Experimental evidence of the multiple microclimatic impacts of bushfires in affected urban areas: the case of Sydney during the 2019/2020 Australian season

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Abstract

This paper presents the results of a monitoring campaign conducted in the inner west of the city of Sydney during the 2019/2020 bushfire season. The combined effects of extreme pollution, heat waves and droughts are analyzed in terms of microclimatic perturbation. A compact meteorological station measured air temperature, relative humidity, barometric pressure, precipitation, wind (speed and direction), solar radiation, UV radiation, UV index, PM1, PM2.5 and PM10, at the one site. The monitoring campaign lasted from the 20th of December 2019 to the 13th of January 2020, when hundreds of bushfires were ravaging the bordering areas. A suite of dependencies emerged between PM concentration and air temperature, relative humidity, wind speed and rain. PM concentration was higher during the night and in the morning, especially after daytime overheating events (temperature above 35°C). Raindrops triggered the highest and most persistent dust levels. Dense layers of PMs, in turn, strongly attenuated the UV radiation. Collected data also indicated anomalies in the intensity of the urban heat island compared to historical trends. This study is a first attempt to link together several different parameters on a local scale under weather anomalies. Future efforts will be directed to strengthening the validity of the above results and approach to broader boundary conditions.

Acronyms

CIE Commission Internationale de l’Eclairage
CRC Cooperative Research Centre
CSIRO Commonwealth Scientific and Industrial Research Organisation
E East
EAS Erythemal Action Spectrum
FFDI Forest Fire Danger Index
FIRMS Fire Information for Resource Management System
IPCC International Panel on Climate Change
Irr Solar radiation [W m⁻²]
LGA Local Government Area
MAE Mean Absolute Error
MSE Mean Squared Error
N North
NASA National Aeronautics and Space Administration
NE North-east

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1. Introduction

The size and destructive potential of the 2019–20 Australian bushfires shocked the world. A recent global-scale analysis on remotely-sensed burned areas during the last 20 years indicates that such fire episodes have burned an unprecedented percentage of continental forest biome [1]. According to the Australian Government, from September 2019 to the 14th January 2020, about 186 000 km² (almost the size of England) have been burnt [2]. The fires claimed the lives of at least 34 people [3] and destroyed nearly 5900 buildings [4]. Moreover, an estimated one billion native animals perished [5], with some species now facing the serious risk of extinction.

According to a 2007 scientific report by the Bushfire CRC, the Australian Bureau of Meteorology, and CSIRO Marine and Atmospheric Research [6], the number of ‘extreme’ fire danger days was expected to increase by 5%–65% by 2020, depending on different global warming scenarios. Furthermore, the fire seasons were projected to start earlier in the year and last longer, with potential repercussions on local air temperature trends [7]. Recent events have confirmed most of these results and anticipated trends. An alarm bell is sounding worldwide as 2019 was also the year when massive fires destroyed vast areas in the Amazon, Siberia and California [8].

It is crucial to have a better understanding of the potential consequences of an increased rate and extension of bushfires, especially to improve the risk preparedness and subsequent coping strategies [9].

Numerous studies have investigated and confirmed the deleterious health implications of bushfires [10–14] as biomass burning is a major source of ambient particulate matter (PM). Comparatively underexplored is the impact on local urban microclimates, concerning not just temperature, but key parameters including solar and UV radiation, relative humidity, wind patterns and gusts, and all potential mechanisms such as urban heat islands, that impact on outdoor livability.

The Black Saturday bushfire event of February 2009 devastated the state of Victoria, Australia, and resulted in 173 deaths. In their investigation of this calamity, Jacobs et al [15] focused on the relative importance of the net energy flux terms and their consequences on the risk of dehydration and hyperthermia. The authors also warned against the dangerous synergy between heat stress and air pollution, but without establishing any link. On the other hand, Aleksandropoulou et al investigated the effect of biogenic volatile organic compounds and windblown dust over urban areas emitted by large forest fires (Athens, 2008 fires) and found that the contribution of these factors was rather small compared to that of anthropogenic emissions [16]. Sapkota et al [17] examined the impact of the 2002 Canadian forest fires on the air quality in Baltimore City, revealing the significant threat to densely populated urban areas, even thousands of kilometers away from the fires. Through a
combination of satellite images, back-trajectory models and LIDAR data, the authors illustrated the local effects on ambient and indoor levels of PM due to long-range transport. PMs penetrated indoors largely unimpeded, with a median indoor-to-outdoor ratio of 0.91. 2002 was also the year of Lithuanian fires. Ovadnevaité et al [18] discussed the air quality and health-related implications in the city of Vilnius. Based on the measurements of ambient air pollutants and meteorological parameters, they found that the correlation coefficient between PM10 and CO, NO, NO2, NOx increased during the fire period in comparison to the after-fire period, due to the higher concentration of ozone precursors and the greater proclivity to photochemical reactions. Documented respiratory diseases increased by up to 20 times during the fires. Indeed, when urban heat combines with intense air pollution, the health risk is exacerbated and the corresponding disease etiology varies, thus impacting a larger basin of vulnerable population [19, 20].

A novel framework that integrates social and health science is needed to better predict and react to such escalating emergencies. Precondition involves the identification of how particulate matter and other pollutants might influence not just the air quality but also the irradiative landscape and the environmental trends in affected areas.

In this paper, a holistic approach based on multi-parameter measurements is proposed to study the connection between bushfires and repercussions on the microclimate of urban areas of interest. The area being investigated is discussed in the next paragraph, followed by a detailed description of the monitoring equipment and experimental analyses. The results indicate the interdependency of PMs and temperature, relative humidity, wind, time of the day, rain, UV radiation and urban heat island (UHI).

2. The investigated area

The monitoring campaign was undertaken in Sydney, the capital of New South Wales (NSW), from the 20th of December 2019 to the 13th of January 2020. During this time, the city experienced a range of significant weather extremes including heat waves, intense droughts and wind gusts of more than 100 km h\(^{-1}\) resulting in unpredictable fire paths and extremely poor air quality in the nearby areas. To put the emergency into perspective, an area larger than the Netherlands was burnt in the NSW, alone. This triggers an especially health-threatening vicious circle of complex self-reinforcing feedbacks: extreme pollution suppresses rain, which prolongs drought, which sustains heat waves and bushfires persistence [21, 22].

Figure 1 shows a satellite view of the bushfires in Australia and a close-up of regions in the outskirts of the city of Sydney. Displayed data represents a 24-day temporal horizon of observation.

From September 2019, fires heavily impacted the regions in and around the Blue Mountains, such as Hawkesbury and Wollondilly in Sydney’s far west, as well as Illawarra in the near south side. On the 12th of November, a ‘catastrophic’ fire danger warning was issued for the Greater Sydney region for the first time since its introduction. Meanwhile, the lack of precipitation triggered an intense heat wave that peaked on the 4th of January: the western suburb of Penrith hit a high of 48.9 °C, setting a new record in the Greater Sydney area (previously 47.8 °C in Richmond in 1939) [24].

The measurements were taken in the suburb of Petersham (Sydney’s Inner West), in a spot located approximately 50 kms away from the Blue Mountains National Park and 2 kms away from both the city center and the nearest coastline.

The monitoring station was placed in the green backyard of a suite of one-storey buildings, with an unobstructed view of the sky (SVF = 1 as visible in figure 2(c)) and subject to wind from any direction.

3. Monitoring equipment and post-processing

In this study, a holistic investigation was undertaken to determine the interplays between extreme weather events (bushfires, droughts, heat waves) and a local urban microenvironment. Therefore, multi-parameter monitoring was conducted simultaneously and at the same site, aimed at both climatological and air quality characterization. A compact unit comprising different sensors was mounted on a tripod at a height of about 1.1 m. The list of measured/derived parameters is given in table 1, along with their technical specifications.

The station (figures 2(d) and 2(e)) retrieved data every second, and saved the output every minute. Derived parameters were calculated based on an internal scrolling register that stored 600 s of historical wind data which was used to calculate maximum, minimum and average wind speeds and wind direction over 2 min and 10 min. Gust was calculated as maximum value of 3s-average wind speed at 10 min intervals, as recommended by the World Meteorological Organization [25]. Solar and UV radiation were measured to establish whether any attenuation occurred under the thick layer of bushfire smoke that frequently blanketed the city during the period of observation. Ultraviolet radiation can damage the skin in a number of ways, causing erythema, premature aging, skin cancer, burning etc [26, 27]. It can also harm the body’s immunological system [28] and the eyes.
cataracts and other ophthalmohelioses) [29]). It can be manipulated to obtain a unitless measure of its effects on the human skin, known as the UV index (UVI). The UVI is calculated by means of a standard reference spectrum that represents the average skin response to UVB and UVA, termed Erythemal Action Spectrum (EAS), first defined by McKinlay and Diffey [30] and then implemented by the Commission Internationale de l’Eclairage (CIE) [31]. UVI ranges from 0 to 15, categorized as minimal (0–2), low (5–6), high (7–9) and very high (≥10).

Particulate matter was also monitored. Three sizes were considered (PM1, PM2.5 and PM10), since particle size is linked to:

(i) the level of toxicity [32],
(ii) the mortality rate and hospital admissions [33],
(iii) the oxidative damages and carcinogenic mechanisms [34], and
(iv) the site of deposition in human lungs [35].

The collected datasets were used to uncover and quantify synergistic/antagonistic links between environmental and air quality parameters under the concerted action of bushfires, drought and heat wave. As such, statistical analyses were carried out to relate PMs’ distribution to air temperature, relative humidity, wind speed, wind direction, precipitation and UV index, making use of a supervised learning approach to deepen the investigation, where appropriate. From a temporal perspective, the likelihood of higher/lower pollutants concentration was associated to the different times of the day, by binning. The temperature distribution alteration due to the intense bushfires was also inferred by comparison with historical multi-point temperature measurements. Notably, temperature data from the BoM (Bureau of Meteorology) meteorological station located at Observatory Hill were retrieved during the monitoring campaign. Observatory Hill was selected as the reference station in order to assess the urban heat island intensity (UHII) at the monitoring site, in line with several other UHI studies for the city of Sydney [36–38]. Seventeen years of historical temperature series obtained from the reference station, as well as from another six BoM stations located in the Greater Sydney area (Canterbury, Olympic Park, Bankstown, Richmond, Penrith and Camden), were used to identify potential UHI anomalies.
4. Results

Figure 3 shows the time series of PM10, relative humidity, temperature, accumulated rain and solar radiation (on the secondary axis) over the 24 days of observation. As evident, this is a very significant time frame as it was during this period of the bushfire season that weather extremes were experienced: the temperature reached 46.2 °C whereas the accumulated rain was just 13.6 mm, PM2.5 exceeded the national and WHO standard of 25 μg m\(^{-3}\) (24-h mean) \([39, 40]\) on three days, with other three days closely approaching the threshold. Notably, on the 8th of January, the daily level of PM2.5 was more than twice the limit. Also on that day, the PM10 exceeded the suggested upper bound of 50 μg m\(^{-3}\) \([39, 40]\). Having established the representativeness of the considered time frame, a suite of observations on the collected datasets could be derived and trends could be identified. These are described in the following subparagraphs and subsequently discussed.

4.1. On the relationship between particulate matter and local meteorology

Particulate matter concentration was variously associated with the local meteorology, namely air temperature, relative humidity, wind patterns, solar radiation and rain. Figure 4 presents the distribution of PM10, PM2.5 and

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Table 1. List of sensors and corresponding technical information. Refer to the acronyms section for the interpretation of coded names.

| Variable                  | Principle       | Range                  | Accuracy\(^a\) | Resolution |
|---------------------------|-----------------|------------------------|----------------|------------|
| T                         | MEMS sensor     | −40 °C ÷ 80 °C         | ±0.5°C         | 0.1 °C     |
| RH                        | MEMS sensor     | 0 ÷ 100%               | ±2%            | 0.1%       |
| P                         | MEMS sensor     | 150 ÷ 1100 hPa         | ±1 hPa         | 0.1 hPa    |
| Precipitation             | Radar           | 0 ÷ 100 mm h\(^{-1}\)  | ±10%           | 0.01 mm    |
| Derived parameters: Accumulated precipitation |             |                        |                |            |
| ws                        | Ultrasonic      | 0 ÷ 40 m s\(^{-1}\)    | ±5%            | 0.1 m s\(^{-1}\) |
| Derived parameters: Gust; Average, Maximum and Minimum in previous 2 and 10 min |             |                        |                |            |
| wd                        | Ultrasonic      | 0 ÷ 359°               | <3°            | 1°         |
| Derived parameters: Average, Maximum and Minimum in previous 2 and 10 min |             |                        |                |            |
| Irr                       | Silicon         | 0 ÷ 2000 W m\(^{-2}\)  | ±5%            | 1 W m\(^{-2}\) |
| UV                        | Silicon         | 0 ÷ 2000 W m\(^{-2}\)  | ±5%            | 1 W m\(^{-2}\) |
| UVI                       | Silicon         | 0 ÷ 15                 | ±5%            | 1          |
| PM1/PM2.5/PM10            | Laser scattering| 0 ÷ 500 μg m\(^{-3}\)  | ±10%           | 1 μg m\(^{-3}\) |

\(^a\) percent accuracy is given as % of the range.
PM1 with respect to the different values of air temperature and relative humidity, recorded during the campaign. Statistically higher contents were recorded when the temperature was in the 19–29 °C range and the relative humidity was 60%–87% (greyed areas). Conversely:

1. for $T < 19$ °C, the maximum concentration of particulate matter was generally limited.
2. For $T > 29$ °C and especially above 33 °C (green areas), PMs’ volumetric densities fell into specific bands (approximately between 20 and 60 μg m$^{-3}$ as for PM10 and PM2.5, between 20 and 40 μg m$^{-3}$ as for PM1).

Wind speed was also investigated due to the prominent role of transport mechanisms in the advection and dilution of biomass burning plumes. A sensitivity analysis demonstrated that the average wind direction and speed in the previous 10 min had a stronger influence on PMs compared to both the instantaneous readings and the 2-min averages. The 10-min data were clustered to extract information related to wind patterns and prevalence (figure 5).

During the monitoring campaign, PM10, PM2.5 and PM1 levels were all higher under local winds blowing from the south and south-east, corresponding to the prevailing conditions. The maximum 90th percentile was also related to southerly winds, regardless of the particle size. PMs tended to be sparser (lower P90) when the wind was blowing from the west.

On another note, biomass-burning aerosols interact with the incoming radiation through scattering, absorption and cloud condensation [41]. Direct measurement of the UV index indicated that the UVI tended to decline with PMs densification (figure 6). Notably, several thresholds could be identified:

- if PMs $< 20$ μg m$^{-3}$ approximately, then the UVI could surpass a value of 5. Above this limit, the UV index never went higher;
if PM10 > 140 μg m⁻³ or PM2.5 > 110 μg m⁻³ or PM1 > 60 μg m⁻³ approximately, then the UVI could go as down as zero.

An AI-based approach based on evolutionary algorithms was utilized to verify those parameters, among all the recorded/derived ones (table 1), that had greater impact on the UVI. Interestingly, the final Pareto-optimal equations showed how UVI could be accurately predicted (R² equal to 0.91) by knowing only the concomitant solar radiation and PM content.

Figure 7 overlaps the modelled and measured UVI, showing a very good agreement.
Under close scrutiny, the collected data suggest that other than very high daily temperatures, rain was also a precursor to accentuated pollution (see figure 3). On the 7th and 8th of January, 3 mm of rain were recorded after a prolonged persistence of dry conditions. Despite this, on the 8th of January at around 8am, the PMs reached the highest levels with 10 μm particles exceeding 150 μg m⁻³. Pollution remained extremely high over the whole day.

4.2. On the relationship between particulate matter and time of the day
To investigate whether the contents of PMs increased or decreased according to the time of day, all of the ranges of PM10, PM2.5 and PM1 were binned into eight groups and distributed among four time slots (morning, afternoon, evening and night) as shown in figure 8. Bin 1 and bin 8 collect the lowest (magnitude equal to the bin width in figure 6) and the highest pollution levels (80, 130 and 160 μg m⁻³), respectively.

Between 5 and 8 pm, all PMs tended to be lower. There was no reading for bin 8 during the afternoon and the evening. After 8 pm, the volumetric density of particulate matter tended to increase significantly for bin 2, bin 3 and bin 4 (18%, 15% and 15% for PM1, PM2.5 and PM10, respectively).

In terms of PM size, PM2.5 and PM10 followed a similar time-dependency. However, the PM1 had lower content during the night compared to other times of the day (about 90% of night-time occurrences for bins 1 and 2), while tended to reach higher values over the morning and the afternoon. No PM1 was recorded during the evening in bins 5–8.

4.3. On the relationship between particulate matter and urban heat island
The afore-mentioned perturbations caused by the smoky plume altered the thermal balance and the radiative forcing in affected urban areas. Therefore, it was anticipated that the urban heat island pattern could be responsive. In order to discover any anomalies, the UHII at the monitoring site during the 2019/2020 bushfires was compared to the historical data at six different locations in the Greater Sydney Area. Figure 9 shows the statistical distribution of the recorded UHII in the form of boxplots. Interestingly, the UHII assumed a purely positive character during the bushfire only. The interquartile range was amply skewed towards the 3rd quartile, meaning that higher values than the median were much more frequent than lower values. Such a pronounced asymmetry is rarely observed in historical trends all over the considered area.

5. Discussion
In the above paragraphs, a suite of experimental observations is presented and hereinaft discussed. Figure 4 demonstrates how particulate matter tended to accumulate when specific thermohygro metric conditions were met. Indeed, at a lower temperature and/or higher RH, deliquescence was more likely to occur. PMs absorbed moisture from the atmosphere, undergoing gradual dissolution and liquefaction [42]. This is in line with [43], in which PM10 were measured in Switzerland at more than ten sites simultaneously during a full year period. An increase in relative humidity was found to decrease the PM10 (negative regression coefficient). In [44], it was demonstrated that relative humidity also has a similar bearing on atmospheric dust. The authors found that
higher relative humidity triggers the cohesion of soil particle; hence, the minimum friction velocity required for
the mobilization of particles from the ground into the atmosphere (saltation) increases.

On another note, over a certain temperature threshold, the volumetric densities of PMs fell into size-specific
maximum probability bands. This is not the result of intensified bushfire activity only, but also of pronounced
convective processes that, on the one hand, could have impeded the deposition of airborne particles, and on the
other, could have increased the inflow of dust. A similar condition is detected also for RH < 60% and especially
below 40%. In [44], for 0 < RH < 25%, the PM10 content increased with relative humidity to invert the trend
right above that threshold. The authors suggested that the increase in dust emissions could be due to weakened
inter-particle cohesion at soil level as water began adsorbing on dry particles, which is consistent with the results
of Ravi et al [45].

Southerly and south-easterly winds were conducive to higher PM contents possibly due to the fact that,
during the entire monitoring campaign, the southern region of Illawarra had been under ‘catastrophic’ or ‘very extreme’
fire danger. As expected, stronger north-westerly winds were associated with lower PMs. This is
reported extensively in the literature. By way of example, the Spearman rank correlation analysis by Zhao et al
[46] explicitly demonstrated that the concentrations of PM10 and PM2.5 have a strong negative correlation with
wind speed. Nonetheless, no evident correlation could be discerned, which is partly due to the local nature of the
measurement (which could not have captured larger air circulations) and partly to the competition with other
driving parameters. Similarly, observations in the USA and Mexico [44] found that PM10 concentrations were
not directly correlated with wind speed. The authors expressed the need for multi-parameter investigations as
limited datasets do not allow the examination of additional interplays.

The extremely high level of particulate matter, recorded when the local wind was blowing from the sea (NE, E, SE)
can be explained by considering the travel of the smoke plumes across the Pacific Ocean ([47]). In all
likelihood, plumes of hot gases containing airborne pollutants ascended from the bushfires into the mixed layer
to be advected over long distances by prevailing winds from the north and north-west [48] in the free
troposphere where fewer loss mechanisms and more efficient transport occurred [17, 49–51]. Long-range

| PM    | Range [μg/m³] | Bin width [μg/m³] |
|-------|--------------|-------------------|
| PM1   | 0–80         | 10.00             |
| PM2.5 | 0–130        | 16.25             |
| PM10  | 0–160        | 20.00             |

| Time         | 6:01 am – 12:00 pm |
|--------------|-------------------|
| Afternoon    | 12:01 pm – 5:00 pm |
| Evening      | 5:01 pm – 8:00 pm  |
| Night        | 8:01 pm – 6:00 am  |

**Figure 8.** Progressively severer pollution events (from bin 1 to bin 8) and their frequency of occurrence in different time slots of the
day. The width of the bins and of the time slots is defined in the top-left corner tables.
transport is especially attributable to the finer fraction of particles (less than 2.5 μm for thousand km distance [17], less than 5 μm for 500 km distance [52]), namely those too small to settle by gravity and too large to coagulate [53]. Suspended particles might have been propelled towards the city by the stronger and longer lasting local sea breeze. Furthermore, it is widely acknowledged that in the case of dense maritime conurbations, such as Sydney, the sea breeze strongly interacts with the air circulation within the urban heat island [38], being attracted by convergence zones over the city center and stalling for a longer time at a decelerated rate [54, 55]. Indeed, sea breeze has been frequently identified as a major cause of pollutant advection over coastal cities [56, 57].

Biomass-burning aerosols have a strong and direct impact on surface-level radiation exposure through scattering and absorption while also having a secondary indirect effect as cloud condensation nuclei [41]. This scenario has been well documented worldwide regardless of the specific setting; from Amazonia [58–60] to Zambian Savanna [60], from Northwestern Spain [61] to Russian peatbogs [62, 63], from Polar regions [64] to

Figure 9. Map of the eight locations considered for the UHI evaluation followed by UHII boxplots. The top-left single boxplot represents the UHII statistical distribution during the bushfires at the monitoring site while the following charts represent the historical trends between 2000/2017 at six locations within the Greater Sydney area. Colors in the map match the colors in the boxplots. Map data: Reproduced with permission from ©2020 Google Earth, SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat/Copernicus.
eastern United States [65], from South Asia [66] to southwestern British Columbia in Canada [67]. However, few studies report specifically on ultraviolet (UV) radiation [68–70]. Kalashnikova et al [69] suggest that estimates of the radiative impacts of Australian aerosols would be valuable inputs to UV Index forecasts. They compared the measured UV irradiances during several episodes of relatively high aerosol activity against clear-sky conditions. By using satellite and ground-based sunphotometer measurements, they proved that smoke aerosols over the city of Darwin attenuated the surface UV irradiance by as much as 40%–50% at 290–300 nm and 20%–25% at 320–400 nm near active fires and by 15%–25% at 290–300 nm and ~10% at 320–350 nm, downwind of fires. Similarly, Chubarova et al [62] report that during the intensive fires sweeping across Central Russia in 2010, the high aerosol optical thickness and small single scattering albedo caused a maximum irradiance loss of 64% for global shortwave irradiance, of 91% for UV radiation and of 97% for erythemally-weighted UV irradiance. The maximum losses occurred after the solar noon at a solar elevation of 47°. In a geophysical research study on zooplankton distribution, carried out in the United States (Lake Tahoe, CA), it was found that wildfire smoke selectively reduced the incident ultraviolet solar radiation [71]. Irradiance was recorded in three UV wavelengths (305, 320, and 380 nm). The maximum daytime decrease of UV radiation occurred at 305 nm and reached 8% when smoke haze was present. The impact was milder at longer UV wavelengths (4% and 1% respectively). Furthermore, this study found a link between particulate matter concentration and UV, especially in terms of erythemally-weighted irradiance. Notably, it was observed that above a certain content (PMs > 20 μg m–3), the UVI could not reach high levels, thereby reducing the health risk. Further, from the upper bounds defined above for each particle size, the smoke haze was so dense that it acted as a perfect barrier to UV radiation, bringing the UVI down to zero.

Aggravated pollution was also linked to rain events. This evidence contradicts the well acknowledged afferent effect of rain that is, that it cleanses the air of pollutants and dust, unless cascading rain splash is considered in all its potential ramifications. Sulphate, nitrate, ammonium, elemental carbon and particulate organic material (POM) are major components of totally fire-driven PM2.5 and PM10, as demonstrated in urban site sampling [72]. The mechanisms governing the formation of these particles are still a grey area [73] and tend to be neglected in atmospheric models [74]. Raindrop impacts have been recently identified as an unexpected and underexplored source of fine soil particles in the atmosphere. In 2015, Joung and Buie advocated that rainfall could be responsible for soil-generated sub-micrometre aerosol [75]. The results of their lab experiments were further supported by Wang et al in a 2016 study published in Nature Geoscience [73]. The authors investigated the generation of soil organic matter after rain events. By means of chemical imaging and micro-spectroscopy of particles collected right after natural precipitation, as well as experimental irritation, they demonstrated that raindrop impact caused the ejection of sub-micrometre SOMs (soil organic matters) from the soil surface into the air, contributing to up to 60% of atmospheric particles. The authors also claimed that the impact was more pronounced when soils were exposed to strong, episodic precipitation events [76]. The inner mechanism relies on the intense generation of bubbles within a layer of the impinging droplets: the dislodgement of fine particles occurred upon the bursting of the bubbles on the air–water interface. This is especially likely during bushfires since plant-derived products are labile in the soil matrix and thus, soluble components may be prone to raindrop-associated aerosolization [73]. Therefore, the strongly acknowledged cleansing effect of rainfall can be actually attenuated by organic particles spattering up from the soil into the atmosphere. Our data supports the aforementioned results with further evidence, based on heavy rainfall events. Weak precipitation as well as water sprinkling or misting are still expected to have a positive impact on urban pollution [77–79].

From a temporal perspective, the lowest levels of PMs occurred between 5 and 8 pm, due to the onset of deliquescence processes. Conversely, the highest levels were recorded overnight and in the morning. Apparently, as the Sun’s rays diminished, the air was able to settle closer to the ground and stagnate, allowing the accumulation of pollutants. This mechanism extended to the early morning. Daily patterns of sea breeze might have played a key role as well: in the late morning and afternoon, the high-pressure zone on the land drew fresh air from the sea and, with it, the entrained smoke. This was particularly evident on heat wave days, when the pressure difference was exacerbated, which explains why the worst pollution events systematically followed days of extreme urban overheating (refer to figure 3). Conversely, in the evening, the pressure tended to equalize and therefore this mechanism’s effect decreased or ceased.

Analysis of the UHII patterns showed a distinct anomaly during the bushfires that had never occurred in the previous 20 years over the same calendar days: the UHII was always positive, with a statistical distribution strongly leaning towards UHII higher than the median. The change in radiative forcing and thermal balance emphasized the typical heat entrapment caused by built features, thereby preventing the occurrence of cool island events. Hence, it is expected that during days of high pollution, rich in particulate matter, the UHI might be exacerbated.
6. Conclusions and outlook

This paper presents the results of an environmental and air quality monitoring campaign conducted in the city of Sydney, during the massive bushfires that afflicted Australia between December and January 2020. A compact sensor network recorded air temperature, relative humidity, barometric pressure, precipitation, wind (speed and direction), solar radiation, UV radiation, UVI, PM1, PM2.5 and PM10.

The monitoring campaign lasted from the 20th of December 2019 to the 13th of January 2020, right in the midst of the most ferocious blazes in the area. During this time, the PM10 content reached a maximum of 160 μg m⁻³, the temperature peaked at 46.2 °C, while the accumulated rain was 13.6 mm. Therefore, extreme pollution, heat wave and drought were recorded simultaneously.

It was demonstrated that specific combinations of air temperature and relative humidity were conducive to higher/lower levels of pollutant accumulation, in agreement with findings from previous scientific studies. In general, higher PM concentration was recorded for night-time and early morning, especially after daytime overheating events (temperature above 35 °C). It was also observed that long-transport mechanisms and complex interactions between prevailing and local winds could have played a major role, making it difficult to establish definite correlations between PMs and single environmental parameters.

Intense rain splashing was also associated with the most intense concentration of dust. Scientific literature reports on the potential of airborne soil organic particles to be generated by precipitation. Our data confirm that, despite their acknowledged air-cleansing properties, heavy raindrops also trigger a mechanism that produces solid particles from soil, which can substantially raise the local pollution levels.

Another link was established between UVI and PM concentration. Several PM thresholds could be identified above which UV radiation was strongly blocked and below which the UVI was likely to surpass moderate levels. This relationship was further demonstrated by using evolutionary algorithms, and supports previous scientific evidence of the attenuating effects of smoke aerosols on UV irradiance.

Additionally, the urban heat island intensity during the bushfire event was compared to that recorded during the same period over the previous 20 years. Data from several BoM meteorological stations indicated an additional effect of the microclimatic perturbation induced by the bushfires: the disappearance of cool island events and the exacerbation of UHI events over the median.

This study provides insights on the multiple interplays between local meteorological and air quality parameters when a combination of weather extremes interacts with the urban microclimate. It offers a new holistic approach to environmental monitoring. However, the lack of multi-point measurements significantly reduces the scope of this analysis; hence, quantitative evaluations should be interpreted with caution. This notwithstanding, the discovered associations would be extremely valuable in building up a cohesive national health protection strategy and encouraging better responsiveness from governments and city planners. In future, other experimental activities will be carried out to extract general laws and climate dependencies.

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