Hydro-Meteorological Trends and Thermal Comfort of Khartoum Sudan

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Abstract. This study looked at the trends in hydro-meteorological parameters (relative humidity, temperature, rainfall, and wind speed) in Khartoum, Sudan, from 1965 to 2020. The hydro meteorological data used in this study were obtained from the Khartoum Meteorological Station. The above parameters were statistically investigated, and their trends were established using Microsoft excel. The thermal comfort details for Khartoum were also analyzed on a monthly and seasonal basis. The trends of hydro-meteorological parameters and the analysis of the thermal comfort results revealed that Khartoum has experienced global warming, which causes a drop in thermal comfort.

Keywords: Khartoum · Rainfall · Relative humidity · Temperature · Thermal comfort · Wind speed

1 Introduction

The relevance of hydrological data in climate studies cannot be overstated. Hydrological resources, on the other hand, cannot be effectively managed without knowledge about their location, quantity, quality, and likelihood of availability in the foreseeable future. Water management and modelling, climate change research, flood modelling and forecasting, and other hydrological research activities all require hydrological data records. Due of the prevailing conflict in developing countries such as Sudan, gathering hydrological data is challenging. As a result of inadequate documentation and poor data archive management, large amounts of data are lost. It has been extensively reported that monitoring of the Earth's hydrology declined in the late twentieth century. The World Meteorological Organization (WMO) performed research in 2006 that demonstrated widespread international concern about the status of historical data records and the necessity for data rescue initiatives in virtually all countries (Fry 2010). The Khartoum meteorological station has been a major source of concern for climate researchers because of this

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hydro-meteorological data trend analysis. Furthermore, the city has experienced many extreme climatic incidents in recent years (Osman & Sevinc 2019).

Since the previous century, many researchers exploring the built environment have focused their attention on the evaluation of weather indicators. Thermal comfort is an important consideration in building research since it has a significant impact on the overall quality of a building. On the other hand, hydro-meteorological data collected in the intended design location has a significant impact on thermal comfort. A thermally comfortable built environment necessitates careful consideration of hydro-meteorological data.

Temperature, relative humidity, and rainfall are some of the climatic variables that are examined in climate change research, which can lead to frequent and extreme weather events (Ahmed et al. 2014). Policymakers throughout the world have used research findings from meteorological station data to develop long-term planning and prevent calamities. When evaluating the hydrology of earlier years, time series analysis provides a tremendous advantage (Mirza et al. 1988; Shi & Xu 2008; Ahmed et al. 2014).

Temperature, rainfall, and wind speed data patterns were analysed in the first half of this study whereas Khartoum city thermal comfort details were analysed in the second phase of this study. From 1965 to 2020, linear trends were drawn for all hydro-meteorological parameters examined in this study to identify their increasing or decreasing tendency based on seasonal changes in the year. The computer-based programme Climate Consultant 6.0 is used to undertake a thermal comfort assessment for Khartoum. This computer software requires the energy plus weather (EPW) file. The relevant computations were performed using the available weather files between 1965 and 2020, which were typically based on hourly values. In this study, because the Khartoum Metrological Station does not keep track of hourly climatic data, the EPW file was created using average data imported from the Meteonorm 7.2 programme (Meteonorm 2018). Furthermore, two thermal comfort models are employed to calculate the thermal comfort zone for Khartoum: the adaptive comfort model and the ASHRAE Standard 55 with its current handbook of fundamental models.

2 Study Area

Khartoum is the capital of the Republic of Sudan, and it is in the central part of the country, where the White and Blue Niles converge and flow into the Mediterranean Sea, much like the Nile River does in Egypt. The two rivers meet in the shape of an elephant's trunk (al-Khartûm – elephant's trunk in Arabic), as shown in Fig. 1 (Osman & Sevinc 2019). The data for this study was obtained from the Khartoum meteorological station, which is located at 15°33′06″ N latitude and 32°31′56″ E longitude and has an average height of 380 m above mean sea level (Shakurov et al. 2016).

Fig. 1. The geographical location of Khartoum City Center (Osman & Sevinc, 2019).

2.1 Climatic Condition of the Region

Khartoum's summer climate is hot and dry, with low relative humidity during the hot period, interrupted by scanty light rain showers. During the dry season (winter), temperatures are normally cold in the early morning and warm at midday, with low relative humidity.

Khartoum is classified as having a hot-arid climatic zone by the Köppen climate classification. Earlier research conducted by Elagib and Mansell (2000), classified the city's climate into three seasons: (1) the dry season (winter) consists of the months of November, December, January, and February, (2) the summer season begins in March and ends in May, and (3) the wet season (autumn) lasts from June through October.

2.2 Thermal Comfort

Thermal comfort, a critical aspect of building design since human life began (Iyendo et al. 2016), has been defined as the state of mind that reflects satisfaction with the thermal environment and is subjectively judged (ANSI/ASHRAE 2017). People nowadays spend between 80% and 90% of their daily time indoors (Rupp et al. 2015; Kuchen 2016). This brings the importance of thermal comfort to the attention of building and environmental researchers. However, global population growth has coincided with an increase in urban densities, resulting in significant thermal stress and health risks. These circumstances need the development of a long-term or sustainable measure of thermal comfort. Such a measure can assist building designers in designing climate-responsive buildings that lessen dependency on fossil fuels (Hirashima et al. 2018). The goal of our research is to calculate the thermal comfort zone of Khartoum using two thermal comfort models: the adaptive comfort model and the ASHRAE Standard 55 with its current handbook of essential models (ANSI/ASHRAE 2017).

Thermal Comfort Model
Climate Consultant 6.0 was used to calculate the thermal comfort of Khartoum city (EPW), using the Energy Plus Weather File. The EPW file was calculated using the average climate data for the city from 1996 to 2020. Most weather data are based on hourly climatic parameter values. There are no records of hourly climate data at the Khartoum Metrological Station. As such, the average data was imported into the Meteonorm 7.2 program to generate an EPW file using the following procedure: Meteonorm takes the long-term monthly averages of the parameters. With a stochastical process (Markov Chains), daily and then hourly values are synthetically generated. For the derived radiation parameters, diffuse and direct irradiance, are calculated using the Perez model to split the global radiation value into the diffuse and direct part (Albatayneh et al. 2017; Meteonorm 2018).

ASHRAE Standard 55 with Current Handbook of Fundamental Model
With the current handbook of thermal comfort model, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55 considers dry bulb temperature, clothing level (clo), metabolic activity (met), air velocity, humidity, and mean radiant temperature (MRT). The Predicted Mean Vote (PMV) model is used to determine or calculate the comfort zone for most people. Furthermore, the adaptive comfort model indicates that in residential buildings, which are mostly naturally ventilated, people adjust their apparel to match seasonal conditions and feel at ease in greater air velocities. Accordingly, they have a greater range of comfort than those in buildings with central air conditioning (Altahir 1988).

3 Results and Discussions

A trend analysis technique was evaluated for climate data from 1965 to 2020 to observe seasonal and monthly fluctuations in climatic factors. Appropriate months that define Khartoum's seasons are categorised, and seasonal long-term averages of hydro-meteorological data (relative humidity, dry bulb temperature, rainfall, and wind speed) are considered.

3.1 Season-Based Trends Analysis

Dry Season (Nov, Dec, Jan, and Feb)
The winter (dry season) in Khartoum is marked by extremely low relative humidity (RH), which ranges between 8 and 10%. As seen in Fig. 2, the RH has been falling by about 0.02% annually during the Dry Season.

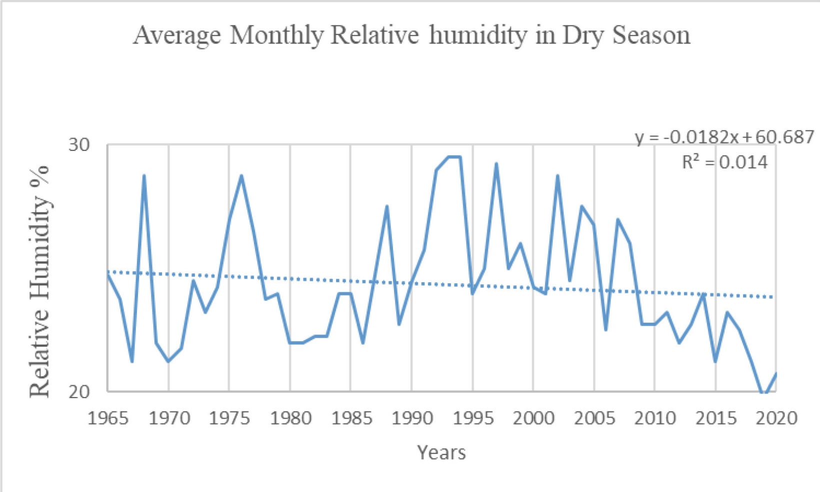

Fig. 2. Linear trends analysis of relative humidity of dry season, Khartoum Sudan for 1965–2020.

On the other hand, as shown in Fig. 3, the seasonal temperature rises by 0.03 °C/year based on linear trend analysis.

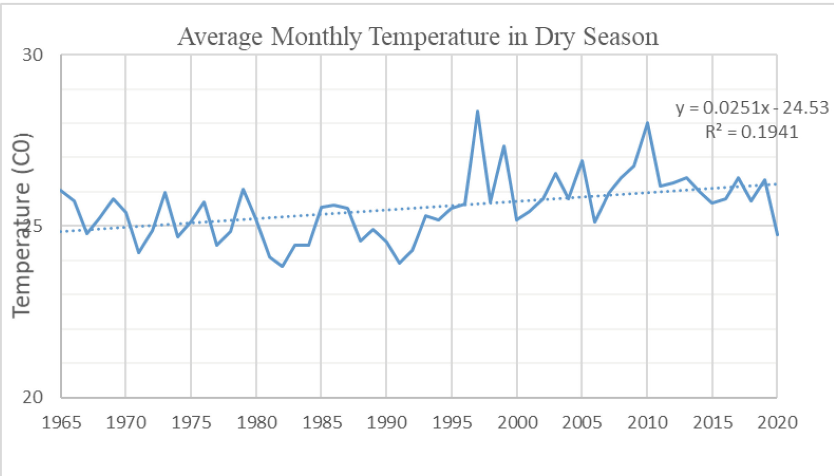

Fig. 3. Linear trends analysis of temperature of dry season, Khartoum Sudan for 1965–2020.

According to Tahir and Yousef (2013), plant cover reductions accounted for both the drop in RH and rainfall. However, it was discovered in this study that seasonal rainfall decreased by 0.005 mm/year during the study period, as seen in Fig. 4.

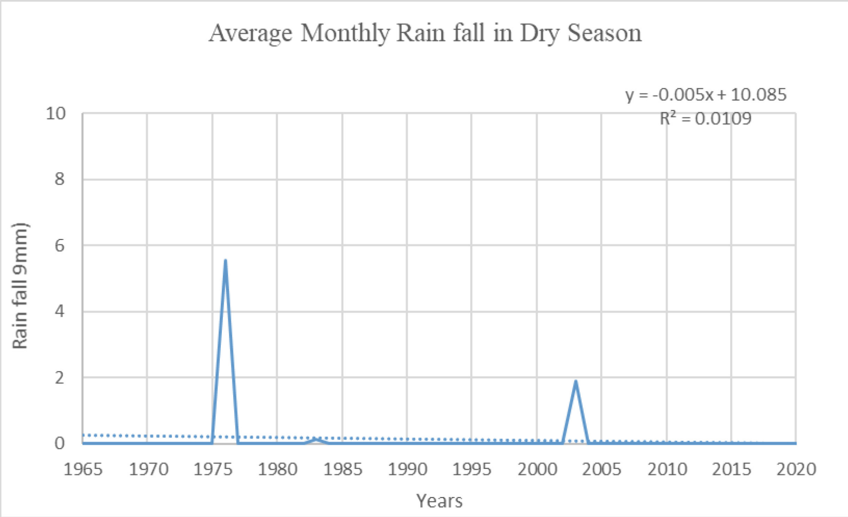

Fig. 4. Linear trends analysis of rainfall of dry season, Khartoum Sudan for 1965–2020.

The Dry Season in Khartoum has traditionally been marked by northern winds passing through the greater desert, followed by dust and sandstorms. Dust and sandstorms are more often than ever before, demonstrating the effects of climate change. Similarly, as shown in Fig. 5, a trend analysis of wind speed revealed an annual rise of 0.003 m/s.

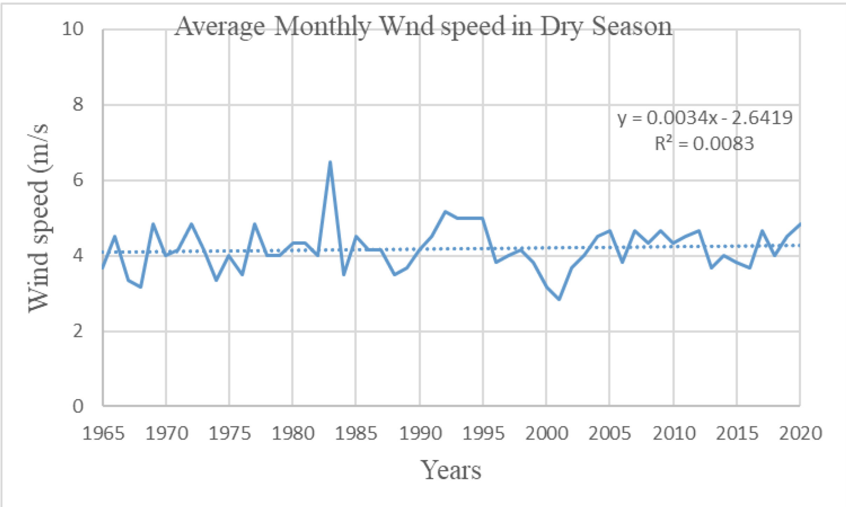

Fig. 5. Linear trends analysis of wind speed of dry season, Khartoum Sudan for 1965–2020.

Hot Season (March, April, and May)
Khartoum's hot (summer) season features low relative humidity, with temperatures reaching 40 °C in some areas. As illustrated in Fig. 6, this study's trend analysis revealed a 0.3% yearly decrease in RH. There is a significant reduction in the year 1975, showing strong climate fluctuations.

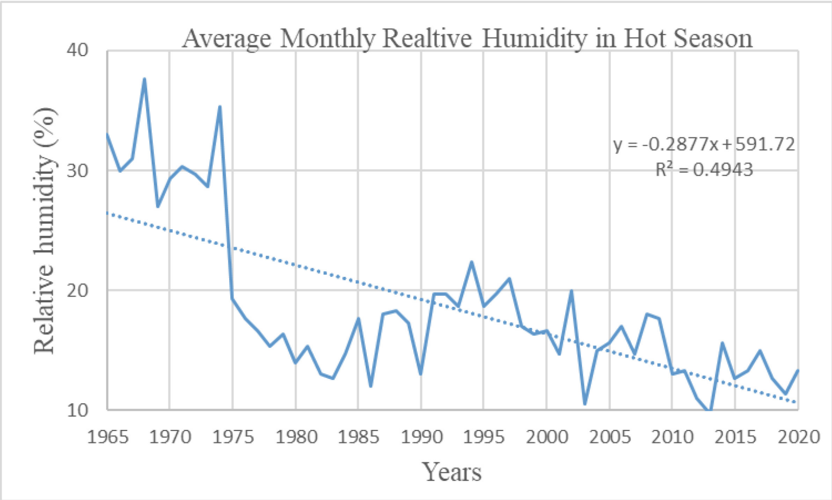

Fig. 6. Linear trends analysis of relative humidity of hot season, Khartoum Sudan for 1965–2020.

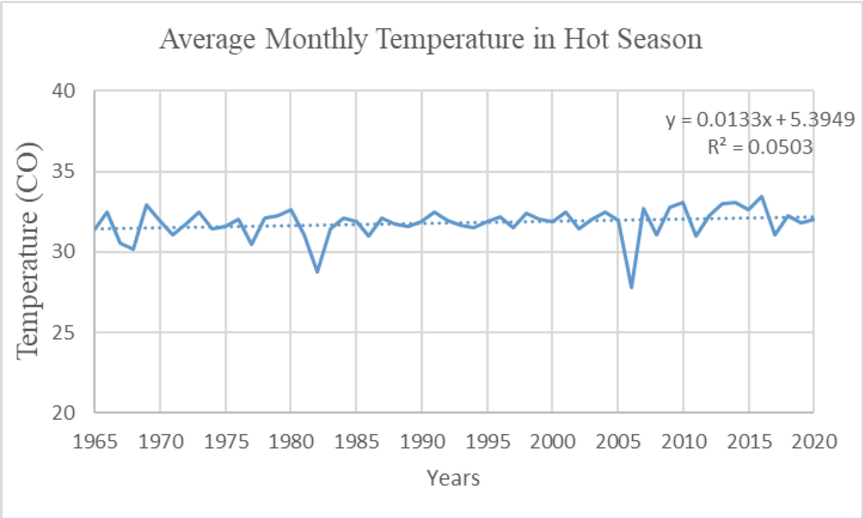

Fig. 7. Linear trends analysis of temperature of hot season, Khartoum Sudan for 1965–2020.

As seen in Figs. 7, 8, and 9, there is an annual rise of 0.01 °C in temperature, 0.0003 mm in rainfall, and 0.003 m/s in wind speed throughout this season. These findings show that there has been a climatic shift during the hot seasons from 1965 to 2020, which is consistent with Yousif and Hashim (2013) who revealed that Khartoum was the hottest city in the world in 2009 (Osman & Sevinc 2019).

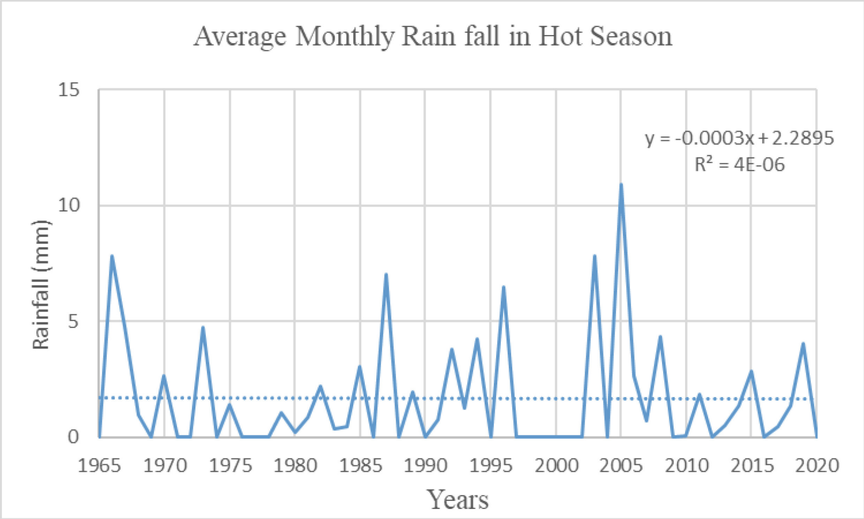

Fig. 8. Linear trends analysis of rainfall of hot season, Khartoum Sudan for 1965–2020.

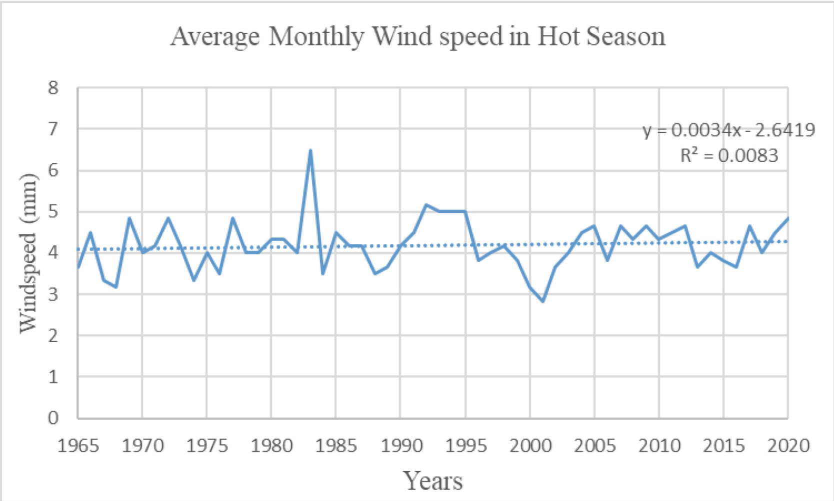

Fig. 9. Linear trends analysis of wind speed of hot season, Khartoum Sudan for 1965–2015.

Wet Season (June, Jul, Aug, Sept, and Oct)
The wettest month in Khartoum is August, which falls during the autumn (wet) season. As seen in Fig. 10, there was a 0.06% annual rise in RH. This may be considered a sign of climate change on its own, but Khartoum also saw an annual temperature increase of 0.01 °C over this period, as seen in Fig. 11.

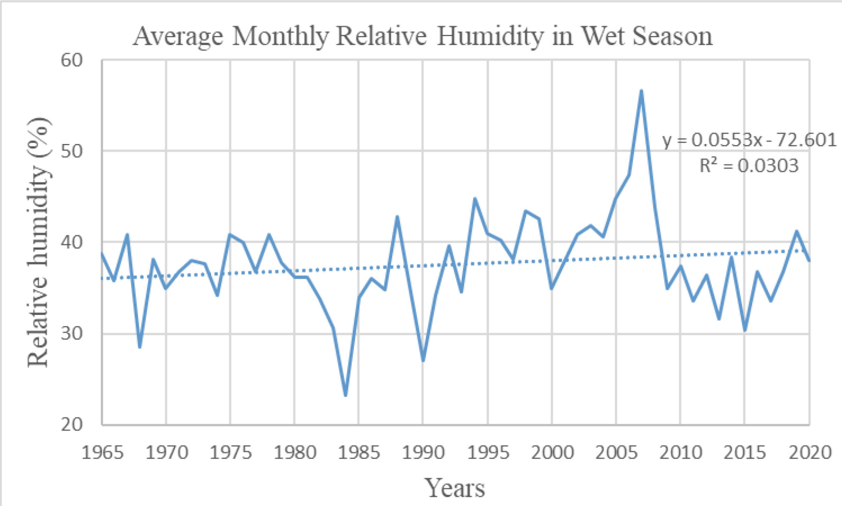

Fig. 10. Linear trends analysis of relative humidity of wet season, Khartoum Sudan for 1965–2020.

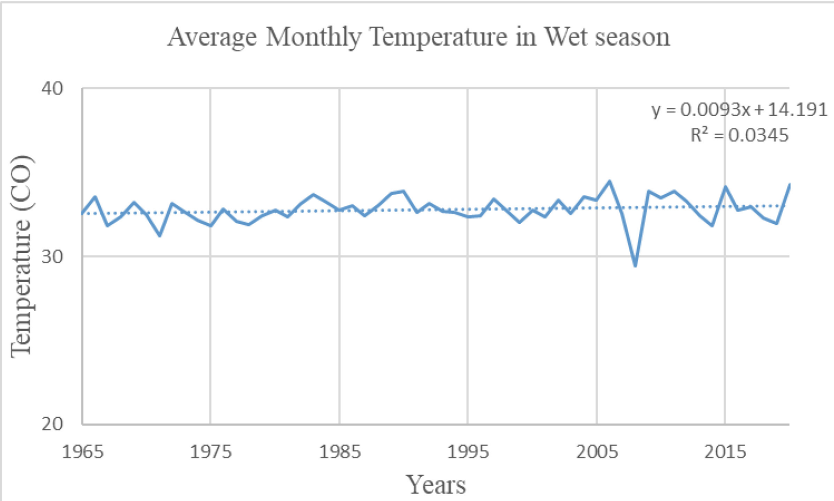

Fig. 11. Linear trends analysis of temperature of wet season, Khartoum Sudan for 1965–2020

Despite a 0.12 mm decrease in annual rainfall during this season, as seen in Fig. 12, the area experienced significant floods due to high rainfall events in 1988, 2003, 2007, and 2009. Despite the decrease in rainfall, there was a 0.01 m/s annual rise in wind speed, as seen in Fig. 13. These findings are consistent with Altahir (1988), and Tahir and Yousif's (2013) investigations.

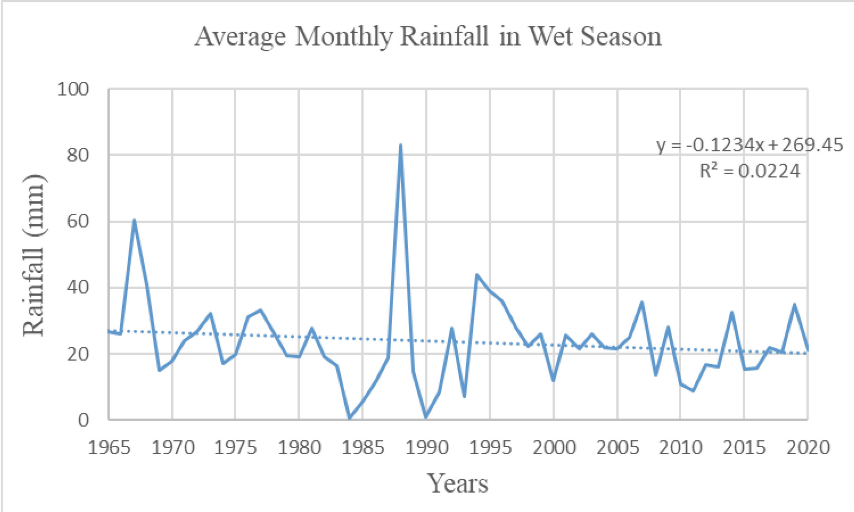

Fig. 12. Linear trends analysis of rainfall of wet season, Khartoum Sudan for 1965–2020

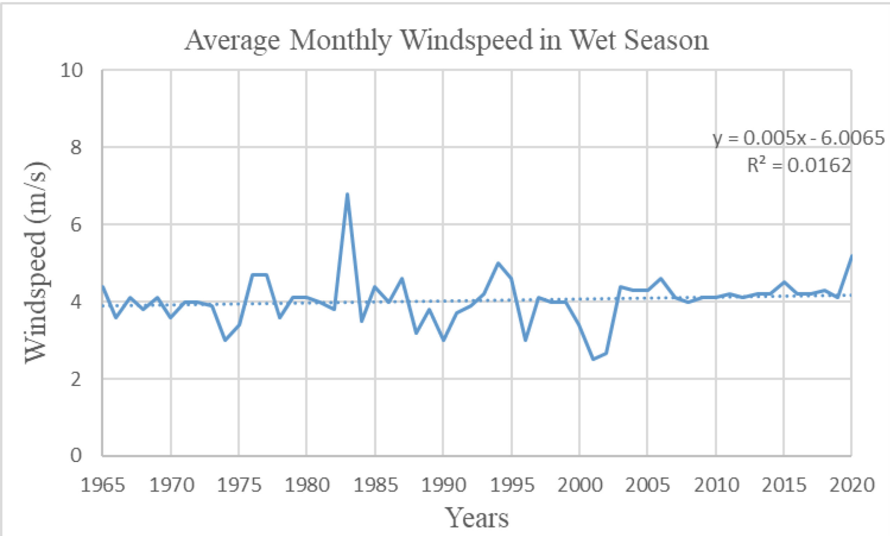

Fig. 13. Linear trends analysis of wind speed of wet season, Khartoum Sudan for 1965–2020

3.2 Thermal Comfort of Khartoum

Without the use of mechanical cooling systems, it is impossible to attain 100% thermal comfort. Even with thermal-comfort strategies and a mechanical cooling system, Khortum can only achieve 72.9% thermal comfort (i.e., 6385 h out of 8760 h), as shown in Fig. 14. The adaptive comfort model raised the comfort range from 21.3% to 24.2%. The little differences gained via this research are due to the contribution given to global horizontal solar radiation control and relative humidity alteration using a thermal comfort model. It should be emphasised that, in recent decades, the drop in relative humidity as a result of reduced plant cover in the city may have also been an influencing factor.

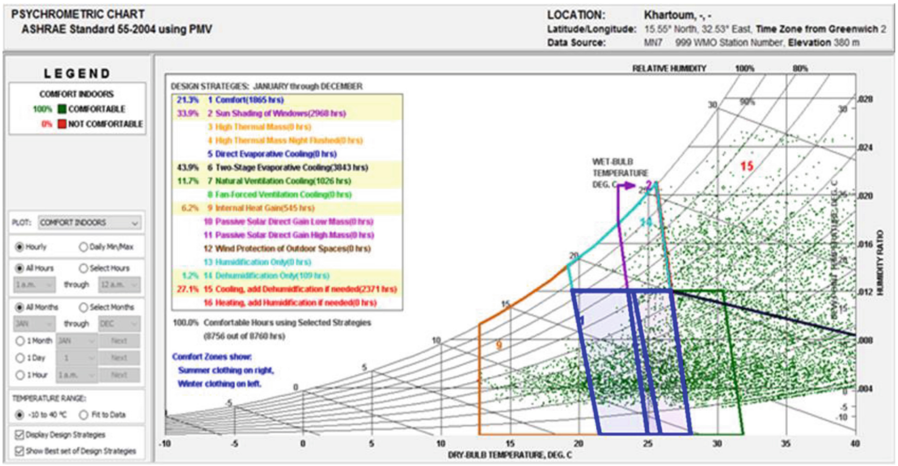

Fig. 14. Psychometric chart with climate-responsive design strategies applied to the city of Khartoum (Meteonorm 2018)

Table 1. Design strategies of seasons based a whole day data for Khartoum

Seasons (months)	Time schedule	Temperature (min-max °C)	Humidity (min-max %)	Thermal comfort without applying design strategies (hours/ year; %)
Dry (Nov, Dec, Jan& Feb)	6 am–12 noon	12.7–38.5	18–56	43.5%
	12 noon–6 pm	19.2–40.6	10–59	15.7%
	6 pm–12 midnight	13.5–36.3	10–34	52.6
	12 midnight–6 am	12.5–30.3	13–47	53.8%
Hot (March, Apr & May)	6 am–12 noon	17–43.5	17–46	53.8%
	12 noon–6 pm	20.2–45.4	10–43	23.4%
	6 pm–12 midnight	20.2–41.2	10–20	0.2%
	12 midnight–6am	16.6–35.1	11–34	13.7%
Wet (Jun, Jul, Aug, Sep & Oct)	6 am–12 noon	22.7–43.9	20–99	4.6%
	12 noon–6 pm	26.3–43.9	12–93	0%
	6 pm–12 midnight	24.9–43.9	11–88	1.1%
	12 midnight–6 am	21.5–42.4	18–84	13.2%

Table 1 shows the thermal comfort for a complete day in Khartoum on a seasonal basis, Table 2 shows the monthly fluctuations, and Table 3 shows the season-based thermal comfort for Khartoum.

Table 2. Monthly based thermal comfort for Khartoum

Months	Comfort (%)	Comfort hours	Total hours
January	28.4	211	744
February	27.8	187	672
March	28.1	209	744
April	26.4	190	720
May	6.3	47	744
June	0	0	720
July	18.1	135	744
August	33.2	247	744
September	30.8	222	720
October	30	223	744
November	32.9	237	720
December	28.4	211	744
Annual	24.2	2119	8760

Table 3. Seasonal based thermal comfort for Khartoum

Design strategies	Dry season	Hot season	Wet season
Thermal Comfort	41.7% (1200 h)	22.9% (506 h)	4.3% (159 h)

4 Conclusion

In this study, the average monthly values were used to conduct a seasonal trend analysis of Khartoum's hydro-meteorological data sets from 1965 to 2020. The following findings emerged from the analysis: Relative humidity (RH) decreases in the dry and hot seasons while increasing in the rainy (wet) season. Temperatures rise in all three seasons of the year, but rainfall decreases in all three seasons as well. Khartoum's thermal comfort level in these seasons is usually reduced when humidity drops in the dry and hot seasons. Although wind speed rises throughout the year, it may be beneficial for improving thermal comfort, but it may not contribute much to increasing the degree of thermal comfort.

The greatest thermal comfort in Khartoum, Sudan is 41.7% (1200 h) during the dry season, while the lowest is 4.3% during the wet season (159 h). As a result, the dry season is regarded as the most pleasant of Khartoum's climatic seasons. Conclusively, it should be highlighted that the Khartoum climatic region has seen climate change in these time series (1965–2020) as temperature increases, rainfall decreases, and more frequent sand-dust storms and floods. They would undoubtedly diminish the region's thermal comfort.

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