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Beyond the 24-hour norm: PM2.5 air quality challenges at athletics events in South Africa

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ABSTRACT
The health implications of particulate matter 2.5 (PM2.5) exposure are well documented, particularly its penetration into the respiratory tract, posing serious health risks. This prospective longitudinal study investigates PM2.5 exposure levels during athletics events in South Africa, highlighting the short-term exposure risks for athletes. PM2.5 concentrations were measured at four events across rural, central metropolitan, and industrial metropolitan settings in 2023. Results indicated significant variations in PM2.5 levels, with mean concentrations ranging from 28.6 μg/m^3 in rural areas to 132.7 μg/m^3 in industrial metropolitan regions, exceeding WHO 24-hour exposure recommendations. Factors such as local industries and cooking methods at event sites contributed to these elevated levels. The findings underscore the need for establishing short-term PM2.5 exposure standards for outdoor activities, where added respiratory stress from exercise could exacerbate underlying conditions; we also highlight the importance of location selection to mitigate health risks for athletes.

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Introduction

Particulate matter 2.5 (PM2.5) constitutes microscopic particles with diameters less than 2.5 micrometres (μg/m^3). These particles originate from various anthropogenic and natural sources, including vehicle emissions, industrial processes, fuel combustion, and pollen release (Howlett-Downing et al. 2023). The health implications of PM2.5 exposure are due to their capacity to penetrate the respiratory tract; ultra-fine pollutants (usually <0.01 μm) are a subset of PM2.5 and can reach more sensitive areas of the respiratory system compared to PM2.5. All PM2.5 particles bypass the body's natural defences and can infiltrate the lungs and bloodstream, initiating possible adverse health effects (Analitis et al. 2006). Short-term consequences can include respiratory symptoms such as coughing and breathlessness, which have been postulated to impact an athlete's performance (Nieckarz and Zoladz 2020; Zacharko et al. 2021, 2022). However, the health repercussions of chronic exposure are far more severe, potentially leading to cardiovascular disease (Dominici et al. 2006; Brook et al. 2010). Consequently, the monitoring of PM2.5 concentrations in the ambient air is a critical factor in athlete health, particularly at outdoor sporting events (Giles and Koehle 2014). It provides valuable insights into the air quality athletes are exposed to, enabling interventions aimed at mitigating detrimental health effects and optimising performance. The effect of other environmental factors, such as wet-bulb globe temperature (WBGT), humidity, and wind, should also be taken into account when assessing PM2.5 concentrations. Recognising this growing health risk, World Athletics launched its Air Quality project in 2019 (World Athletics 2019), intending to have 1000 Air Quality Measurement Stations (AQMS) at various stadiums worldwide, allowing organisers and athletes to make informed decisions about their participation in events. These studies saw minimal PM2.5

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concentrations, with a median of 12–16.5 μg/m^3 (Reche et al. 2020), indicating very low levels. In one study during a marathon, higher values have been shown, reaching 80 μg/m^3, and in extreme cases, concentrations up to 287 μg/m^3 have been recorded (Guo and Fu 2019; Ribalta et al. 2024). However, there are no data currently from South Africa's stadia.

There is a significant gap in understanding and addressing this issue. The exposure that athletes face during sports events to PM2.5 and other harmful pollutants typically spans shorter durations – during training, warm-up, and the main competition. This brief exposure does not align with the standard 24-hour exposure average health agencies commonly use to quantify health impacts (Griffiths et al. 2018). In certain regions, athletes, particularly those from underprivileged backgrounds, might endure high pollutant levels daily during training and normal lifestyle activities, intensifying the adverse effects (Cohen et al. 2021). Prior research on short-lived exposures, such as those reviewed by Griffiths et al. (2018), predominantly involves non-athletic groups like volunteers, soldiers, and firefighters. These studies highlight a surge in inflammatory responses and/or the presence of proinflammatory proteins. For athletes, the health implications could be even more pronounced. As exercise transitions from moderate-to-severe intensity, not only does the volume of inhaled air increase, but the efficiency with which ultra-fine particles (UFPs) deposit deeper in the lungs also rises. This is illustrated in the modelled data presented by Cruz et al. (2021), where both exercise intensity and exposure duration were shown to drive higher cumulative UFP deposition. These effects are compounded by the fact that during intense activity, athletes typically shift from nasal to oral breathing, bypassing upper airway filtration mechanisms and allowing more particulates to reach distal airways (Rundell 2012; Schwellnus et al. 2022). Therefore, even short-term exposure to elevated PM concentrations during exercise may result in disproportionately high internal pollutant doses, particularly in endurance events. This altered inhalation, and particularly an increased ventilation rate, combined with heightened exposure, may increase the prevalence of asthma in high-performance athletes, especially in endurance sports (Helenius et al. 1997, 1998).

Air-quality guidelines used internationally are primarily designed to protect the general population from long-term and acute health effects. The current WHO 24-hour PM2.5 Air Quality Guideline (AQG) of 15 μg/m^3 and the annual guideline of 5 μg/m^3 are derived from large epidemiological cohort studies examining associations between population-level pollutant exposures and outcomes such as hospitalisations, cardiovascular events, respiratory morbidity, and mortality (WHO, 2021). These studies are based on typical daily living exposures and do not incorporate the substantial increases in ventilation, inhaled dose, and deposition that occur during strenuous exercise.

The main aim of this study was to describe the environmental conditions that athletes participate in with a specific focus on PM2.5, as quantifying PM2.5 health impacts during these short exposures remains a challenge due to the lack of a relevant standard.

Data and methods

The study was conducted at four Athletics South Africa (ASA) high-performance athletics meetings (World Athletics 2023). At each event, a suite of instruments was deployed to monitor PM2.5 and environmental conditions. These included a TSI SidePak AM510 PM2.5 Monitoring device, responsible for airborne particulate matter detection. The TSI SidePak AM510 measures aerosol mass concentration in real time using a light scattering principle to quantify the mass concentration of airborne particles. DS-2 sonic anemometers were used to measure wind speed and direction. Temperature and relative humidity were monitored using CS215 Campbell Scientific sensors and a TR-525USW tipping bucket rain gauge to measure rainfall. At the athletics events, these instruments were stationed on the field of competition. All SidePaks were calibrated, and before each event, a zero cal, flow check, and internal cleaning were conducted. The SidePaks were cross-validated with other SidePaks in a lab setting before deployment. If the readings varied by more than 0.05 during cross-checks, it was not used. One SidePak was used at all stadiums to ensure consistency. An additional SidePak was present, but it served as a backup in case of power or memory failures. All other instruments undergo a yearly calibration. Solar radiation for Potchefstroom (rural location) was derived from a ClimaVUE50 radiation sensor deployed 1.9 km from the stadium site; this was particularly important for the National Championships, as the other events followed a late afternoon/night program, and direct incoming solar radiation was not applicable. The calculation of WBGT assumes similar clothing, metabolic rate, and physical activity across a range of participants, but it provides a good measure of heat stress for the *average* athlete. In this paper, the Liljegren method to calculate wet-bulb globe temperature (WBGT) (Liljegren et al. 2008; Kong and Huber 2022) from the R heatstress package (Casnueva et al. 2019; Gerrett et al. 2019; Brimicombe et al. 2023) was used; the method estimates outdoor WBGT based on fundamental heat and mass transfer principles using standard meteorological inputs – air temperature, dew point, wind speed, solar radiation, and location. Two submodels within the method iteratively solve energy balance equations to estimate the natural wet bulb temperature and globe temperature, which are then combined with air temperature using the weighted formula:

$$WBGT = 0.7T_{nwb} + 0.7T_g + 0.1T_a$$

where T_{nwb} *is the natural wet bulb temperature (°C)*
T_g *is the globe temperature (°C)*
T_a *is the air (dry bulb) temperature (°C).*

Events held during the evening did not require solar radiation measurements, as incoming shortwave radiation at those times approaches zero (0 W/m^2).

Description of measurement sites

Our study area (Figure 1) involved monitoring four high-performance athletic meetings located within the South African Highveld, each representing diverse urban environments. The Grand Prix Series is an ASA initiative for the country's top athletes to compete in high-level events beyond the national championships, which are traditionally the only major event where top athletes meet on an annual basis. The event also attracts top participants from outside South Africa with competitors from Norway, Kenya, Botswana, Swaziland, Mozambique, Namibia, and Seychelles competing in the 2023 events (World Athletics – ASA Grand Prix).

Two meetings were held in Potchefstroom (26.7167° S, 27.1000° E), a rural city in the North West Province where no significant industrial activities exist near the event's location. This allowed the consideration of PM2.5 levels in an environment with relatively low industrial influence. The third athletic

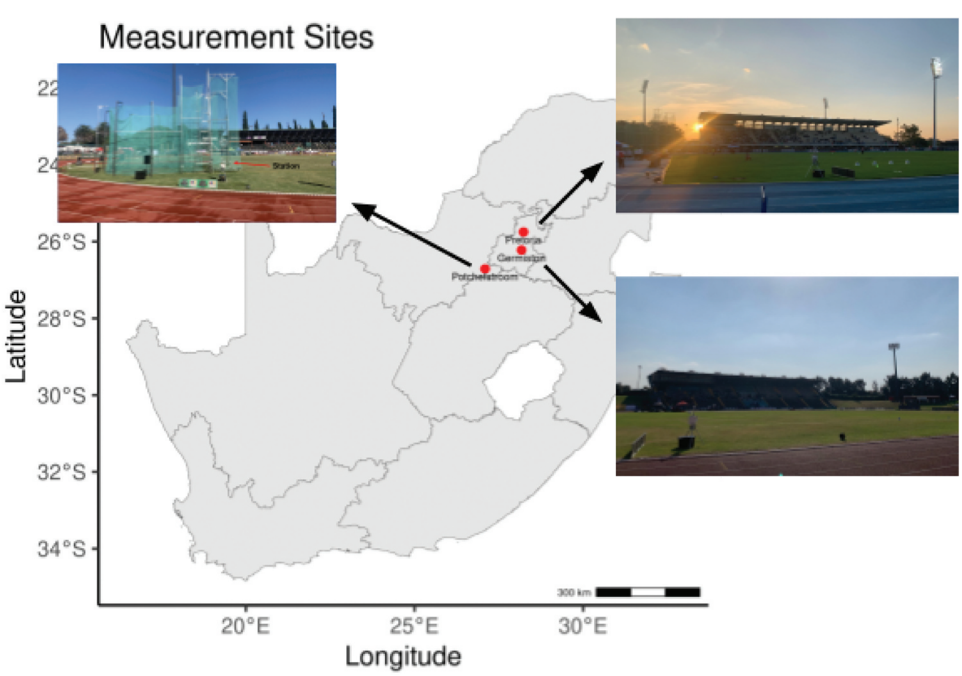

Figure 1. Sites where environmental measurements took place.

meeting occurred in Pretoria (25.7456° S, 28.1878° E), South Africa's administrative capital in the northern part of Gauteng Province. As a major urban metropolitan region encompassing a wide array of economic activities, Pretoria presented a complex backdrop for potential air pollution sources as a central metropolitan city. Germiston (26.2348° S, 28.1703° E), an industrial metropolitan city in the East Rand area of Gauteng, was the site of the fourth meeting. With a history as a gold mining region and subsequent urban and industrial developments surrounding the competition field, Germiston provided an environment with multiple possible sources of background air pollution. At all stadiums, the station was placed at the 300 m mark on a grass surface. Meteorological sensors were mounted at a height of ~1.7 m, while the SidePak was positioned in the logger box with an inlet tube that extended to the height of the meteorological instruments. The SidePaks' flow rate and zero cal were done with the inlet inserted at the sites. This setup was replicated at all sites. The location was arbitrary and selected because it was out of the way of most participants and officials and provided easy access to check the instrument function between events.

At all events, there are typically food stalls that cater to the fans and athletes, and at all events, there were stalls that used gas and/or wood burning to cook food. The vendors trading in the stadiums either have permission from the local municipality to utilise the facility or permission from ASA to sell food at the events. There are, however, no restrictions on the type of cooking material used, as open fires are quite a common cooking method in South Africa during events.

Data management

All parameters were collected at 1-minute intervals. On the SidePak, data were recorded on the internal memory, and all measurements from the weather station were stored onto a Campbell Scientific CR300 logger. Data were collected immediately post the event. Quality control included a range check for realistic measurements both in terms of what the instrument can measure and the physical parameters of the particular variable observed. PM2.5 outliers within were not removed as individual peaks in PM2.5 were correlated with plume events in the vicinity (documented by the scientists at the station). All calculations were done using R (R Core Team 2017). Mean calculations are available in the R base package. All meteorological results presented show the mean measurement taken at the site. Temperature is recorded in degrees Celsius (°C), wind speed in metres per second (m/s), wind direction in degrees (°), and relative humidity in %. WBGT was calculated using the R Heatstress package (Casnueva et al. 2019; Gerrett et al. 2019, Brimicombe et al. 2023) and is expressed as (°C). Mean (average ambient concentration for the duration of the event using the 1-minute interval data collection) and maximum instantaneous (1-minute) PM2.5 are presented.

Results

The monitoring campaign, which spanned four athletic events, demonstrated significant variations in PM2.5 concentrations.

As can be seen in Table 1, the rural events had a much lower mean PM2.5 compared to both the metropolitan and industrial areas.

Table 1. Environmental conditions and PM2.5 concentrations at the athletics events.

	Mean PM2.5 (μg/m^3)	Maximum 1-minute PM2.5 (μg/m^3)	Mean Temp (°C)	Mean Relative Humidity (%)	Mean WBGT (°C)	Mean Wind Speed/ Direction (m/s/deg)
Potchefstroom – National Championship (rural)	28.62 μg/m^3	174.00 μg/m^3	21.06°C	60.59%	18.85°C	1.99m/s/193.70°
Pretoria – ASA Grand Prix 1 (metropolitan)	61.01 μg/m^3	179.00 μg/m^3	19.69°C	56.35%	15.42°C	1.13m/s/222.80°
Germiston – ASA Grand Prix 2 (industrial)	132.7 μg/m^3	385.00 μg/m^3	21.23°C	36.84%	14.70°C	1.01m/s/178.66°
Potchefstroom – ASA Grand Prix 3 (rural)	33.06 μg/m^3	53.00 μg/m^3	24.66°C	42.08%	18.44°C	1.41m/s/203.81°

ASA: Athletics South Africa.
WBGT: Wet bulb globe temperature.
Mean: average over 4 hours for the Grand Prix events and the average over 3 days, 10 hours per day.

Figure 2. Illustration of pollution sources at Germiston Stadium, South Africa.

The WBGT readings were relatively stable, with a range of 14–18°C, remaining in the low-risk category. The humidity levels did not exceed 60%, and the wind speeds were below 2 m/s.

For the national championships, the maximum instantaneous (1-minute) concentration was 174 μg/m^3. This concentration coincided with a “plume event” (open-fire cooking) from the food stalls in the stadium. PM levels exceeded 100 μg/m^3 for 10 minutes during this period. The second event held in Potchefstroom had a similar mean concentration; however, the maximum (1-minute) concentration was substantially lower during the one evening event.

The highest levels of PM2.5 were recorded at the Germiston stadium in Johannesburg (industrial). Here, it was evident that industrial sources played a major role (see attached Figure 2). Here, the mean PM2.5 concentration at the event was 132.7 μg/m^3, and the maximum instantaneous (1-minute) concentration was 385 μg/m^3. Concentrations at this site were never below 73 μg/m^3 and exceeded the mean concentration for 35% of the event period (measurements started an hour before the main program).

Discussion

The aim of the study was to report the findings of a PM2.5 monitoring campaign completed at various athletics events in South Africa. An evaluation of the data illustrates disparities in PM2.5 concentrations across different event locations, their alignment with daily exposure limits, and possible repercussions on athlete health; however, there is limited literature investigating the effect of short-term exposure (other than acute symptoms). These fluctuations are not only the result of the larger area in which the competitions took place but also the local activities in the direct vicinity of the event.

Comparison across locations

In Potchefstroom (rural), mean concentrations of PM2.5 during both events were significantly lower than other areas of competition. The 2023 National Championships in Potchefstroom were held over 3 days, and the mean concentration during this period was 28.62 μg/m^3 (exceeding WHO 24-hour Air Quality Guidelines (AQG)). The spike to 174 μg/m^3, as a result of local open-fire cooking (Supplementary Figure S1), shows the influence of micro-scale activities on PM2.5 concentrations. One of the researchers was at the event when a visible and stable smoke plume moved over the field. Subsequent investigation led to the discovery of the source, and no other burning or pollution sources were present in the surrounding area at the time. If an athlete were competing over all 3 days, then they would have been competing in what can be considered an elevated PM2.5 environment, with high instantaneous concentrations. This also emphasises the fact that micrometeorology, in combination with pollution activities (i.e. burning), can have a substantial impact on measurements.

In Pretoria, the mean PM2.5 concentration was 61.0 μg/m^3, with peaks reaching 179 μg/m^3. Metropolitan areas, such as Pretoria, typically experience more pollution from industry, traffic, and other human-made sources than rural areas (Harrison et al. 2004). Such elevated levels, as argued by Harrison et al. (2004), can typically result from a dense mesh of vehicular emissions, industrial activities, and other anthropogenic sources prevalent in city landscapes. To pinpoint pollution sources in urban areas, comprehensive source apportionment measurements are necessary. These can break down potential PM2.5 contributors through both observational methods and chemical analysis. Conducting such studies might reveal pollutant origins for targeted interventions. While no evident pollution sources were near the stadium in Pretoria, cooking activities could have contributed to the peak measurements. However, these don't account for the consistently higher background levels compared to rural locations.

Within the greater Johannesburg area, industrial activities, particularly around the Germiston stadium, were a critical factor in the mean PM2.5 concentration of 132.7 μg/m^3. With levels consistently above 73 μg/m^3, the data indicate persistent exposure to harmful particulate concentrations. Considering that an athlete's heightened respiratory activity already starts during warm-up and continues after competition during cool-down, the risk of adverse response in such industrial settings is much higher than rural settings. It should be noted that, given that this was a 1-day event, with short-duration activities, the effects of training (prolonged increased ventilation and duration) at these facilities would increase the risk of long-term health impacts.

The diverse environments studied and the sources of PM2.5 concentrations should be viewed in the context of the health impact. For the industrial event, PM2.5 exposure would most likely be exceptionally high on most days (regardless of an event taking place), whereas the rural setting has increased PM2.5 exposure for short periods, particularly related to the event and fan engagement (food stalls for spectators). The rural setting would therefore be preferential for training, and restrictions placed on event days could decrease the levels easily. However, for the industrial event, the PM2.5 levels will always be high, making it a public health issue, as well as detrimental to athletes as a training and competition venue.

Lower windspeeds (<3 m/s) can contribute to higher PM2.5 levels (as dispersion decreases and pollutants accumulate) (Fang et al. 2024), which could have contributed to the concentrations we found, particularly as the industrial venue had the lowest windspeed and highest PM2.5.

The mean PM2.5 for our events ranged from 28 to 133 μg/m^3, whereas if you compare to the events previously studied by World Athletics, the range was from 17.8 to 72 (Reche et al. 2020; Viana et al. 2022; Ribalta et al. 2024). Our events, on average, showed higher PM2.5 concentrations than other events, and we also had much higher maximum instantaneous (1-minute) concentrations. The study did not expand to source apportionment, and while a casual infernal of the background and local sources are made, a more detailed analysis of pollution sources will increase our ability to improve air quality at these events.

Comparative analysis with AQG standards

Comparing the exposure of PM2.5 to the current AQG is particularly challenging. The 3-day event (Potchefstroom 1) is the only event that was similar to the World Health Organisation (WHO) 24-hour AQG of 15 μg/m^3, and in this case, PM2.5 levels slightly exceeded the recommended guidelines. At all the Grand Prix events, the mean PM2.5 was higher than the AQG. However, all these events lasted less than 5 hours, including the pre-program. What needs to be considered is that these stadiums are also used as regular training facilities for some of the country's top athletes. At the same time, our measurement only sampled a small subset of the total period, indicating the need for further investigation. Within the larger area (where all three sites are located), studies have shown that PM2.5 concentrations exceed AQG on an annual level at a majority of sites (Feig et al. 2019).

Implications of PM2.5 exposure

Exceeding daily exposure limits, especially for short durations, might amplify the health risks athletes face. As athletes often have elevated respiratory rates during training and competition, their PM2.5 intake during such events can be disproportionately high. Prolonged exposure to elevated PM2.5 concentrations is linked to health risks, ranging from respiratory distress to cardiovascular problems (González-Rojas et al. 2025).

These implications aren't confined to athletes; spectators, officials, and local residents may also face increased health risks during outdoor activities. Further analysis will need to focus on the intake fraction during exercise compared to current methods that focus on the average human, engaged in moderate activity. Future studies should also investigate using sensing nodes to determine the sources of pollutants, in order to develop mitigation strategies, in an attempt to protect the athletes (Viana et al. 2022).

Challenges in quantifying air pollution during exercise

Air pollution, especially PM2.5, is a recognised public health threat, particularly in urban settings and the South African context. Various research underscores the adverse impacts of PM on respiratory and cardiovascular health. However, understanding the interplay between air pollution and physical exercise presents unique challenges, exposing a gap in our existing health guidelines and standards.

Most current standards, including those proposed by the WHO, primarily address health implications based on prolonged exposure durations, often spanning 24 hours or more. Athletes and individuals engaged in vigorous physical activities are exposed to potentially high PM concentrations for much shorter but intense durations. Further complicating this scenario is the heightened respiratory rate during intense activities. During exercise, inhalation is more profound, allowing pollutants to penetrate further into the lungs. Resting individuals might inhale 10/15 l/min, which can surge beyond 100 l/min during exercise activities, amplifying the amount of pollutants absorbed by the body (Sciomer et al. 2021). Furthermore, research has shown that the PM2.5 levels have an impact on VO_2 max in mild or moderate asthmatic participants (higher PM2.5, lower VO_2 max) – in these cases, athletes could face a performance decrease as their $V0_2$ max temporarily decreases, and if asthmatic, they might increase their risk of neutrophilic inflammation (McCreanor et al. 2007). With an increased inhalation rate during exercise and higher PM2.5 levels, the effects could be exponentially larger. As shown by Ribalta et al. (2024) differences in ventilation rate between sexes and at different running speeds, along with variation in exposure duration and time-of-day pollutant trends, can affect the total inhaled dose of PM2.5 during porting events. Measurements taken at a single time or location may not adequately represent athletes' true exposure during a race or an athletic event.

Variance in local air quality should also be considered. Standard AQMS, designed to measure background pollution in different locales, might not effectively capture the air quality of specific micro-environments, such as roads, parks, tracks, or trails, frequented by athletes. Moreover, the compounded health implications of increased respiration combined with heightened PM levels during exercise could result in significantly magnified adverse health effects, especially when compared to the general populace exposed to similar ambient pollution levels (Dominici et al. 2006; Feng et al. 2016; Southerland 2022). Furthermore, existing guidelines may not adequately cater to vulnerable populations, such as children, the elderly, or those with pre-existing health conditions, all of whom may face exacerbated risks during exercise (Rundell 2012). To safeguard the health of those engaging in physical activities in varied pollution contexts, there's an urgent call for revising and refining existing standards, focusing on these short-term, high-intensity exposures.

Limitations

One of the primary limitations is the absence of data on the particle size distribution. PM2.5 represents a subset of the total particulate matter suspended in the air. By not analysing the entire spectrum of particle sizes, ranging from ultra-fine to coarse particles, the study might not fully capture the range and nature of particulate pollution at the event locations. Different particle sizes could originate from different sources and have varying respiratory effects, which, if identified, will allow for a more nuanced understanding of the pollution dynamics at the event sites. The health effects of PM2.5 also depend on composition. This study did not assess chemical constituents, which may affect toxicity and source attribution. Secondly, the study did not employ regression analysis to determine potential correlations between the proximity of industrial activities and recorded PM concentrations. Such an analysis could indicate the relationship between pollutant sources and observed concentrations. Despite these limitations, the research highlights critical issues surrounding air quality at athletic events, offering a foundation for subsequent investigations that can delve deeper into these aspects.

Conclusion

The mean PM2.5 levels for the duration of all events exceeded 28 μg/m^3, with one event having a mean of 132.7 μg/m^3. The need to understand the effects of participating in events where the PM2.5 levels are high in comparison to daily standards is becoming increasingly important, in an attempt to mitigate the risk placed on athletes. The need to understand the effect of both health and performance will assist organisations in planning events. This paper adds to the knowledge base and is the beginning of understanding the air quality where current sporting events are held.

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