 84 samples were taken for each season, totaling 336 samples per year. As a consequence, the total number of samples for all three parameters is 1008. An anemometer model Windtronix 2 was used to measure wind speed, a HORIBA thermometer and thermography was used to measure temperature, and a rain gauge was used to collect precipitation data. These data were then statistically analysed using the Origin 8 and SPSS 19 versions of the software. These data will assist in the understanding of the interactions between environmental factors that affect dust and sand storms. During the overall research period, data were collected for seven years, from 2010 to 2016, for all seasons. Statistical analysis such as descriptive statistics, T-test, ANOVA one-way test, Tukey test, Levene test, and Correlation test were performed.

*Descriptive statistics*

Descriptive statistics is a technique for calculating the central tendency and spread of a set of data. The central tendency for wind speed, temperature, and precipitation was calculated in this study. T-test was performed based on the results of the descriptive statistics. A T-test is a useful tool for determining whether there is a significant difference between the means of two groups that are related in some way.

*Correlation Test*

The correlation test is a statistical method for evaluating the degree of a linear relationship between two variables. The range of correlation analysis is between 1 and 1. If the values obtained are closer to 1 or -1, there is a clear positive linear relationship between the variables being correlated; however, if the values obtained are closer to 0, there is no linear relationship between the variables being correlated.

## RESULTS

***Seasonal changes in atmospheric pressure and wind***

In Yemen, the annual atmospheric pressure and wind data can be divided into four periods based on the seasons mentioned below.

*Atmospheric pressure and wind during winter*

During the winter season the superheat center travels towards the southern hemisphere therefore the northern hemisphere would be colder. In the meantime, the water bodies hold the temperature and become warmer than the land. Over Siberia, a high Asian atmospheric pressure (Siberian) is formed (mid- Asia, Arabian Gulf, Eastern, and Central of Arabian Peninsula). The high atmospheric pressure is generated in the Atlantic Ocean's north, spreading eastward which include North Africa. The high atmospheric pressure is developed between the height of the Arabian Peninsula and the height of the Sahara Desert. The atmospheric pressure values range between 1018-1020 mbars (Allaby & Garratt, 2007). The Mediterranean Sea's water bodies are dominated by low atmospheric pressure, caused by the thermal variations between the warm water and the surrounding landmasses. The Arabian Sea, the Gulf of Aden, the Red Sea, the Abyssinia plateau, Sudan, the equator zone, and southern Africa are all affected by the low atmospheric pressure. The dry and cold wind is produced in Central North Asia and the Arabian Peninsula, and it travels towards the low atmospheric pressure centers in the Indian Ocean's north. This is due to variations in atmospheric pressure and heat distribution across the world; triggering northern and northeast winds (Collier and Corporation, 1957; Yiannopoulos, 2018). Yemen and the rest of the Arabian Peninsula are affected by these winds, which keep the temperature steady and bring winter rain. In general, the temperature of these winds is near 0°C, but in the highland areas of Yemen, it can drop below 0°C, retaining the temperature of the surrounding area. The collision of cold and warm air masses caused by the wind moving through water bodies causes rain in Yemen's south and east. Rainfall is often in the form of sudden rains, which has a detrimental effect on agricultural land. The Mediterranean Sea also has an effect on Yemen's climatic conditions, as some meteorological fronts, depressions, and air masses cross the northern Arabian Peninsula from the Mediterranean Sea. The cold northern air fronts have been left behind; creating an unstable frontal depression that is causing rainfall in Yemen's west region and to a lesser degree in the coastal plains.

*Wind speed during winter*

During the winter, the prevailing winds are the north trade winds and north-eastern winds. The wind speed varies from region to region due to topographical variations, direction, and the constant movement of pressure areas (Allaby & Garratt, 2007). Based on our data (Fig. 3) during the summer, the recorded minimum wind speed was 0.4 m/s. During the winter, while raining, a mean wind speed of 0.5 m/s was recorded. During the autumn season, a maximum speed of 7 m/s was recorded. During the winter and spring seasons, the mean wind speed was 2.01 m/s. Similarly, during the summer and autumn seasons, the mean wind speeds was within 2.0 m/s and 2.1 m/s, respectively. In the coastal areas, winds were stronger (Al Hudaydah: 4.9 m/s; Al Mukalla: 3.8 m/s; and Aden: 4.09 m/s). The equability of the surface, the heat disparity between the surface water, and the relatively low atmospheric pressure with land adjacent to it all contribute to this. The winds were strong in Sa'dah, Al Jowf, Taiz, and Al Mahwit, with gusts ranging from 2.1 to 2.9 m/s, medium in Dhamar, Al Kawd, Marib, Ar Riyan, Abyan, and Al Habilayn, (1.5-2 m/s) and weak in the rest of the stations, with gusts ranging from 1.1 to 1.3 m/s. The wind speed with the lowest rate was recorded in Alnajob, Rad, Zabid, Lahij, Ad Dali, and Shabwah, which was less than 1 m/s in Alfayoush and Seiyun. Figure 3 shows a graphical representation of wind speed in 28 stations during various seasons.

*Atmospheric pressure and wind during spring*

Between the winter and summer solstices, spring is a transmission season. The weather is influenced by the Arabian Peninsula's high atmospheric pressure centers, which begin to drop out to the far north, where atmospheric pressure values reach between 1010 and 1012 mbars (Allaby & Garratt, 2007). The seasonal air depression, which is located/centered on the plateau of the lakes on the African continent, moves towards stations above the eastern regions and north from Sudan's center. These changes cause air depressions due to the relatively high temperatures which replace

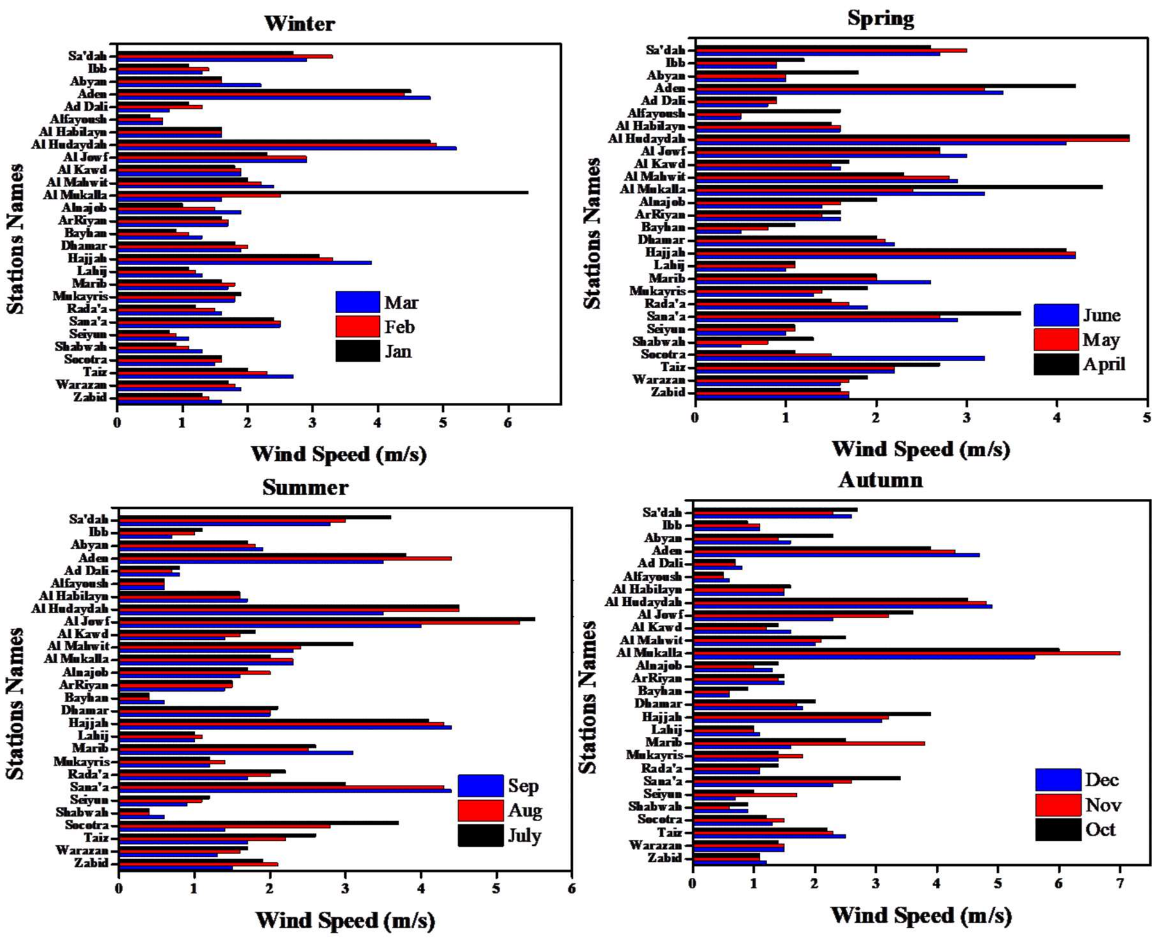


*Fig. 3* Seasonal variations in wind speed in 28 stations at Yemen in 2010

the air heights above the center of the Arabian Peninsula and North Africa.

Yemen is subjected to different air blocks originating in the north and south while high atmospheric pressure increases in the southern hemisphere. This results in spring air turbulence and rainfall, particularly in Yemen's central and southern regions (Ibb, Al Mahwit, Hajjah, Aden, and Al Rayyan), which varies year to year. The predominant winds in the country's southern stations are mostly from the south to southeast. In late April and early May, southwest winds are the dominant winds in the north and western stations. In the spring, there is also an increase in rainfall, but only in small amounts for short periods (Elzz et al., 1991; Algifri, 1998).

*Wind speed during spring*

Several stations, such as Hodeidah, Al Rayyan, Mokiras, and Habelin, do not experience any changes in wind speed between winter and spring (Elzz et al., 1991; Algifri, 1998). In contrary, Sa'dah, Al Jowf, Ad Dali, Al Mukalla, Al Kawd, and Socotra are among those stations where the wind speed is lower in the spring than in the winter. Wind speed increases in the rest of the stations during the winter. During the spring, the highest fast rates are recorded at Hajjah and Aden Stations, ranging from 4.1 to 4.9 m/s, followed by 2.9 to 2.5 m/s at mountain high stations like Sanaa, Al Mahwit, and Taiz. The lowest wind speeds, 0.9 m/s, were recorded at the Ad Dali and Alfayoush stations.

*Atmospheric pressure and wind during summer*

The Yemeni seasons are similar to Indian seasons, with a low atmospheric pressure of 998 mbar on average and low eastern Sudanese atmospheric pressure that affects Yemen. South of the equator, there is a high level of atmospheric pressure. As a result, the Indian Ocean is dominated by hot, humid south-western monsoon winds. Summer rains in Yemen are caused by the monsoon wind colliding with the mountain slopes. Summer is the most popular season in Yemen for dust and sand storms, which occur from June to the end of September every year. The strength of the dust and sand storms decreases during the rainy season. Rainwater cleans the air by removing dust particles and allowing them to settle. Furthermore, rainy years, which are typical in most parts of Yemen, hold the soil moist, minimizing soil erosion, which would otherwise be transferred as dust. Meanwhile, areas with less rain, especially in the west and south, contribute to the spread of dust, which is then dispersed throughout the atmosphere.

*Atmospheric pressure and wind during autumn*

The autumn season is a transitional period between the summer and the winter seasons. The depressions above the Arabian Peninsula and North Africa start to deteriorate during this season and are replaced by air blowing in from Asia. The atmospheric pressure is between 1012 and 1016 mbar during autumn. Meanwhile, the Sudanese air depression has influenced the surrounding environment, causing them to settle over the Abyssinia plateau and eastern Sudan. Meanwhile, during the summer in India, the seasonal low atmospheric pressure is dominant. The atmospheric pressure begins to fall to the east and is replaced by high Siberian pressure, which begins to spread westward. The northeasterly wind moves to Yemen, carrying steady rain until mid-September. At the beginning of October, the northern cold winds approach Yemen. Yemen is subjected to a combination of northern and southern air currents, resulting in atmospheric pressure centres that are still in the transitional stage. During the autumn, the south air mass brings moisture and travels north, triggering rainfall in Yemen's southern regions.

*Wind speed in autumn*

In most stations, the wind speed is lower in the autumn than in the summer. Except for a few stations on the east, west, and southern coasts, it is relatively quiet (Elzz et al., 1991; Algifri, 1998). Al Mukalla Station has the greatest average speed of 6.2 m/s, followed by Hodeidah 4.7 m/s, Aden 4.3 m/s, Hajjah 3.1 m/s, and Al Jowf 3.03 m/s respectively. The slowest speed was registered at Alfayoush station, which was less than 0.5 m/s. The average wind speed in Bayhan, Shabwa, and Al-dale was 0.7 m/s (Fig. 3).

***Seasonal change in temperature***

Dust storms have indirect relationship with temperature. The change in temperature plays a major role in physical and chemical weathering, which aid in the fragmentation and breaking of rocks in their immediate surroundings. Rising temperatures and decreasing rainfall cause an increase in the evaporation rate, leading to desiccation in surrounding desert areas. As a long term result, in the Republic of Yemen's the desert and semi-desert regions are expanding. Mountain breezes, valley breezes, land and sea breezes are caused by temperature variations within Yemen's topography, during day and night, and between water bodies. These are the result of differences in atmospheric pressure, which cause local winds to form, which contribute to the formation of sand storms and the spread of dust. Throughout the year, the temperature in desert and semi-desert areas ranges from 20 to 32°C, with significant differences in monthly and seasonal temperatures between Yemen's various regions, reaching up to 40°C in some areas (Hoddeidah, Aden, Hajjah and Marib). Because of the altitude factor, it decreases slightly in highland areas. During the summer, the minimum temperature was 12.3°C, and during the winter, spring, and autumn seasons, it was 22.4°C, 29.7°C, and 24.2°C. Summer temperatures reached 55.2°C, while winter, spring, and autumn temperatures reached 48.2°C, 54.4°C, and 49.9°C, respectively. Figure 4 shows a graphical representation of the seasonal variation in temperature at the 28 meteorological stations.

***Seasonal changes in precipitation***

The seasons of spring and autumn are considered transitional periods between monsoon seasons. Since

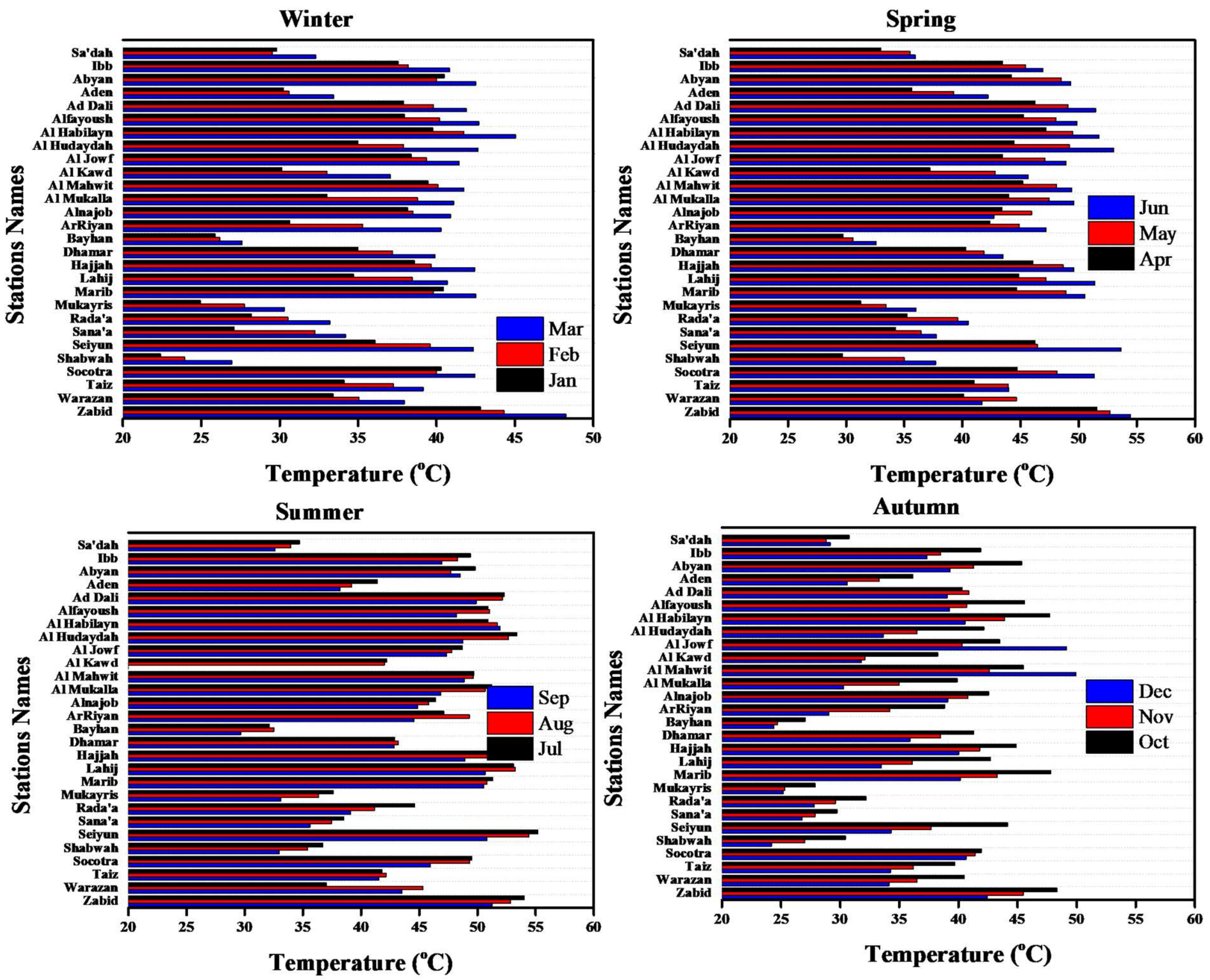


*Fig. 4* Seasonal variations in the temperature in 28 stations at Yemen in 2010

1960, the precipitation has been decreasing at a rate of 1.2 mm/month/decade, and this trend is expected to continue (Sweeney et al., 2010). During the winter, the lowest amount of rainfall recorded was 0.0 mm, while the highest amount was 330.8 mm. The highest recorded value was 196.4 mm in the summer. Figure 5 shows the seasonal variation in monthly precipitation at 28 meteorological stations.

### *Statistical Analysis*

*Descriptive statistics*

The descriptive statistical results obtained for the wind speed data and T-statistic values are listed in Table 1. Based on the above data, we can conclude that each season has a significant variation in all variables. Because the P-value of all the seasons is greater than 0.05, the T-test data reveals that the group means (wind speed) for all seasons are significantly different at the 0.05 level.

There is a significant variation in all variables during each season (Table 2). The T-test results show that the group means (temperature) for all seasons are significantly different at the 0.05 level (Table 2) because the P-value for all seasons is greater than 0.05.

In each season, there are significant variations in all variables (Table 3). The T-test results show that the group's means (precipitation) for all seasons differ significantly at the 0.05 level (Table 3). The mean value is greater than zero in all three cases, i.e., wind speed, temperature, and precipitation, so we reject the null hypothesis and conclude that the values obtained for all three parameters are significantly different at the 0.05 level, because the P-values for all three seasons are greater than 0.05.

*Oneway ANOVA Test*

The one-way analysis of variance (ANOVA) is used to determine whether the means of three or more independent (unrelated) groups differ statistically significantly. In this study, each of the three parameters/environmental factors is treated as a separate group. All three parameters were subjected to an ANOVA test in this study. Table 4 shows the descriptive statistical data obtained for the samples. Table 5 shows the results of the one-way ANOVA.

We can conclude from the results that the means of all parameters are significantly different at the 0.05 level, rejecting the null hypothesis. The ANOVA test revealed that F (2, 1005) = 301.683, P=0 for the three parameters of wind speed, temperature, and precipitation. The null hypothesis is rejected because the P-value is less than 0.05. Since we reject the null hypothesis, we must use/opt for another test, the Tukey test and Levene's Test.

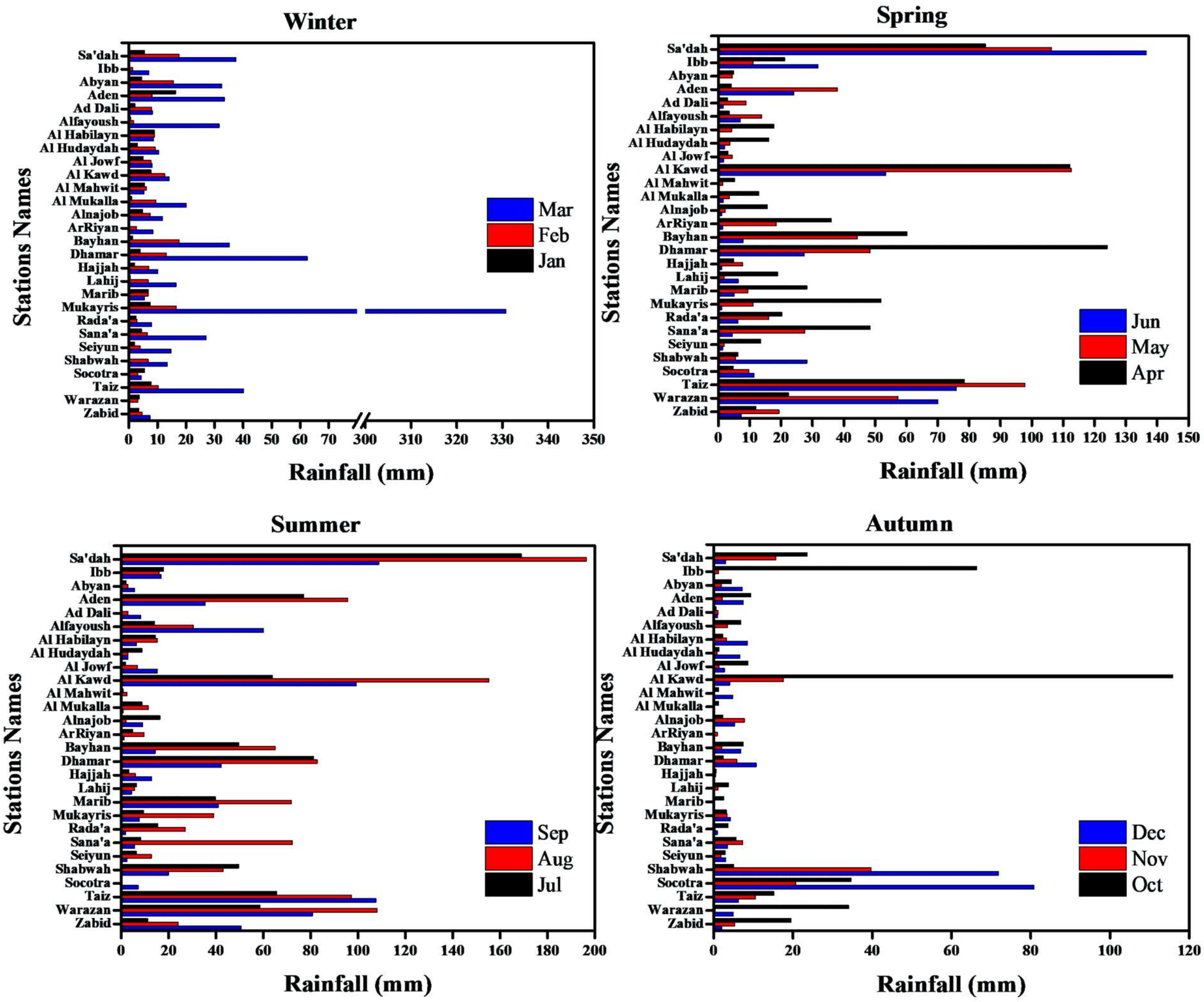


*Fig. 5* Seasonal variations in monthly precipitation in 28 stations at Yemen in 2010

*Table 1* The descriptive statistics and T-test results of wind speed

| Seasons | # of samples | MEAN | STDEV | SUM | MIN | MED | MAX | t- Statistic | DF | Prob>\|t\| (P) |
|---|---|---|---|---|---|---|---|---|---|---|
| Winter | 84 | 2.016 | 1.119 | 169.4 | 0.5 | 1.7 | 6.3 | 16.510 | 83 | 5.94563E-28 |
| Spring | 84 | 2.014 | 1.067 | 169.2 | 0.5 | 1.7 | 4.8 | 17.293 | 83 | 2.98687E-29 |
| Summer | 84 | 2.102 | 1.253 | 176.6 | 0.4 | 1.75 | 5.5 | 15.372 | 83 | 5.25922E-26 |
| Autumn | 84 | 2 | 1.354 | 168 | 0.5 | 1.5 | 7 | 13.529 | 83 | 1.06277E-22 |

Null Hypothesis, Mean=0; Alternative Hypothesis, Mean <>0; Winter - At 0.05 levels, the population mean is significantly different from the test mean; Spring - At 0.05 levels, the population mean is significantly different from the test mean; Summer - At 0.05 levels, the population mean is significantly different from the test mean; Autumn - At 0.05 levels, the population mean is significantly different from the test mean

*Table 2* The descriptive statistics and T-test results of temperature

| Seasons | # of samples | MEAN | STDEV | SUM | MIN | MED | MAX | t- Statistic | DF | Prob>\|t\| (P) |
|---|---|---|---|---|---|---|---|---|---|---|
| Winter | 84 | 36.541 | 5.518 | 3069.45 | 22.4 | 38.175 | 48.25 | 60.692 | 83 | 1.53413E-70 |
| Spring | 84 | 43.829 | 6.096 | 3681.7 | 29.7 | 44.775 | 54.45 | 65.888 | 83 | 1.92414E-73 |
| Summer | 84 | 45.168 | 7.236 | 4697.55 | 12.35 | 47.525 | 55.2 | 63.651 | 103 | 1.61097E-84 |
| Autumn | 84 | 37.138 | 6.559 | 3119.6 | 24.2 | 38.675 | 49.95 | 51.888 | 83 | 4.90731E-65 |

Null Hypothesis, Mean=0; Alternative Hypothesis, Mean <>0; Winter - At 0.05 levels, the population mean is significantly different from the test mean; Spring - At 0.05 levels, the population mean is significantly different from the test mean; Summer - At 0.05 levels, the population mean is significantly different from the test mean; Autumn - At 0.05 levels, the population mean is significantly different from the test mean

*Table 3* The descriptive statistics and T-test results of precipitation

| Seasons | # of samples | MEAN | STDEV | SUM | MIN | MED | MAX | t- Statistic | DF | Prob>\|t\| (P) |
|---|---|---|---|---|---|---|---|---|---|---|
| Winter | 84 | 13.728 | 36.572 | 1153.21 | 0 | 7.2 | 330.8 | 3.440 | 83 | 9.11391E-4 |
| Spring | 84 | 24.269 | 32.313 | 2038.62 | 0 | 10.35 | 136.5 | 6.883 | 83 | 1.02907E-9 |
| Summer | 84 | 33.046 | 41.469 | 2775.9 | 0 | 14.15 | 196.4 | 7.303 | 83 | 1.55517E-10 |
| Autumn | 84 | 9.345 | 18.869 | 784.98 | 0 | 3.25 | 115.8 | 4.538 | 83 | 1.89283E-5 |

Null Hypothesis, Mean=0; Alternative Hypothesis, Mean <>0; Winter - At 0.05 levels, the population mean is significantly different from the test mean; Spring - At 0.05 levels, the population mean is significantly different from the test mean; Summer - At 0.05 levels, the population mean is significantly different from the test mean; Autumn - At 0.05 levels, the population mean is significantly different from the test mean

*Table 4* Overall descriptive statistics

| Samples | # of samples | MEAN | STDEV | SE of Mean |
|---|---|---|---|---|
| Wind Speed | 336 | 2.033 | 1.199 | 0.06543 |
| Temperature | 336 | 40.649 | 7.478 | 0.40801 |
| Precipitation | 336 | 20.097 | 34.495 | 1.8819 |

*Table 5* One-way ANOVA/ Overall ANOVA

| | Sum of Squares | Mean Square | DF | F Value | Prob>F (P) |
|---|---|---|---|---|---|
| Model | 250866.449 | 125433.224 | 2 | 301.683 | 0 |
| Error | 417856.680 | 415.777 | 1005 | | |
| Total | 668723.129 | | 1007 | | |

Null Hypothesis - The means of all level are equal; Alternative Hypothesis - The mean of one or more level are different; At the 0.05 level, the population means are significantly different

The quality of linear regression is given in Table 6. Here, the R- Square or coefficient of determination (COD) value is nearer to/lies between 0 and 1and hence we can say that there is a strong relationship between the parameters analyzed.

*Tukey test and Homogeneity of Variance Test/ Levenes Test*

The Tukey test compares the means of the three groups to determine which group's mean is different (Table 7). It was discovered that the Sig value in all three cases is 1. The mean difference is significant at the 0.05 level, as evidenced by this. The homogeneity of variance test was also carried out.

*Table 6* Fit statistics

| R-Square | CoeffVar | Root MSE | Data Mean |
|---|---|---|---|
| 0.375 | 0.974 | 20.390 | 20.926 |

At the 0.05 level, it was discovered that there is a significant difference in variance (Table 8). Figure 6 shows a graphical representation of the data distribution.

Wind speed, temperature, and rainfall vary greatly from season to season and month to month (Table 9). The day-to-day fluctuations in the variability and differences in the climatic elements have a major impact on dust and sand storms, especially in Yemen's desert and semi-desert areas and surrounding areas (Akhtar, 2018).

*Correlation Test*

The correlations of climatic variables in all research samples are indicated in Table 9. To evaluate the linear relationship between seasonal variables, correlation analyses were conducted. The effects of the seasonal variation of all parameters, including wind speed, temperature, and precipitation, were analysed using correlation analysis. According to the overall statistical findings, there are fourteen positive and ten negative correlations that are significant at the 1 and 5% levels. By comparing the findings, we can see that the parameters have a greater positive correlation and are statistically relevant at the 1% stage. The power of the positive correlation, on the other hand, is weaker (Table 9).

*Table 7* Means comparison / Tukey test

| Comparison | MeanDiff | SEM | q-value | Prob | Alpha | Sig | LCL | UCL |
|---|---|---|---|---|---|---|---|---|
| Temperature / Wind Speed | 38.615 | 1.573 | 34.714 | 0 | 0.05 | 1 | 34.923 | 42.308 |
| Precipitation / Wind Speed | 18.064 | 1.573 | 16.238 | 0 | 0.05 | 1 | 14.371 | 21.756 |
| Precipitation / Temperature | -20.551 | 1.573 | 18.475 | 0 | 0.05 | 1 | -24.244 | -16.859 |

Sig equals 1, indicates that mean difference is significant at 0.05 level; Sig equals 0, indicates that the mean difference is not significant at the 0.05 level

*Table 8* Homogeneity of variance Test/ Levenes test

| | Sum of squares | Mean square | DF | F-value | Prob>F |
|---|---|---|---|---|---|
| Model | 76810.833 | 38405.416 | 2 | 153.977 | 0 |
| Error | 250668.914 | 249.421 | 1005 | | |

At the 0.05 level, the population variance is significantly different.

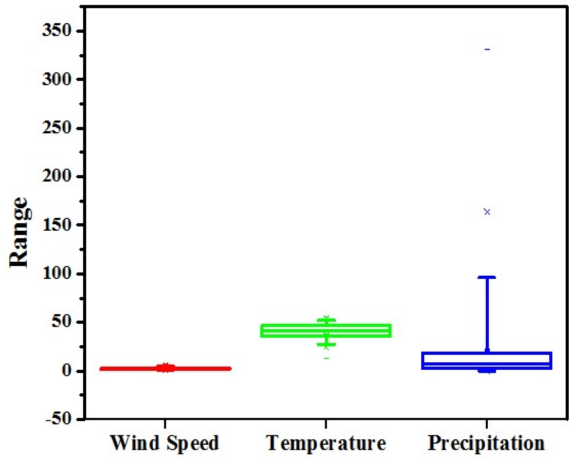


*Fig. 6* Graphical representation of data distribution (wind speed, temperature, and precipitation)

There are fourteen positive correlations and ten negative correlations in all the studies analyzed since the majority of the correlations between the parameters are statistically insignificant. The most significant positive correlation between variables was found, while the others were all negative.

### *Impact of dust and sand storm*

Dust storm and sand storm have both positive and negative effects on the environment.

*Negative impact of dust and sand storms*

Dust and sand storms have impact on the main roads, which are linked to an internal network between the highland, coastal regions and island region. Hoddeidah, Aden, and Hadramout are Yemen's most important cities and ports, and they serve as the country's key transportation hubs. Yemen and Saudi Arabia are linked by an international line in this area. Furthermore, desert areas are of similar significance in terms of transportation routes. Yemen is linked to Saudi Arabia via the Al Jowf and Marib international lines, while the country is linked to Oman via the governorates of Shabwah, Hadramout, and Al Mahrah. Sands and dust storms minimize the horizontal visibility on these highways, resulting in horrific traffic accidents (Notaro et al., 2013). Besides, the accumulation of sand on all major roads and sub-roads is a problem, as it triggers the closing of some of them, and drivers who are unaware of the sandstorm's occurrence have their vehicles crash, resulting in major material and human injuries.

Sandstorms transport sand and dust to agricultural lands, destroying crops, especially those that can't withstand the force of wind or the deposition of sand and dust. Meanwhile, farmers are trying to restore agricultural lands that have been buried by sand. Year after year, sand and dust storms intensify desertification in arid and semi-arid regions. The storms also transport certain plants and crop diseases from the blown-out areas to the target lands. There have been a few cases when fungi have been transported from the south of Saudi Arabia to Yemen by these storms and have directly affected plants (Stefanski & Sivakumar, 2009).

Sand and dust storms cause large-scale economic losses in the short term as well, such as livestock disease leading to death, crop destruction, building and infrastructure damage, and vehicle damage. Besides, to clean the accumulated sand and dust, costs a lot of money (Sufian et al., 2017). Sand storms are having a big effect on Yemeni tents. Due to war in some areas, such as the Aljafnah camp in the Marib governorate in August 2018, the majority of people took refuge in tents. These storms have raised their tents. Similarly, tents were raised in areas where African refugees fled their countries due to violence and found refuge in UN refugee shelters along the coast. Owing to the extreme dust storm that passed through those regions, many schools and educational institutions were forced to close. Aden city was recently subjected to violent dust storms on September 11, 2019, with winds exceeding 22 km/h and a temperature of 35°C (according to the National Center for Meteorology and in Aden).

*Table 9* Correlation of all studied variables during the seasons

| Variables | | Wind | | | | Temperature | | | | Rainfall | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Wi | Sp | Su | Au | Wi | Sp | Su | Au | Wi | Sp | Su | Au |
| Rainfall | Au | NS | NS | NS | NS | NS | NS | NS | NS | NS | .245* | NS | |
| | Su | NS | NS | NS | NS | -.328** | -.395** | -.509** | -.300** | NS | .778** | | |
| | Sp | NS | NS | NS | NS | -.381** | -.438** | -.454** | -.266* | NS | | | |
| | Wi | NS | NS | NS | NS | NS | NS | -.263* | -.288** | | | | |
| Temperature | Au | NS | NS | NS | NS | .683** | .657** | .733** | | | | | |
| | Su | NS | NS | NS | NS | .666** | .720** | | | | | | |
| | Sp | NS | NS | NS | NS | .933** | | | | | | | |
| | Wi | NS | NS | NS | NS | | | | | | | | |
| Wind | Au | .800** | .802** | .665** | | | | | | | | | |
| | Su | .697** | .785** | | | | | | | | | | |
| | Sp | .858** | | | | | | | | | | | |
| | Wi | | | | | | | | | | | | |

Wi = winter, Sp = Spring, Su = Summer and Au = Autumn

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed) and NS = Non Significant

In the long run, it involves soil degradation, habitat pollution, and desertification, as well as the costs of health care and wasted labor. According to a UN (United Nations) survey published in 2016, dust storms and the sediments resulting from sand and dust storms cost the Arab region's total local production about 13 billion dollars per year. It obstructs irrigation canals and covers drainage routes, causing contamination of river water and streams (Prakash et al., 2015; Karagulian et al., 2019). Dense dust is highly dangerous during aircraft landings and takeoffs, causing landing positions to be changed and takeoff times to be postponed. The engines are damaged by the effect of dust on the aircraft's surface (Notaro et al., 2013). Solar power plants, particularly those that depend on direct solar radiation, are also influenced by dust. Keeping solar collectors clean of dust so that dust particles do not obstruct the incoming radiation which takes time and effort, and is a major source of concern for station operators.

*Positive impact of dust and sand storm*

The renewal of the soil is a beneficial result of sand and dust storms. During dust storms, loads of dust is transported to the troposphere, from where it is deposited during a calm weather or rain, and falls on the ground in areas hundreds of kilometers away from the dust storm's origin. This dust becomes mixed with the soil and can transfer to sedimentation areas. Thousands of tons of new soil are applied annually for agricultural terraces in the bottom and above the surface layer of Yemeni land, which are affected by sand storms and dust. Dust storms and dust contribute in plant pollination, as well as the movement of certain plant seeds from the source to the destination areas. An investigation found that new plants, which were previously unknown in many areas of Yemen, originated in desert and semi-desert areas and were carried by storms. (Karagulian et al., 2019).

The dust serves as a soil fertilizer and assists in the ripening of fruits. The dust layer that forms above the fruits in Yemen aids in their rapid ripening. The dust in the wet ripening of palm products in the Tihamah plain helps farmers in that area. Instead of using pesticides and industrial fertilizers, farmers in many areas use dust to regenerate fresh leaves and speed up their development. Nutrient minerals (e.g. iron) and other elements in the dust are beneficial to land and water ecosystems. Hawaii's rain forests get their nutrients from dust brought by the wind from Central Asia. Phytoplankton in the Mediterranean Sea benefit from metals and nutrients brought by desert winds coming from the north of Libya and the Sahara dust provides phospholipids additives that offset the loss of the Amazon rainforest as a result of river flow. The Mediterranean Sea's habitats, which form the plankton at the base of its food pyramid, are being threatened by rising drought in the upper soils (Forner et al., 2018).

*The effects of dust on human health*

The dust storm and dust in air can cause allergy of the eye, of the nose and ear, asthma attacks, dermatitis, and it can negatively influence the condition of people with cardio-vascular diseases. Fine dust enters the eye and causes conjunctivitis in the eyelids region, causing redness and itching, as well as tears (World Health Organization, 2013; Aili & Oanh, 2015).

The small dust particles brought by dust storms (Fig. 7) can get into the respiratory system, causing inflammation of the mucous membranes, clogged noses, and respiratory irritation when inhaled. It also induces shortness of breath when exerting physical activity, as well as an itchy nose that can spread to the eyes and ears. They can even make the nose run, in case of increased sensitivity, nosebleeds can appear (Ghio et al., 2014; Gross et al., 2018). The ear's sensitivity to dust causes inflammation, which causes extreme itching (World Health Organization, 2013; Ghio et al., 2014; Aili & Oanh, 2015). Dust asthma attacks are also common, particularly if the person is exposed to dust because dust can carry bacteria and pollen that cause asthma (World Health Organization, 2013; Ghio et al., 2014; Aili & Oanh, 2015; Gross et al., 2018). When some people inhale dust, it causes skin inflammation, especially eczema, which causes itching (World Health World Health Organization, 2013; Ghio et al., 2014; Aili & Oanh, 2015). Chest diseases affect a large percentage of heart patients. Because of their susceptibility to dust particles, they suffer from heart muscle inflation and high pulmonary arterial pressure, which contributes to emphysema and capillary breakage (World Health Organization, 2013; Ghio et al., 2014; Aili & Oanh, 2015; Gross et al., 2018).

*Problems faced by the Yemen Government relating to the dust and sand storms phenomenon*

The Yemeni Government is grappling with a slew of issues related to dust and sand storms. The absence of advanced meteorological stations, for precisely monitoring and recording this phenomenon. The shortage of well- equipped laboratories. Scientific evidence related to this phenomenon is unavailable due to a lack of financial resources and hence financial support or sufficient funding is very essential. There is a lack of knowledge about environmental initiatives related to this phenomenon and how to deal with it both before and after it happens. There are no short or long-term plans or initiatives in place to mitigate or eliminate the risk associated with this phenomenon that exists across wide areas of Yemen. If the Yemeni government can update and fix all of the above-mentioned problems, we can at least reduce the potential impact of the dust storm and sand storm in Yemen.

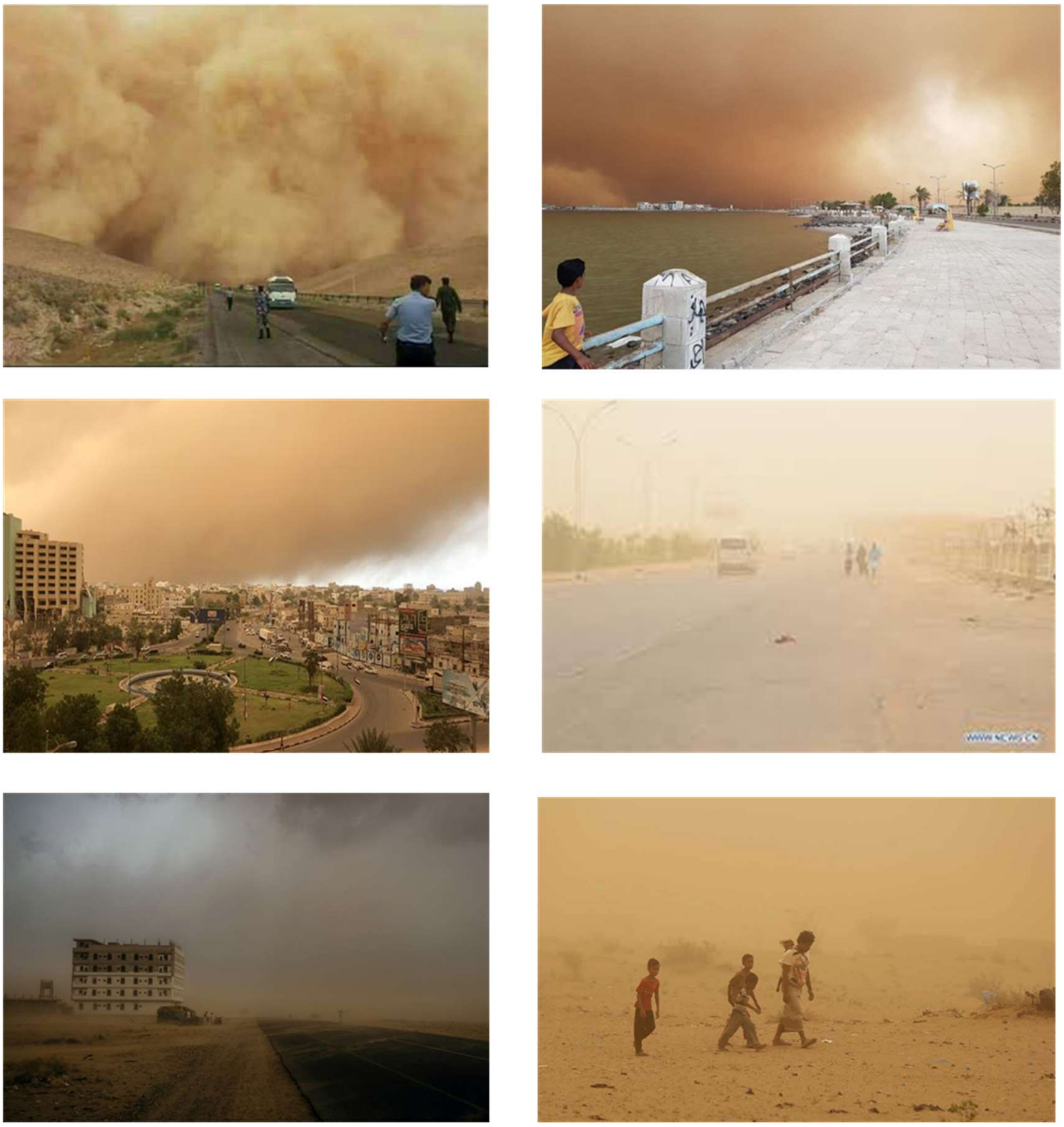

*Fig. 7* Heavy dust storms crossing some of the Yemeni cities (source: Yiannopoulos, 2018)

## CONCLUSION

Yemen is affected by dust all over year, although it is less prevalent in the winter and more prevalent in the summer, although it is unpredictable in the spring and autumn due to the general weather condition. Coastal areas (Hajjah, Hoddeidah, Taiz, Lahg, Aden, Abyan, Shabwah, and Hadramout) and desert areas (Marib and Al Jowf) are the most affected by dust and sandstorms during the year, while the western and central governorates of Yemen in the mountainous region are predominantly affected by dust over the winter. Wind speeds in coastal areas such as Al Hudaydah (4.9 m/s), Al Mukalla (3.8 m/s), and Aden (4.09 m/s) rise in intensity. The equability of the surface, the contrast heat between the surface water, the relatively low air pressure, and land adjacent to it all contribute to the change in wind speed. Yemen is subjected to different air blocks, originating in the north and south, forming spring, air turbulence, and rainfall, particularly in the central and southern areas, as atmospheric pressure rises in the southern hemisphere. In between summer season, rain continues to fall until mid-September, as the result of the return of the northeast storms. Different atmospheric pressures generate different forms of wind, including sea and land breezes, mountain and valley breezes, Fohen, Al Ghawbah, and warm (Al-Kawi) winds. The presented research shows that environmental factors play an important role in the creation of dust and sand storms. According to the statistical analysis, environmental parameters are significantly correlated with one another, resulting in the development of dust and sand storms. Dust storms in Yemen have several effects on humans, animals, plants, and all-natural habitats, and they can be categorized as both positive and negative based on their impact on environmental components.

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