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Indigenous Knowledge of seasons delivers a new way of considering annual cycles in atmospheric dispersion of pollutants

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ABSTRACT

Poor air quality is recognised as the most important environmental health issue of our time. Meteorological variables like temperature and wind speed can strongly influence air quality and these variables often show clear annual cycles. It is therefore common to analyse atmospheric pollutants within a seasonal framework. However, the commonly used seasons in Australia do not align well with all of the most important annual weather patterns that influence air quality in the Sydney Basin. We used Indigenous perspectives on 'seasons' as identified by the co-authors and combined these with statistical analysis of the local climatology. This enabled us to create a set of locally informed 'quasi-seasons' that we named IKALC-seasons (Indigenous Knowledge Applied to Local Climatology). Engaging with the IKALC-seasons improved our understanding of temporal variability of air pollution in western Sydney, mainly due to a better identification of the time of year when cold, still weather conditions result in higher levels of fine particulate pollution, carbon monoxide and nitrogen oxides. Although the IKALC seasons identified in this study are intrinsically local in nature, the methodology developed has broadscale application. This approach can be used to identify the times of year when micrometeorological conditions are most likely to drive poor air quality thereby helping to inform effective decision-making about emission controls.

Keywords: air pollution meteorology, air quality, CO, Indigenous Knowledge, NO_X, O_3, $PM_{2.5}$, seasonal cycles, seasons, Sydney.

1. Introduction

The negative health impacts of poor air quality on urban populations are well established (e.g. Dockery *et al.* 1993; Cohen *et al.* 2005; Beelen *et al.* 2014). Lelieveld *et al.* (2015) estimated that worldwide, more than 3 million premature deaths were caused by outdoor air pollution, with $PM_{2.5}$ (particulate matter less than 2.5 μm in diameter) the primary culprit (Lelieveld *et al.* 2015). Long-term exposure to elevated concentrations of ozone is also known to be linked with negative health outcomes (Jerrett *et al.* 2009).

Despite the fairly good air quality of the city of Sydney, Australia, significant health impacts are still evident (Broome *et al.* 2015). For example, exposure (even at low concentrations) to atmospheric pollutants (e.g. $PM_{2.5}$, ozone, O_3, and oxides of nitrogen, NO_X) has been found to increase hospital admissions for five types of cardiovascular disease in elderly people in Sydney (Barnett *et al.* 2012). A longitudinal cohort study has further found evidence of an association between long-term exposure to the low concentrations of $PM_{2.5}$ and NO_2 in Sydney and detrimental health effects (Hanigan *et al.* 2019), with ~2% of deaths in Sydney being attributed to $PM_{2.5}$ and O_3 pollution (Broome *et al.* 2015). These pollutants dominate exceedances of national air quality standards in Sydney (NSW Office of Environment and Heritage 2017, 2018) and unsurprisingly have been identified as the pollutants of most concern in Sydney (Paton-Walsh *et al.* 2019).

The temperate coastal basin geography of Sydney results in heterogeneous air quality, with worse air quality often observed in the west of the city. This is due to a combination of topography and meso-scale meteorology (Jiang *et al.* 2017), including cold air drainage into the Sydney Basin that can trap pollution close to the surface during the coldest times of the year; and afternoon sea breezes that can push polluted air-masses (with high O_3 concentrations) into western Sydney during the hottest part of the year (Paton-Walsh *et al.* 2018; Chambers *et al.* 2019*b*).

The $PM_{2.5}$, O_3 and other atmospheric pollutants can themselves exhibit strong annual variability, as the source strength of precursor pollutants and the meteorological conditions that affect chemical processing in the atmosphere change with the seasons (Oltmans and Levy 1992; Jaffe *et al.* 2005; Kandlikar 2007; McCarthy *et al.* 2007; Barnaba *et al.* 2010; Rastogi *et al.* 2016; Wang *et al.* 2016). Photochemical production of ozone peaks when temperatures and radiation levels are highest (Oltmans and Levy 1992), along with emissions of biogenic volatile organic compounds, that are precursors to the production of O_3 and secondary organic aerosols (Guenther *et al.* 2012; Emmerson *et al.* 2016). Other pollutants peak in colder times of the year when the planetary boundary layer is low and atmospheric mixing is suppressed (Chambers *et al.* 2015).

In Sydney, both $PM_{2.5}$ and O_3 are strongly influenced by meteorological conditions and emissions that change throughout the year. Maximum O_3 concentrations occur most often on hot days early in the year (Utembe *et al.* 2018), whereas high $PM_{2.5}$ concentrations are most frequent in the coldest parts of the year, when domestic wood-heaters are commonly used in the city and atmospheric mixing is low (Robinson 2011; Desservettaz *et al.* 2019). Extreme pollution events can also occur in warmer months due to wildfires (e.g. Rea *et al.* 2016; Simmons *et al.* 2022). Owing to heterogeneity in the frequency, magnitude and characteristics of poor air quality events throughout the year, it is useful to examine atmospheric pollutant concentrations through a seasonal lens.

Recent awareness of the catastrophic impacts of human population growth and industrial development has led Western science to seek different approaches and models to the use and management of natural resources. These new approaches align more closely with the Indigenous worldviews of sustainability and coexistence. This has supported Indigenous Knowledge and Western science becoming more compatible partners in research (Green *et al.* 2010; Bohensky *et al.* 2013). Traditionally, and still today, Indigenous peoples hold an alternative way of understanding the world around them. Intimate knowledge and understanding of weather and seasonal change, and the resultant effect on resource availability has enabled Indigenous peoples to coexist rather than dominate the environment for several millennia (Woodward *et al.* 2009, 2012; Green *et al.* 2010; Nuggett *et al.* 2011; Prober *et al.* 2011; Giblett 2012; Liedloff *et al.* 2013). It is difficult to translate the complex concepts of Indigenous Knowledge for understanding in Eurocentric methods of thinking and analysis without oversimplifying and commodifying the Indigenous line of thought (Haynes 2010).

The Western scientific method is complementary to Indigenous Knowledge production in that both are based on an accumulation of observations over time and generations, and rely on the testing of those observations to create 'truths' (Roös 2015). Many Indigenous people continue to live immersed in understandings of the landscape and understand that its processes, including weather patterns, rarely follow set time periods, nor occur at the same time each year (Prober *et al.* 2011; Clarkson *et al.* 2017). Nevertheless, there is value in recognising typical weather patterns at fixed times of year for the purposes of understanding and regulating air quality. However, the division of the year into four set time periods of summer, autumn, winter and spring is neither informative nor particularly useful in reflecting on weather patterns experienced in south-eastern Australia (Giblett 2012; Entwisle 2014).

The concept of 'seasons' has historically varied between cultures worldwide and are sometimes arbitrarily identified. The Gregorian-based seasonal cycle of summer, autumn, winter and spring is very familiar to western nations; however, the actual definitions used for these seasons vary from country to country. In the meteorological definition (as used in Australia), the seasons start on the first day of those months that include the solstices and equinoxes. In some other countries, the first day of spring is taken to be the day of the astronomical vernal equinox (which varies between 19 and 21 March) and the summer solstice is considered to be the first day of summer. Yet others consider these astronomical markers of the year to be mid-spring and mid-summer respectively. Thus, although some cultures define seasons strictly by astronomical events, in Australia the seasons are defined by months of the year:

- Summer months are December, January and February,
- Autumn months are March, April and May,
- Winter months are June, July and August; and
- Spring months are September, October and November.

In this paper we refer to these as 'European' or 'Western' seasons since it was Europeans that first brought these Western cultural ideas to Australia. The division of the year into 12 months (and then further into four seasons) is a result of European cultural traditions that date back more than 2000 years to Roman times.

This cultural practice of dividing the year into four seasons of almost equal length has persisted to modern times; however, these 'Western' seasons do not align well with synoptic-scale weather patterns that occur in the Sydney Basin. Although the fundamental driver of seasonal changes throughout the year is the earth's tilted orbit around the sun (and the resultant impacts on the global circulation patterns), how this translates to synoptic scale weather patterns varies across the globe. In south-east Australia, the oceanic east-Australian current can also be an important driver of synoptic-scale weather (Hopkins and Holland 1997). Additionally, meso-scale processes can be an important driver for meteorological conditions likely to affect air quality in the Sydney Basin (Jiang *et al.* 2017; Chambers *et al.* 2019*b*). It is therefore useful to have an understanding of local 'seasonality' (meaning how different weather parameters change during the year), in order to understand annual variation of air quality within a specific region of interest. For this reason we were motivated to explore whether Indigenous perspectives of climate could provide insight into creating more meaningful set of local 'seasons' for western Sydney, that might inform our understanding of annual cycles in atmospheric pollutant concentrations in the region.

Indigenous perspectives of seasonality provided inspiration for our aim of finding a more-appropriate and useful way of describing Australian annual weather patterns, for application in air quality research in the Sydney Basin. The aim was to work collaboratively with Indigenous partners to ensure our interpretations of Indigenous ideas of seasonality was consistent with Indigenous observations of seasonal change (Prober *et al.* 2011; Law 2012; Bohensky *et al.* 2013; Leonard *et al.* 2013), and then apply this to better understand air quality patterns in the region.

Australia's Indigenous peoples have been custodians of the land for over 60 000 years (Rose 1996, 2000; Clarkson *et al.* 2017), and their connection to the land and sea is intrinsic to their existence (Rose 1996, 2000; Woodward *et al.* 2020). The interconnected relationship between local Indigenous people and the landscape, including animals, plants and weather, is interwoven with their detailed knowledge of seasonal cycles and associated resource availability that has been passed down through generations over thousands of years (Woodward *et al.* 2009; Green *et al.* 2010; Woodward 2010; Prober *et al.* 2011). Drawing on their unique and complex knowledge systems, Indigenous Australians have been able to adapt to, and thrive, within the changing landscape.

The Indigenous spiritual connection to the landscape has created a deep knowledge of the workings of the environment, which has been passed on through generations, including an intricate understanding of weather cycles and the corresponding indicators of past and future weather events. This all revolves around the availability of food throughout changes in weather often indicated by phenological events (O'Connor and Prober 2010). This is supported by archaeological examination of campsite residue, 'middens', as proof of seasonal variation in pollens, seeds, and animal, fish and shellfish types and species, identifying the movement patterns of communities related to knowledge of seasonal availability (Bursill 1993; Roös 2015). Many Indigenous seasonal calendars have recently been developed in Australia; however, to date these have not been investigated in terms of air quality data (see the Bureau of Meteorology's Indigenous Weather Knowledge website, http://www.bom.gov.au/iwk/index.shtml).

In more recent times, the western scientific community has taken an increasing interest in Indigenous Knowledge and perspectives as opportunities for enhanced, collaborative approaches to management of the environment (Bohensky *et al.* 2013). Engaging across knowledge and value systems requires a rethinking of how people come together to collaborate. This has inspired the development of research methods and approaches that are more sympathetic to engagement of multiple views, perspectives and knowledge systems, including a move toward co-designed and Indigenous-led research that seeks to weave across knowledge systems (Bohensky *et al.* 2013; Johnson *et al.* 2016; Tengö *et al.* 2017). This contrasts with previous scientific research that drew exclusively on Western views and methods of viewing the world, based on predicting the way the natural world functions, excluding and marginalising non-Western knowledge systems (Green *et al.* 2010; Bohensky *et al.* 2013).

The landscape has changed significantly in the last 200 years due to the continued impacts of colonisation. In the Sydney region especially, there is very little land left untouched by colonisation. Even locations that have been preserved, such as national parks, have changed since the Indigenous peoples have been unable to continually and actively care for and manage the land and pass on related knowledge to future generations. As a result, the traditional seasonal indicators either no longer exist or have become hidden. This dramatic change in landscape has made it difficult for Indigenous Knowledge to be applied because the introduction of built environments has resulted in a loss in vegetation and driven animals away.

However, Indigenous Knowledge is a process, where the people continuously learn new knowledge and pass it on through generations. Oral tradition allows for flexibility of knowledge – nothing is static (Goodall 2008). This project focuses on the adaptability of Indigenous culture to the changes in landscape, where Indigenous concepts are adapted to understand the workings of the current landscape and by extension, increase our understanding of weather patterns (Roös 2015).

This project aimed to avoid superficial engagement with Indigenous Knowledge, as we recognised that Indigenous Knowledge is dynamic and changes with the landscape (Haynes 2010). Indigenous culture is contextually adaptive with the goals to survive by reciprocal relationships and custodianship of the sacred landscape. Australian Indigenous peoples recognise with respect, that every aspect of life is interconnected, including humans. Western belief systems often consider human life separately from the rest of nature and so Western culture is separate from nature. This has led to assumptions that Indigenous Knowledge is a set of unchanging rules and beliefs that have been passed on over the thousands of years that Indigenous peoples have inhabited the Australian landscape; however, this is not the case (Muir *et al.* 2010).

In this paper, we describe our efforts to determine whether Indigenous perspectives can define a more-meaningful set of seasons (or natural weather cycles) for the western Sydney region. We describe our findings of applying an Indigenous framework of understanding weather patterns and how we used this understanding together with decadal-scale weather records from western Sydney and a statistical clustering technique to create a set of IKALC-seasons (Indigenous Knowledge Applied to Local Climatology). Finally, we compare the IKALC-seasons to other Australian seasonal calendars and compare how the different sets of seasons help elucidate patterns in air quality in the Sydney Basin.

2. Methods

2.1. Partnership with Indigenous Knowledge holders

This project partnered with Indigenous Knowledge holders of the Sydney area to reveal Indigenous understanding of seasonal weather patterns and explored how different knowledges tell varied stories of seasonality within Sydney. The Indigenous language group located in the Western Sydney area is the Darug people (Bursill *et al.* 2007). Owing to the proximity of the Darug people to the Dharawal people to their south, elders and knowledge holders from both (language and cultural) groups were invited to contribute their understanding of weather patterns through co-authorship of a paper. Indigenous contributors to this study were partners in all stages of the research and are co-authors of this paper. Through engaging with different knowledges about seasonality of Sydney, the co-authors were mindful of obtaining permissions if any Indigenous cultural and intellectual property was to be included in the research. The authors acknowledge that certain people within the Indigenous community have the authority to share this knowledge as well as hear the depth of this knowledge. It is also understood that each family or clan may have different views on this topic, and we know that the views presented in this paper may not represent the understanding of all Indigenous Knowledge holders within the Sydney area.

The objective of bringing together different knowledges was to find the following:

- General weather patterns annually and over extended periods in the Sydney area (Indigenous perspectives and observations of the current landscape).
- Seasonal indicators within the biophysical landscape, both traditional and new. This consists of flora or fauna species, and changes in their behaviour that reflect changes of weather within the local ecosystem of western Sydney. A focus was expected to be on sources of food such as animals, flowers, roots, seeds and fruits.
- Biogeographical and Indigenous knowledge differences in relation to geography, including any differences between eastern and western Sydney.

The authors engaged in conversations about different understandings of seasonal perspectives in Sydney, their traditional lands, also referred to as 'Country'. Specific questions were asked of Indigenous co-authors including 'from any teachings or observations you have made throughout your life, tell me about the weather in your Country. How do you tell the time of year?'. The IKALC conceptual model was reviewed by all authors and found to be a good boundary object for discussing observations of seasonal change. Indigenous contributors saw value in being part of the process to build their own understanding of local scale atmospheric change to build on their own understanding of their Country.

2.2. Atmospheric data sources and selection

Following these discussions between co-authors, we decided to apply this framework of seasonal understanding to inform a statistical analysis of historical meteorological observations to help define the local weather cycles. Meteorological data were obtained from the Bureau of Meteorology for various sites in the western Sydney region. Sites were chosen based on the availability of weather parameters and the length of records. Hourly data were available at Bankstown Airport (1989–2017) and Sydney Olympic Park (1995–2011, 2011–2017), whereas 3-hourly data were available at Sydney Olympic Park (1995–2011, 2011–2017), Bankstown Airport (1969–2017), Prospect Reservoir (1965–2017) and Parramatta North (1967–2017).

The time series were plotted to look for gaps and discontinuities in the records. Prospect Reservoir had a step change in several variables in *c*. 2000 and Parramatta North only started recording precipitation, dew point temperature and relative humidity in 1987, so these stations were excluded from the main analysis. The hourly data were excluded from the main analysis because of their fairly short records. The main analysis was therefore based around the 3-hourly data from Bankstown airport, which offers a 49-year record (1969–2017 inclusive) of precipitation, temperature, dew point temperature, relative humidity, pressure and wind (decomposed into its u and v components). The dataset from Bankstown Airport was chosen as it provided the longest reliable dataset without step changes or major gaps. Comparative analyses of 30-year records (1988–2017) from Parramatta North and Bankstown Airport and 15-year records (2002–2017) from Prospect Reservoir, Parramatta North and Bankstown Airport were also undertaken. Composite time series from Bankstown airport were obtained for each weather parameter by averaging by 'day of year' (DOY), e.g. by averaging together all data recorded on 1 January in any year from the 49-year record, all data recorded on 2 January.

Air quality data were obtained from the NSW Office of Environment and Heritage air quality monitoring network in Sydney. A 10-year (2005–2015) time series of hourly air quality data from Chullora station, located ~7 km northeast of Bankstown Airport, was selected.

Radon data were obtained from the Australian Nuclear Science and Technology Organisation (ANSTO). A 5-year (2007–2011) time series of continuous hourly atmospheric radon concentrations measured at the University of Western Sydney's Richmond campus was available. A dual-flow-loop two-filter radon detector developed by ANSTO was used to measure radon 2 m above ground level. Details regarding the site and equipment setup for these measurements was provided in Chambers *et al.* (2015).

2.3. Clustering analysis

The meteorological data were grouped into 'pseudo-seasons' using non-hierarchical *k*-means clustering following the algorithm of Hartigan and Wong (1979), which minimises the Euclidian distance between clusters. This method is an iterative process that aims to partition the data points into *k* groups (or clusters) such that the sum of squares from points to the assigned cluster centres is minimised (Jain 2010).

The process proceeds as follows:

1. A number *k* of initial 'means' are randomly generated from within the data domain;
2. A number *k* of clusters are created by associating every observation with its nearest mean;
3. The centroid of each *k* cluster then becomes the new mean;
4. Steps 2 and 3 are repeated until convergence is reached.

To encourage clustering of consecutive days, DOY was included along with the meteorological variables in the clustering; however, to minimise the impact of the start day (since DOY 1 and 365 (or 366) are unlikely to be clustered together, even though they are consecutive days), clustering was repeated 366 times, with a different start date assigned as DOY 1 each time. In order to equally weight each variable, prior to clustering, each variable was scaled by subtracting its mean and dividing by its standard deviation. This produced a standardised variable (sometimes called a *z*-score or a standard score) by rescaling each variable to have a mean of zero and a standard deviation of one (Milligan and Cooper 1988; Mohamad and Usman 2013). One caveat to this approach is that several of the meteorological variables used are correlated or anticorrelated (such as temperature and relative humidity and pressure and wind speed), and in this sense the equal weighting of each variable does not work perfectly for interdependent variables. A range of *k* (number of clusters or 'seasons') values (3–8) were tested on the 49-year record from Bankstown Airport and on 30-year records from Parramatta North and Bankstown Airport and 15-year records from Prospect Reservoir, Parramatta North and Bankstown Airport (see the 'Comparison of IKALC-seasons from Bankstown airport with other nearby meteorological observations' section in the Supplementary material). To help interpreting the clustering results, periods of the year were identified during which certain weather parameters were 'stable', for example, periods during which the westerly component of wind was strong, or during which relative humidity was elevated.

3. Results

3.1. Key team learnings from discussions about Indigenous seasonal knowledge

Through discussion the research team came to understand that a lot of Indigenous seasonal knowledge of the Sydney region has been lost, confirming that this is largely the result of the intense impacts of colonisation in this intensively developed region. Initially, colonisation drove high mortality rates in Indigenous populations, whereas forced migration led to disconnection from Country and assimilation into other Indigenous language groups, further damaging knowledge, language and culture.

Qualitative analysis of the information that emerged through these discussions showed a common perspective that weather pattern knowledge relates to indicators including knowledge of food availability and animal behaviours, which leads to knowledge of land management for the availability of food (Fig. 1). Current food availability is an indicator of past weather, and current weather is an indicator of future food availability. Each factor is interdependent and varies throughout time. This is distinct from the concept of a set of fixed seasons.

Contributors of Indigenous knowledge communicated that there is no recognition of strict seasons within an Indigenous climate framework. Traditionally, in this area, combinations of words were used to describe climatic conditions. These words were also linked to what food was available at the time or shortly after (O'Connor and Prober 2010; Prober *et al.* 2011). The combination of words; for

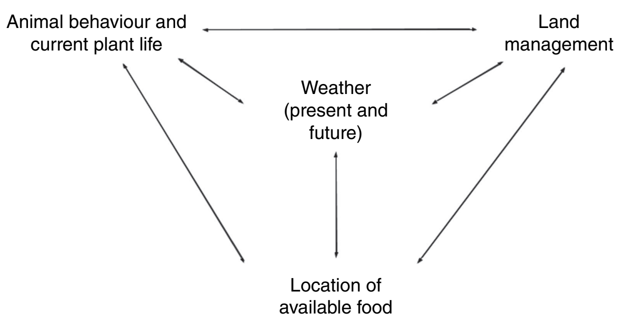

Fig. 1. Indigenous climate framework (interrelationship between weather, food availability, animal behaviour or current plant phenology and land management).

example, hot and wet, subsequently correspond to the availability of certain foods. The signs from flora or fauna also enable the prediction of weather within their local ecosystem, as suggested by O'Connor and Prober (2010), and fit within the framework presented in Fig. 1.

The time of year in Indigenous culture is determined by cumulative knowledge and observations of temperature, rainfall, wind and availability of food, including animals, flowers, roots, seeds and fruits (Bursill 1993). The time of the year is overall referred to in terms of hot or cold, windy and wet or dry. Several contributors expressed strong views that there were no established seasons recognised in Darug or Dharawal culture, in contradiction of prior claims (Bodkin 2006), which is why we looked to develop the IKALC-seasons.

Owing to the variation, diversity and dynamic nature of knowledge and perspectives within Indigenous communities, there is not a single set of widely accepted local Indigenous seasons for the region (see principle 1.2 b and c from Australian Institute for Aboriginal and Torres Strait Islander Research 2020). Nevertheless, our discussions provided a common theme that seasons could often be described by the combined climatological variables (of hot or cold, windy and wet or dry) and could be mapped to specific days of the year. It was this different perspective that helped us to realise the importance of local-scale weather phenomena when considering impacts on air quality. As a result, we explored a different approach, seeking to combine what we had learned from each other with local climatological data. Ideally, we would have also used biological seasonal indicators such as times when different plants came into bloom, or first sighting of animals in the year; however, such data were not available to us.

3.2. Results from statistical clustering analyses

Our first set of annual weather cycles was formed using Indigenous concepts of weather and the publicly available monthly climate statistics from the Bureau of Meteorology website (http://www.bom.gov.au/climate/averages/tables/cw_066195.shtml) for Sydney Olympic Park. Combining the various data for weather variables including temperature, rainfall and wind speed over the 30 years between 1981 and 2010, with the Indigenous description of times of year including 'wet and hot', and 'windy', we used our subjective judgement to identify a set of pseudo-seasons (see the 'First attempt at defining annual weather cycles for Sydney based on Indigenous concepts (and a 30-year monthly climatology for the region)' section in the Supplementary material for details).

This first attempt created seven pseudo-seasons, but it relied on subjective decision making and used monthly climatological data. In Indigenous culture the European months are meaningless (Woodward 2010), so we decided to explore higher temporal resolution climatological data and statistical techniques that could help define the weather cycles more precisely. Since windiness, cloudiness and rainfall (or combinations thereof) are all known to have profound impacts on the dispersal or removal of pollutants from the lower atmosphere, pseudo-seasons based on groupings of climatological conditions related to Indigenous recognised periods of wet, hot, windy etc., were expected to be more closely related to changing air quality than European months.

The average annual weather conditions from Bankstown airport were obtained by averaging each meteorological parameter by 'day of composite year', i.e. by averaging together all data recorded on 1 January in any year from the composite 49-year record, all data recorded on 2 January, etc. The resulting time series are plotted in Fig. 2.

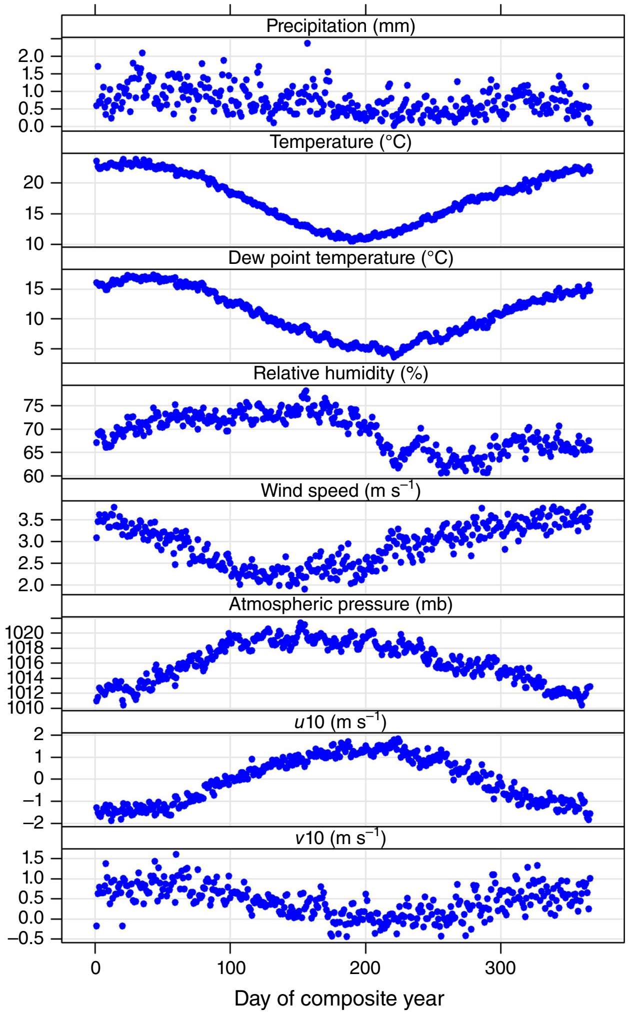

Fig. 2. Time-series of mean daily meteorological parameters averaged by day of composite year at Bankstown Airport using 3-hourly data from 1969 until 2017. Parameters are: 'v10' = meridional wind velocity (i.e. component of horizontal wind towards north) in metres per second at 10 m; 'u10' = zonal wind velocity (i.e. component of horizontal wind towards east) in metres per second at 10 m; atmospheric pressure in millibars; wind speed (i.e. north–south wind speed, m s^{-1}); relative humidity (%); dew point temperature (°C); temperature (°C); and precipitation (mm).

We performed a non-hierarchical cluster analysis (Hartigan and Wong 1979) on the meteorological data averaged by DOY. Fig. 3 shows an example of the results of the 366 clustering repetitions when using 7 clusters, as suggested by the original analysis of monthly climatology. The colours each represent a cluster, and the black line indicates which DOY was set to 1 for each repetition. The figure indicates that, as expected, very few clusters include both the first and last DOY. To summarise the 366 clustering results, the mode of the cluster number distribution is determined for each DOY (for each column of Fig. 3, the mode is the cluster number associated with the colour that dominates).

The clustering results for k = 3–8 are summarised in Fig. 4. The figure illustrates how some transitions are robust to the number of clusters, i.e. they remain the same for most k-values. These are illustrated by vertical lines in the figure. This is the case, for example, for the transition from blue to orange, which happens towards the end of January in all cases except when k = 3. This change in season is due to increased precipitation. Both blue and orange depict warm temperatures, and this is captured by blue when k = 3. For k = 4–8, the blue days within the orange season are days on which there was little precipitation. Fig. 4 also illustrates how some transitions shift in time depending on the number of clusters. These are indicated by diagonal lines.

The optimum solution should avoid transitions that are not robust (i.e. a transition identified in one set of clusters is considered to be robust if it also occurs in other solutions with larger k). For example, k = 5 includes a transition (indicated by a rectangle) that is not seen in any of the other solutions, so this is not considered to be robust. Ideally, each season would be a solid block of a single colour, with periods of transition (such as those circled in Fig. 4) of minimal length. From the results illustrated in Fig. 4, k = 6 was chosen as the optimum solution. This decision was made because k = 5 has a non-robust transition and k = 7 and 8 both show long transition periods. Thus, our statistical analysis of high-temporal resolution meteorological data yields six IKALC-seasons from the Bankstown meteorological data from 1969 to 2017 (Fig. 5). These six IKALC-seasons match

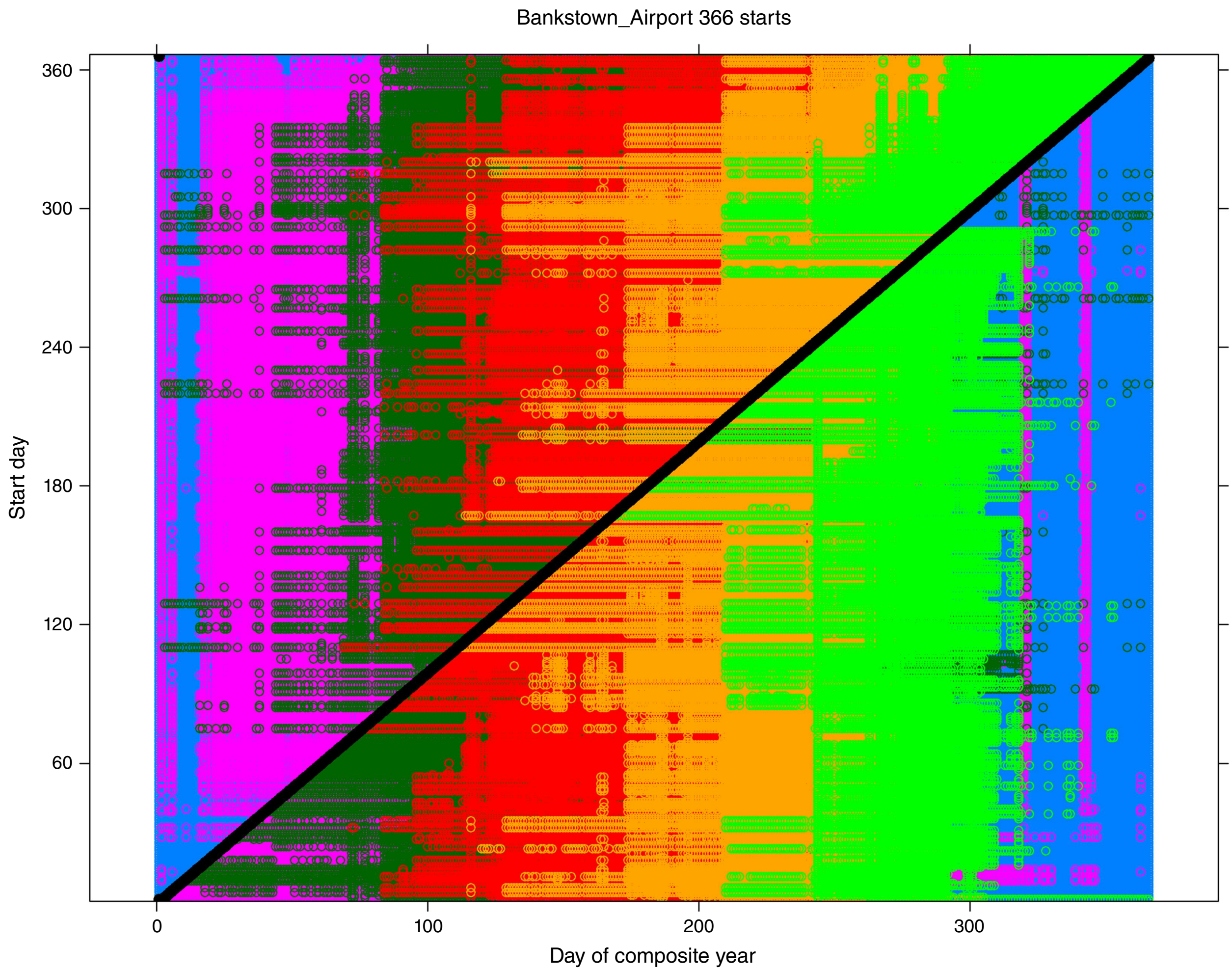

Fig. 3. Results of the 366 k-means clustering repetitions for k = 7. The black line indicates which day of the year was assigned to be 1 for each repetition.

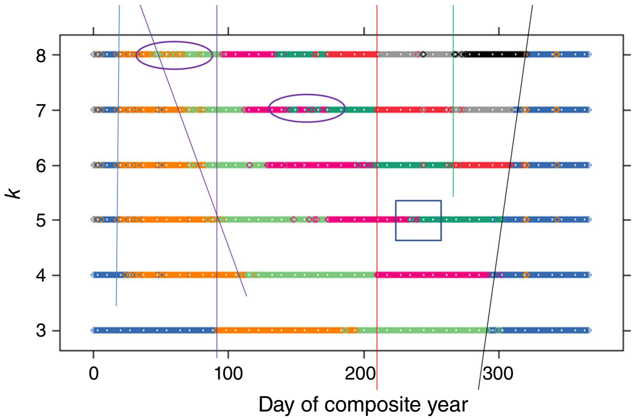

Fig. 4. Summary of clustering results for different *k*-values. Different colours represent different clusters, but the choice of colour is arbitrary. Vertical lines show where transitions from one cluster to another are consistent across most *k*-values whereas diagonal lines show where transitions vary in time with the *k*-value used. Periods of time where the transitions are slowly occurring are marked by ovals or a rectangle depending upon whether they are seen in other solutions or not.

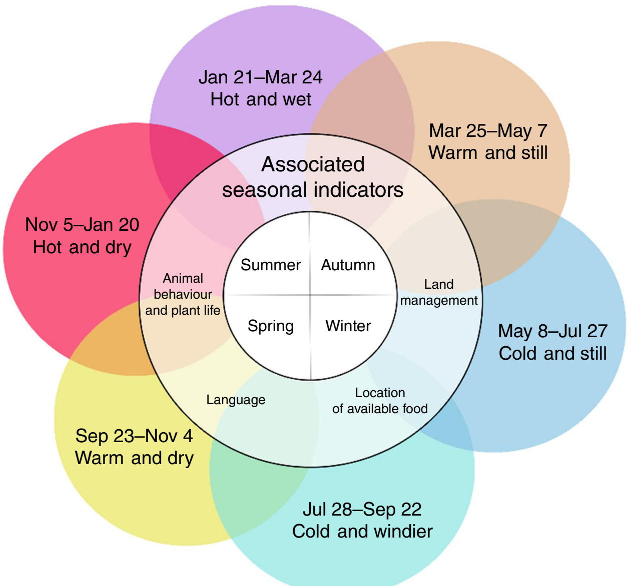

Fig. 5. Final designation of IKALC-seasons using clustering results. The inner circle shows the European and Western seasons, the larger circle shows the seasonal indicators used in Indigenous culture to recognise changing weather patterns and the outer circles are the IKALC-seasons with their dates and descriptors.

six of the seven seasons identified by subjective means in the 30-year monthly climatological data from Sydney Olympic Park (see the 'First attempt at defining annual weather cycles for Sydney based on Indigenous concepts (and a 30-year monthly climatology for the region)' section in the Supplementary material), with only the cooler and drier season not identified in the Bankstown daily data.

4. Discussion

4.1. Assessment of the spatial variability of IKALC-seasons across western Sydney

Our initial motivation was to discover whether Indigenous Knowledge could help to define a more-meaningful set of seasons for western Sydney (that might also be useful for analysis of annual cycles of air quality in the region). Our IKALC-seasons used meteorological data from a single site in western Sydney and so could be dependent on meso-scale processes that are very local in nature as well as regional-scale meteorology. It is therefore useful to assess the degree to which these IKALC-seasons are consistent across a large region of western Sydney.

In order to explore the question of scale, we analysed the available coincident data from the other Bureau of Meteorology sites within western Sydney. The results of the analyses are shown in the 'Comparison of IKALC-seasons from Bankstown airport with other nearby meteorological observations' section of the Supplementary material. Overall our attempt to establish the geographic scale of relevance, although not entirely conclusive, indicated that nearby sites produced broadly consistent IKALC-seasons. This suggests that the clustering is driven largely by synoptic-scale factors. Large variability in rainfall, which can often be influenced by meso-scale factors, was present in the Bankstown Airport record, driving differences between the lengths of the hot and wet IKALC-season derived from different lengths of records (15, 30 and 49 years) at the main site at Bankstown Airport. The longer record is more stable for clustering but may not be a more-accurate representation of the current climate due to evidence of warming and drying in the region (Timbal 2009; Bradstock *et al.* 2014).

4.2. IKALC-seasons and comparison to other Australian calendars

The six IKALC-seasons identified above from the 49-year record from 1969 to 2017 for Bankstown airport are summarised in Table 1. We used the descriptive English names as identified by Indigenous co-authors.

The IKALC-seasons are compared to the Western seasons and with the south-east Australian calendar proposed by Timothy Entwisle (Entwisle 2014) in Fig. 6.

Entwisle proposes five seasons in his book *Sprinter and Sprummer – Australia's changing seasons* (Entwisle 2014), which are entirely based on botanical cues, and start on the first of the month for convenience. Entwisle's seasons are 'sprinter' (August and September), 'sprummer' (October and November), 'summer' (December, January, February and March), 'autumn' (April and May) and 'winter' (June and July). There are some significant similarities between the IKALC-seasons and Entwisle's calendar, including a change of season starting *c.* 1 August (DOY 214), which in

Table 1. IKALC-seasons with dates and descriptions.

Cluster number	DOY range	Dates	'Name'	Description
1	310–20	5 Nov–20 Jan	Hot and dry	South-easterlies, hot, not much rain
2	21–83	21 Jan–24 Mar	Hot and wet	Still hot, more rain, RH increases
3	84–128	25 Mar–7 May	Warm and still	Temperature cooling, easterlies weaken, showers
4	129–208	8 May–27 Jul	Cold and still	Temperature decreasing to its minimum, low wind speeds, high pressure
5	209–266	28 Jul–22 Sep	Cold and windier	Wind speed picks up, RH drops, westerlies, v10 is neutral (no strong north–south component)
6	267–309	23 Sep–4 Nov	Warm and dry	Still dry, little rain, winds shift back to south-easterly, temperature warming

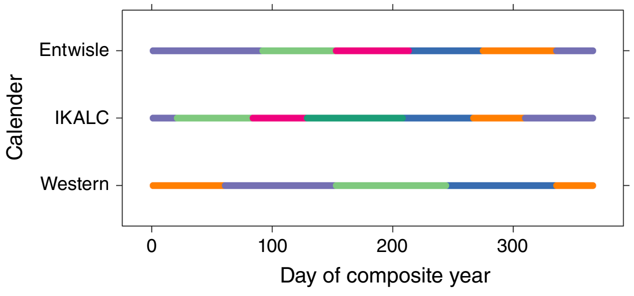

Fig. 6. Comparison of the days of the year for the statistically derived IKALC-seasons using Bankstown meteorological data (purple represents hot and dry; light green represents hot and wet; pink represents warm and still; dark green represents cold and still; blue represents cold and windier; and orange represents warm and dry), with Timothy Entwisle's south-east Australian calendar (purple represents summer; green represents autumn; pink represents winter; blue represents sprinter; and orange represents sprummer) and the Western seasons of summer, autumn, winter and spring. Different colours represent different clusters, but the choice of colour is arbitrary.

the IKALC-seasons indicates the transition from 'cold and still' to 'cold and windier' (at DOY 209). Both calendars also have a transition towards the end of March (IKALC transitions from hot and wet to warm and still on DOY = 84, 31 March is DOY = 90). In contrast, the IKALC-seasons bear little resemblance to the Western seasons of summer, autumn, winter and spring.

Entwisle's seasons have the advantage of being based on botanical cues, which more closely follow the view of seasonal changes as expressed by our team of Indigenous contributors. However, its use of calendar months is a disadvantage, as is its reliance of detailed botanical data that is not publicly available for most regions. The main differences between Entwisle's calendar and the IKALC-seasons follow:

1. The timing of transitions are restricted to calendar months in Entwisle's calendar;
2. Entwisle calendar has a single hot season, whereas the IKALC-seasons differentiate between hot and wet and hot and dry periods.

Despite these differences, the commonalities between the calendars provide some qualitative evidence that the IKALC-seasons capture some of the most important botanical markers of seasonality in the Sydney region.

4.3. Using the IKALC-seasons to improve our understanding of seasonal variability of air quality in Sydney

A 10-year time-series (from 2005 to 2015) of air quality data from the NSW Office of Environment and Heritage air quality monitoring station in Chullora, western Sydney was used to explore the use of the IKALC-seasons for understanding seasonal variability of air quality in the region. The Chullora air quality monitoring station is located ~7 km northeast of Bankstown Airport. We also compare to Entwisle's seasons and the four 'Western seasons' to determine if IKALC-seasons can provide a clearer distinction between air quality experienced at different times of year.

Fig. 7 shows the mean concentrations of $PM_{2.5}$ ($\mu g\,m^{-3}$) and mole fractions of O_3, NO_X and CO (ppb) for each day of the year averaged over the 10-year dataset from Chullora in western Sydney. The data are also presented (along with standard deviations in the mean) in Table 2. The IKALC-seasons provide a better characterisation of seasons for air quality, principally through the better identification of the cold and still time of the year. During this period, concentrations of $PM_{2.5}$, CO and NO_X are at their maximum and O_3 is at a minimum in Chullora (Fig. 6). The IKALC 'cold and still' season runs from 8 May to 27 July and captures the maximum concentrations of these pollutants well. By contrast, the Western season of Austral winter (June–August) starts too late to capture the beginning of the coldest time of year and extends past the cold, still conditions and into the 'cold and windier' IKALC-season. Reduced atmospheric mixing experienced during cold conditions is an important driver of high NO_X, CO and $PM_{2.5}$ during the coldest time of year, along with increased sources due to domestic wood heater usage. Thus, Western seasons do not capture the change from still cold conditions in June and July to windier conditions in August. This is a key factor in the better performance of the IKALC-seasons in predicting air quality in western Sydney.

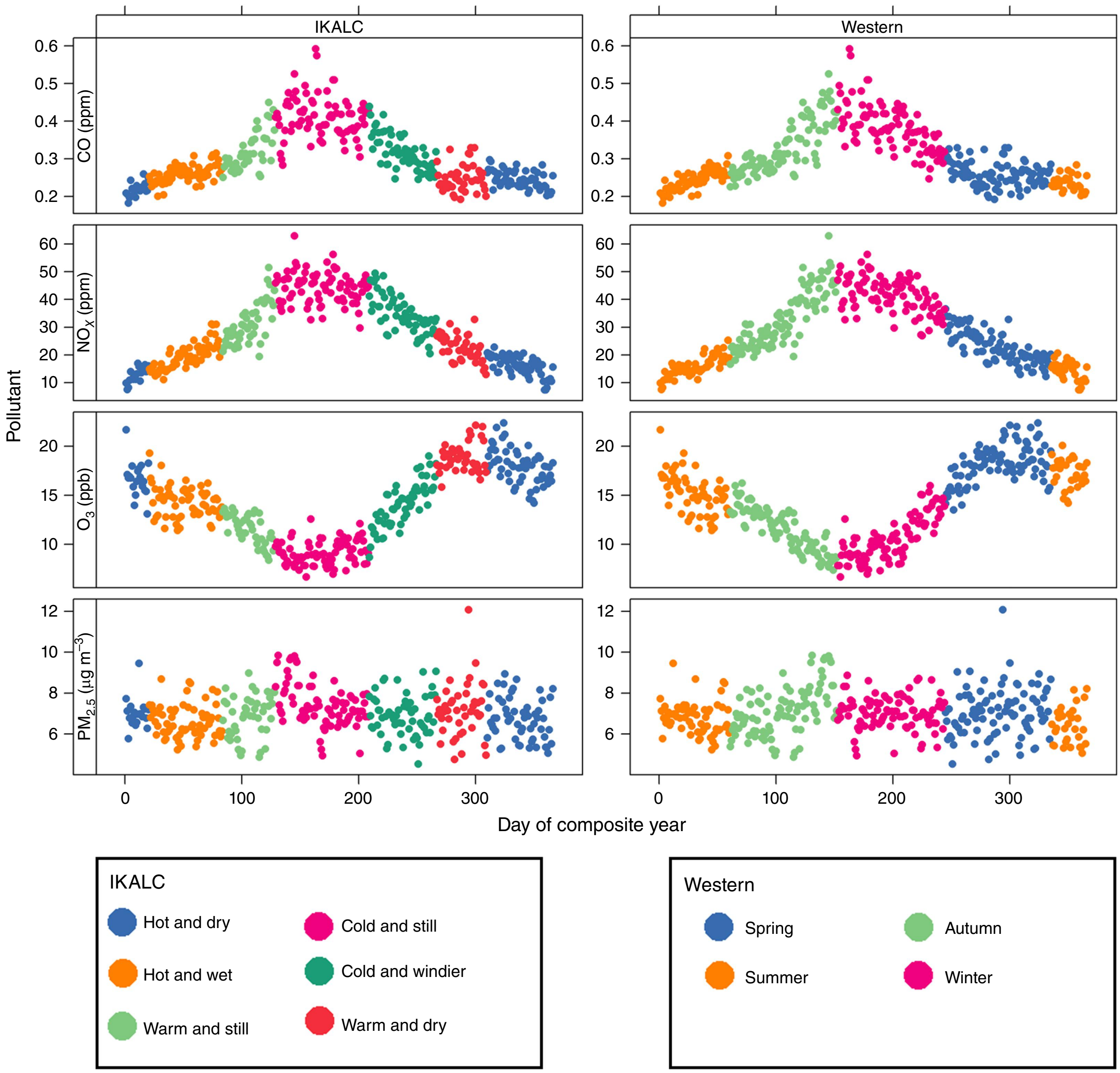

Fig. 7. From bottom to top mean concentrations of $PM_{2.5}$ (µg m^{-3}) and mole fractions of O_3, NO_X and CO (ppb) for each day of the year (averaged from 2005 to 2015) as measured at the air quality station in Chullora in western Sydney. The left-hand panel shows the data coloured by IKALC-seasons and the right-hand panel shows the data coloured by the Western seasons. The data from the dust-storm event in September 2009 have been removed so that the underlying patterns may be observed.

A 5-year dataset of night-time radon measurements was analysed to provide an estimate of nocturnal atmospheric stability. Continuous hourly atmospheric radon concentrations were measured at 2 m above ground level at the University of Western Sydney's Richmond campus from 2007 to 2011. A dual-flow-loop two-filter radon detector developed by ANSTO was used. Details regarding the site and equipment setup for these measurements was provided in Chambers *et al.* (2015). Radon is a naturally occurring, unreactive, radioactive gas with a reasonably consistent, well-distributed terrestrial source function. Owing to the 3.82-day half-life of radon, air masses retain a 2–3-week 'memory' of fetch influences, which contribute to the variability of radon concentration measured at a site (Chambers *et al.* 2015). The balance of observed radon variability at terrestrial sites is primarily contributed to by diurnal dilution effects of changing atmospheric mixing depth. Once fetch effects on radon observations have been removed, as described by Chambers *et al.* (2015), the nocturnal mean radon concentration over a 10-h window (1900–0500 hours) each night is very closely relatable to the mean nocturnal atmospheric mixing state or 'stability' (Chambers *et al.* 2015, 2019*a*; Williams *et al.* 2016).

Thus, high nocturnal radon concentrations are associated with stable nights, when near surface mixing is very weak.

Table 2. Mean (±s.d.) of concentrations of $PM_{2.5}$and mole fractions of O_3, CO and NO_X as measured at the NSW Office of Environment and Heritage station in Chullora in western Sydney from 2005 to 2015.

Calendar	Season	$PM_{2.5}$ ($\mu g\ m^{-1}$)	O_3 (ppb)	CO (ppb)	NO_X (ppb)	Wind speed($m\ s^{-1}$)	Temperature (°C)	Summary
IKALC	Hot and dry	6.8 ± 3.6	18 ± 6	240 ± 100	15 ± 8.7	2.4 ± 0.7	21.2 ± 3.2	Lowest CO & NO_X, low $PM_{2.5}$, high O_3
	Hot and wet	6.7 ± 3.0	14 ± 5	260 ± 110	20 ± 11	2.3 ± 0.8	22.2 ± 2.4	Lowest $PM_{2.5}$, low CO & NO_X
	Warm, still and wet	6.8 ± 3.8	12 ± 4	320 ± 150	31 ± 20	1.9 ± 0.8	17.8 ± 2.4	Low $PM_{2.5}$ & O_3, higher CO & NO_X
	Cold and still	7.5 ± 4.2	9 ± 4	410 ± 210	44 ± 27	1.8 ± 0.9	12.6 ± 2.2	Highest $PM_{2.5}$, CO and NO_X; lowest O_3
	Cold and windier	6.9 ± 4.0[A]	14 ± 5	320 ± 150	35 ± 22	2.1 ± 0.9	13.6 ± 3.0	High $PM_{2.5}$, higher CO & NO_X
	Warm and dry	7.2 ± 4.4	19 ± 5	250 ± 110	22 ± 13	2.3 ± 0.9	17.6 ± 3.5	Highest O_3, low CO
Entwisle	Sprinter	6.9 ± 3.9[B]	15 ± 5	300 ± 150	33 ± 21	2.1 ± 0.9	14.1 ± 3.2	Average concentrations of air pollutants
	Sprummer	7.2 ± 4.5	19 ± 5	250 ± 110	20 ± 12	2.3 ± 0.8	18.7 ± 3.7	Highest O_3; high $PM_{2.5}$; low NO_X and CO
	Summer	6.7 ± 3.1	15 ± 6	250 ± 100	18 ± 10	2.3 ± 0.7	21.9 ± 2.6	Lowest $PM_{2.5}$; low CO and NO_X; high O_3
	Autumn	7.4 ± 4.1	10 ± 4	360 ± 170	38 ± 24	1.9 ± 0.8	16.2 ± 2.6	Highest $PM_{2.5}$; high NO_X; low O_3
	Winter	7.1 ± 4.1	9 ± 5	410 ± 220	44 ± 27	1.9 ± 0.9	11.8 ± 2.0	Highest CO and NO_X; lowest O_3
Western	Spring	7.1 ± 4.2[C]	18 ± 5	260 ± 110	23 ± 14	2.2 ± 0.8	17.7 ± 3.8	Highest O_3, high $PM_{2.5}$, low NO_X and CO
	Summer	6.7 ± 3.0	16 ± 6	240 ± 100	15 ± 8.4	2.4 ± 0.7	22.2 ± 2.7	Lowest $PM_{2.5}$; lowest CO and NO_X; high O_3
	Autumn	7.2 ± 3.9	12 ± 5	330 ± 160	33 ± 22	1.9 ± 0.8	17.8 ± 3.3	High $PM_{2.5}$, CO and NO_X; low O_3
	Winter	7.0 ± 4.1	11 ± 5	380 ± 200	42 ± 26	2.0 ± 0.9	12.1 ± 2.3	Highest CO and NO_X; lowest O_3

The data during the September 2009 dust storm event have been removed.
[A]IKALC cold and windier season $PM_{2.5}$ mean and standard deviation is 7.2 ± 8.1 without the 2009 dust-storm event removed.
[B]Sprinter $PM_{2.5}$ mean and standard deviation is 7.2 ± 7.9 without the 2009 dust-storm event removed.
[C]Spring $PM_{2.5}$ mean and standard deviation is 7.2 ± 7.0 without the 2009 dust-storm event removed.

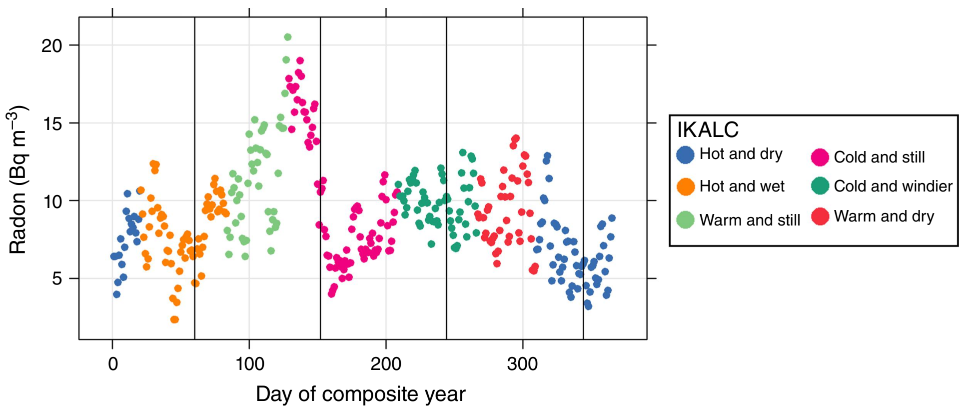

Fig. 8. Changing nocturnal radon concentrations across the year coloured by IKALC-seasons. For comparison Western seasons are indicated by the vertical lines. Each reported daily value represents the average of the nocturnal mean concentration of radon on that day of the year (over the 5 years from 2007 to 2011).

This usually happens under anti-cyclonic conditions, when the night sky is cloud free and geostrophic winds are light-to-calm. Low nocturnal radon concentrations are typically associated with near-neutral stability conditions. This can occur either under conditions of moderate to strong winds, or when cloud cover insulates the surface at night, reducing the near-surface temperature gradient.

Fig. 8 shows the changing nocturnal radon concentrations across the year during different IKALC-seasons. Although the start of the 'cold and still' season lines up quite well with the start of the high nocturnal radon concentrations *c*. DOY 125, the sudden drop back to lower values *c*. DOY 150 (associated with a typical increase in nocturnal mean wind speed at this time of the year) is still in the middle of the cold and still season. The data that we examined for air quality include daytime and night-time concentrations (unlike for radon, which are nocturnal data only), nevertheless the radon data suggest that the ability of the IKALC 'cold and still' season to capture the peak amounts of $PM_{2.5}$, CO and NO_X and the lowest O_3 is due to more than just changes in nocturnal atmospheric mixing. This indicates an additional pollution source during the IKALC 'cold and still' season, with domestic wood-heater emissions the likely source (Keywood *et al.* 2011; Desservettaz *et al.* 2019).

4.4. Social science achievements and limitations of this study

This study attempted to combine different worldviews of seasonality and weather, in order to gain an understanding of localised changes in air and therefore increases applicability and understanding of air quality at a local scale. We used Indigenous perspectives on 'seasons' as identified by the co-authors and combined these with statistical analysis of the local climatology, to come up with the IKALC-seasons. The IKALC-seasons were better at identifying the time of the year when the worst air quality occurred (in terms of $PM_{2.5}$, CO and NO_X pollution) than conventional Western seasons.

This research was not a complete account of local Indigenous Knowledge regarding seasons and weather patterns as could be achieved over a longer time commitment and widespread community engagement. Ideally this concept would be explored further to engage with the intricacies of Indigenous ecological knowledge. A more-complete study would require cross-cultural collaboration with a variety of knowledge holders representing each family or clan from the Indigenous community of Sydney in active focus groups (O'Connor and Prober 2010; Woodward 2010; Roös 2015). This would achieve correct and ethical documentation of the perspectives and knowledge within the Indigenous community. This could be achieved by building strong relationships with a foundation of mutual benefit within the Indigenous community, communication of goals of the project as well as intentions to protect and preserve Indigenous knowledge as per the AIATSIS ethical guidelines (Australian Institute of Aboriginal and Torres Strait Islander Studies 2012). This could be communicated by a printed information sheet (see Supplementary material), as well as ongoing communication throughout every stage of the project with those within the community who offer knowledge. The opportunity for these Indigenous Knowledge holders to provide feedback throughout the project is also crucial (Woodward 2010).

The local language and the seasonal indicators, both traditional and new since European colonisation, could be explored and interpreted into an accessible resource for academia and the Indigenous community. This would need to occur on terms that were agreed to by the Indigenous contributors to show respect for the people and their knowledge. This would occur 'on Country' and according to the customs of their people, with a flexible timeframe to accommodate the lives of the contributors (Muir *et al.* 2010; Woodward 2010). This resource could become a means for elders to pass on knowledge to future generations of the Indigenous community of Sydney (Green *et al.* 2010; Woodward 2010; Prober *et al.* 2011). Historically there has been little documentation because traditionally Indigenous knowledge has been passed on orally. Documentation of Indigenous knowledge and concepts for future generations is essential to avoid further loss of knowledge in future generations (Green *et al.* 2010; Nicholls *et al.* 2016).

In this study, large differences between the weather and separation of time of year between eastern and western Sydney were identified. Separate seasonal calendars for each location would be required to reflect this, including seasonal indicators and language describing each time of the year. There may be conflicting opinions on aspects of Indigenous knowledge within a community, such as language and translation, particularly spelling, as there was traditionally no written language in Indigenous culture (Walsh and Yallop 1993; Attenbrow 2003; Green *et al.* 2010). Ongoing communication with a wide range of community members could minimise the occurrence of these issues.

Owing to the complex history of Indigenous–non-Indigenous interactions in post-colonial Australia, there is tension, distrust, hurt and isolation within Indigenous communities, as well as in the wider community of Australia towards Indigenous peoples. This loss of connection with each other has further reinforced the loss of connection to knowledge. This difficult past has caused disconnection between Indigenous people and knowledge of the intricacies of the Indigenous climate framework.

Projects such as creating a calendar of annual weather cycles that is embedded with Indigenous knowledge, could aid in rebuilding social relationships, where knowledge can be brought together, and to rekindle ecological connection (Muir *et al.* 2010). Ongoing relationships and further collaboration with Indigenous communities can be mutually beneficial in helping increase scientific understanding as well as create accessible resources for the participating Indigenous community (Woodward and Marrfurra McTaggart 2016). This process can both recover previously known Indigenous Knowledge and create new knowledge of the current landscape. Input of time and communication can aid in re-learning knowledge for the post-colonial landscape by application of Indigenous concepts. Keeping Indigenous knowledge authentic is essential when applying Indigenous knowledge and concepts to scientific research to avoid commodifying and oversimplifying to agree with Western viewpoints (Haynes 2010).

4.5. Atmospheric science achievements and limitations of this study

Statistical analyses of meteorological data from western Sydney were combined with Indigenous Knowledge in order to create the IKALC-seasons for western Sydney. Exploration of the geographic scale of relevance for our IKALC-seasons led to an examination of shorter time-series of meteorological data and revealed evidence of a drying climate in the region through the 1990s and early 2000s as has been noted elsewhere (Timbal 2009; Bradstock *et al.* 2014). A lack of consistent long-term data records hindered a more-thorough analysis of the geographical extent to which the IKALC-seasons from Bankstown Airport are likely to be relevant. Nevertheless, these IKALC-seasons were shown to be more useful than the commonly used 'Western' seasons in identifying underlying reasons behind poor air quality in western Sydney in the coldest part of the year. In particular, the winter season starts too late to capture all of the coldest days of the year in Sydney and extends into a time of year when windy weather is common in the region. The separation into cold and still and cold and windy using the IKALC-season framework accurately determines the time of year where pollution levels of $PM_{2.5}$, CO and NO_X are highest.

The IKALC-seasons were not as clearly useful for analysing air quality events in the hotter part of the year. The highest O_3 concentrations span both the warm and dry and the hot and dry IKALC-seasons, and together these seasons capture the peak O_3 season a little better than the Western summer season; however, the separation of the hottest part of the year into hot and dry and hot and wet did not provide significant advantages in identifying times of year for poor air quality. The $PM_{2.5}$ is the main pollutant likely to be influenced by precipitation, by wet-deposition of aerosols during rainfall events reducing $PM_{2.5}$ concentrations. However, $PM_{2.5}$ concentrations are reasonably low in the hottest times of the year due to the warm temperatures inducing reasonably well-ventilated atmospheric conditions. In addition, the transient nature of precipitation events and very large year-to-year variability in rainfall in the region makes identifying statistically significant impacts difficult.

5. Conclusion

We set out to understand local Indigenous knowledge of seasons in the Sydney region. A conceptual Indigenous seasonal calendar was created. The IKALC-seasons created in this project were based on Indigenous perspectives of weather cycles combined with statistical analysis of climatological data. The approach taken within this project showed the strength of combining knowledges from different cultures, provided a rewarding experience for the researchers involved and is easily applicable to other parts of Australia and the world. However, the IKALC-seasons are missing factors of Indigenous knowledge that would be essential in creating a conclusive Indigenous seasonal calendar, such as biological seasonal indicators and local language.

In summary, we do not claim that this conceptual seasonal calendar for western Sydney is a better representation of Indigenous knowledge of weather patterns than others that exist, but simply that it is the best representation that we could make, based on contributions from individual Elders and knowledge holders who contributed to this paper. Even though we used a 49-year climatology in developing the IKALC-seasons, this may not fully represent the local climate as a whole over extended periods. Multi-annual climatological cycles such as El Niño–Southern Oscillation and the Indian Ocean Dipole have a larger influence on climate variability in Australia than in other parts of the world (Letnic *et al.* 2005; Zhou *et al.* 2009). This is a topic that requires further exploration as accounting for these cycles could improve seasonal definitions over long periods.

The IKALC-seasons showed some skill in providing an improved indication of annual changes in air quality with the IKALC 'cold and still' season aligning well with the times of peak CO, NO_X and $PM_{2.5}$ concentrations and lowest O_3 amounts. The approach of combining Indigenous knowledge with statistical techniques applied to relevant local meteorological data for the region proved to be a powerful technique for defining seasonal changes that affect air quality. Although the results for western Sydney are inherently local in nature, the methodology we present is applicable to many other parts of the world.

Supplementary material

Supplementary material is available online.

References

Attenbrow V (2003) 'Sydney's Aboriginal Past: Investigating the Archaeological and Historical Records.' (University of New South Wales Press)

Australian Institute for Aboriginal and Torres Strait Islander Research (2020) 'AIATSIS Code of Ethics for Aboriginal and Torres Strait Islander Research.' (AIATSIS: Canberra, ACT, Australia)

Australian Institute of Aboriginal and Torres Strait Islander Studies (2012) Guidelines for ethical research in Australian Indigenous Studies. (Australian Government: Canberra, ACT, Australia) Available at https://aiatsis.gov.au/sites/default/files/2020-09/gerais.pdf

Barnaba F, Putaud JP, Gruening C, dell'Acqua A, Dos Santos S (2010) Annual cycle in co-located *in situ*, total-column, and height-resolved aerosol observations in the Po Valley (Italy): implications for ground-level particulate matter mass concentration estimation from remote sensing. *Journal of Geophysical Research: Atmospheres* **115**, D19209. doi:10.1029/2009JD013002

Barnett AG, Fraser JF, Munck L (2012) The effects of the 2009 dust storm on emergency admissions to a hospital in Brisbane, Australia. *International Journal of Biometeorology* **56**, 719–726. doi:10.1007/s00484-011-0473-y

Beelen R, Raaschou-Nielsen O, Stafoggia M, Andersen ZJ, Weinmayr G, Hoffmann B, Wolf K, Samoli E, Fischer P, Nieuwenhuijsen M, Vineis P, Xun WW, Katsouyanni K, Dimakopoulou K, Oudin A, Forsberg B, Modig L, Havulinna AS, Lanki T, Turunen A, Oftedal B, Nystad W, Nafstad P, De Faire U, Pedersen NL, Östenson CG, Fratiglioni L, Penell J, Korek M, Pershagen G, Eriksen KT, Overvad K, Ellermann T, Eeftens M, Peeters PH, Meliefste K, Wang M, Bueno-De-Mesquita B, Sugiri D, Krämer U, Heinrich J, De Hoogh K, Key T, Peters A, Hampel R, Concin H, Nagel G, Ineichen A, Schaffner E, Probst-Hensch N, Künzli N, Schindler C, Schikowski T, Adam M, Phuleria H, Vilier A, Clavel-Chapelon F, Declercq C, Grioni S, Krogh V, Tsai MY, Ricceri F, Sacerdote C, Galassi C, Migliore E, Ranzi A, Cesaroni G, Badaloni C, Forastiere F, Tamayo I, Amiano P, Dorronsoro M, Katsoulis M, Trichopoulou A, Brunekreef B, Hoek G (2014) Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. *The Lancet* **383**, 785–795. doi:10.1016/S0140-6736(13)62158-3

Bodkin F (2006) 'D'harawal Seasons and Climatic Cycles.' (F. Bodkin & L. Robertson)

Bohensky EL, Butler JRA, Davies J (2013) Integrating Indigenous ecological knowledge and science in natural resource management: perspectives from Australia. *Ecology and Society* **18**, 20. doi:10.5751/ES-05846-180320

Bradstock R, Penman T, Boer M, Price O, Clarke H (2014) Divergent responses of fire to recent warming and drying across south-eastern Australia. *Global Change Biology* **20**, 1412–1428. doi:10.1111/gcb.12449

Broome RA, Fann N, Cristina TJN, Fulcher C, Duc H, Morgan GG (2015) The health benefits of reducing air pollution in Sydney, Australia. *Environmental Research* **143**, 19–25. doi:10.1016/j.envres.2015.09.007

Bursill L (1993) An examination of the paintings, engravings, drawings, & stencils (P.E.D.S) of Southern Sydney Aborigines. Masters thesis, University of Wollongong. Available at https://www.academia.edu/35908001/Les_Bursill_Thesis

Bursill L, Jacobs M, Corporation KA, Lennis D (2007) 'Dharawal: The Story of the Dharawal Speaking People of Southern Sydney: a Collaborative Work.' (Kurranulla Aboriginal Corporation)

Chambers SD, Williams AG, Crawford J, Griffiths AD (2015) On the use of radon for quantifying the effects of atmospheric stability on urban emissions. *Atmospheric Chemistry and Physics* **15**, 1175–1190. doi:10.5194/acp-15-1175-2015

Chambers SD, Podstawczyńska A, Pawlak W, Fortuniak K, Williams A, Griffiths A (2019*a*) Characterizing the state of the urban surface layer using radon-222. *Journal of Geophysical Research: Atmospheres* **124**, 770–788. doi:10.1029/2018JD029507

Chambers SD, Guérette E-A, Monk K, Griffiths AD, Zhang Y, Duc H, Cope M, Emmerson KM, Chang LT, Silver JD (2019*b*) Skill-testing chemical transport models across contrasting atmospheric mixing states using Radon-222. *Atmosphere* **10**, 25. doi:10.3390/atmos10010025

Clarkson C, Jacobs Z, Marwick B, Fullagar R, Wallis L, Smith M, Roberts RG, Hayes E, Lowe K, Carah X, Florin SA, McNeil J, Cox D, Arnold LJ, Hua Q, Huntley J, Brand HEA, Manne T, Fairbairn A, Shulmeister J, Lyle L, Salinas M, Page M, Connell K, Park G, Norman K, Murphy T, Pardoe C (2017) Human occupation of northern Australia by 65,000 years ago. *Nature* **547**, 306–310. doi:10.1038/nature22968

Cohen AJ, Anderson HR, Ostro B, Pandey KD, Krzyzanowski M, Künzli N, Gutschmidt K, Pope A, Romieu I, Samet JM, Smith K (2005) The global burden of disease due to outdoor air pollution. *Journal of Toxicology and Environmental Health, Part A* **68**, 1301–1307. doi:10.1080/15287390590936166

Desservettaz M, Phillips F, Naylor T, Price O, Samson S, Kirkwood J, Paton-Walsh C (2019) Air quality impacts of smoke from hazard reduction burns and domestic wood heating in Western Sydney. *Atmosphere* **10**, 557. doi:10.3390/atmos10090557

Dockery DW, Pope CA, Xu X, Spengler JD, Ware JH, Fay ME, Ferris BG, Speizer FE (1993) An association between air pollution and mortality in six US cities. *New England Journal of Medicine* **329**, 1753–1759. doi:10.1056/NEJM199312093292401

Emmerson KM, Galbally IE, Guenther AB, Paton-Walsh C, Guerette EA, Cope ME, Keywood MD, Lawson SJ, Molloy SB, Dunne E, Thatcher M, Karl T, Maleknia SD (2016) Current estimates of biogenic emissions from eucalypts uncertain for southeast Australia. *Atmospheric Chemistry and Physics* **16**, 6997–7011. doi:10.5194/acp-16-6997-2016

Entwisle TJ (2014) 'Sprinter and Sprummer: Australia's Changing Seasons.' (CSIRO Publishing)

Giblett R (2012) Rethinking the seasons: new approaches to nature. The seasons: homage to Henry David Thoreau. *Transformations* **21**, 1–13.

Goodall H (2008) Riding the tide: Indigenous knowledge, history and water in a changing Australia. *Environment and History* **14**, 355–384. doi:10.3197/096734008X333563

Green D, Billy J, Tapim A (2010) Indigenous Australians' knowledge of weather and climate. *Climatic Change* **100**, 337–354. doi:10.1007/s10584-010-9803-z

Guenther AB, Jiang X, Heald CL, Sakulyanontvittaya T, Duhl T, Emmons LK, Wang X (2012) The model of emissions of gases and aerosols from nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions. *Geoscientific Model Development* **5**, 1471–1492. doi:10.5194/gmd-5-1471-2012

Hanigan IC, Rolfe MI, Knibbs LD, Salimi F, Cowie CT, Heyworth J, Marks GB, Guo Y, Cope M, Bauman A, Jalaludin B, Morgan GG (2019) All-cause mortality and long-term exposure to low level air pollution in the '45 and up study' cohort, Sydney, Australia, 2006–2015. *Environment International* **126**, 762–770. doi:10.1016/j.envint.2019.02.044

Hartigan JA, Wong MA (1979) Algorithm AS 136: a *k*-means clustering algorithm. *Journal of the Royal Statistical Society – C. Applied Statistics* **28**, 100–108. doi:10.2307/2346830

Haynes C (2010) 10. Realities, simulacra and the appropriation of Aboriginality in Kakadu's tourism. In 'Indigenous Participation in

Australian Economies: Historical and anthropological perspectives.' pp. 165–185 ANU E Press) doi:10.22459/IPAE.12.2010.10

Hopkins LC, Holland GJ (1997) Australian heavy-rain days and associated east coast cyclones: 1958–92. *Journal of Climate* **10**, 621–635. doi:10.1175/1520-0442(1997)010<0621:AHRDAA>2.0.CO;2

Jaffe D, Tamura S, Harris J (2005) Seasonal cycle and composition of background fine particles along the west coast of the US. *Atmospheric Environment* **39**, 297–306. doi:10.1016/j.atmosenv.2004.09.016

Jain AK (2010) Data clustering: 50 years beyond K-means. *Pattern Recognition Letters* **31**, 651–666. doi:10.1016/j.patrec.2009.09.011

Jerrett M, Burnett RT, Arden Pope C III, Ito K, Thurston G, Krewski D, Shi Y, Calle E, Thun M (2009) Long-term ozone exposure and mortality. *New England Journal of Medicine* **360**, 1085–1095. doi:10.1056/NEJMoa0803894

Jiang N, Scorgie Y, Hart M, Riley ML, Crawford J, Beggs PJ, Edwards GC, Chang L, Salter D, Virgilio GD (2017) Visualising the relationships between synoptic circulation type and air quality in Sydney, a subtropical coastal-basin environment. *International Journal of Climatology* **37**, 1211–1228. doi:10.1002/joc.4770

Johnson JT, Howitt R, Cajete G, Berkes F, Louis RP, Kliskey A (2016) Weaving Indigenous and sustainability sciences to diversify our methods. *Sustainability Science* **11**, 1–11. doi:10.1007/s11625-015-0349-x

Kandlikar M (2007) Air pollution at a hotspot location in Delhi: detecting trends, seasonal cycles and oscillations. *Atmospheric Environment* **41**, 5934–5947. doi:10.1016/j.atmosenv.2007.03.044

Keywood M, Guyes H, Selleck P, Gillett R (2011) Quantification of secondary organic aerosol in an Australian urban location. *Environmental Chemistry* **8**, 115–126. doi:10.1071/EN10100

Law J (2012) The almanac projects: seasons experienced through the material world. *Transformations* **21**, 1–13.

Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A (2015) The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **525**, 367–371. doi:10.1038/nature15371

Leonard S, Parsons M, Olawsky K, Kofod F (2013) The role of culture and traditional knowledge in climate change adaptation: insights from East Kimberley, Australia. *Global Environmental Change* **23**, 623–632. doi:10.1016/j.gloenvcha.2013.02.012

Letnic M, Tamayo B, Dickman CR (2005) The responses of mammals to La Niña (El Niño–Southern Oscillation) – associated rainfall, predation, and wildfire in central Australia. *Journal of Mammalogy* **86**, 689–703. doi:10.1644/1545-1542(2005)086[0689:TROMTL]2.0.CO;2

Liedloff AC, Woodward EL, Harrington GA, Jackson S (2013) Integrating indigenous ecological and scientific hydro-geological knowledge using a Bayesian Network in the context of water resource development. *Journal of Hydrology* **499**, 177–187. doi:10.1016/j.jhydrol.2013.06.051

McCarthy MC, Hafner HR, Chinkin LR, Charrier JG (2007) Temporal variability of selected air toxics in the United States. *Atmospheric Environment* **41**, 7180–7194. doi:10.1016/j.atmosenv.2007.05.037

Milligan GW, Cooper MC (1988) A study of standardization of variables in cluster analysis. *Journal of Classification* **5**, 181–204. doi:10.1007/BF01897163

Mohamad IB, Usman D (2013) Standardization and its effects on *K*-means clustering algorithm. *Research Journal of Applied Sciences, Engineering and Technology* **6**, 3299–3303. doi:10.19026/rjaset.6.3638

Muir C, Rose D, Sullivan P (2010) From the other side of the knowledge frontier: Indigenous knowledge, socialecological relationships and new perspectives. *The Rangeland Journal* **32**, 259–265. doi:10.1071/RJ10014

Nicholls S, Booker L, Thorpe K, Jackson M, Girault C, Briggs R, Jones C (2016) From principle to practice: community consultation regarding access to Indigenous language material in archival records at the State Library of New South Wales. *Archives and Manuscripts* **44**, 110–123. doi:10.1080/01576895.2016.1239116

NSW Office of Environment and Heritage (2017) 'Towards Cleaner Air: NSW Air Quality Statement 2016.' (NSW Government: Sydney, NSW, Australia)

NSW Office of Environment and Heritage (2018) 'Clearing the Air: New South Wales Air Quality Statement 2017.' (NSW OEH: Sydney, NSW, Australia)

Nuggett J, Nuggett A, Bangu N, Woodward E (2011) Walmajarrijarti Wangki Martuwarra Kadaji – Walmajarri words from the river side, Fitzroy Valley, Western Australia. (CSIRO Land and Water) Available at https://publications.csiro.au/rpr/download?pid=legacy:381&dsid=DS1 [Verified 9 February 2023]

O'Connor MH, Prober SM (2010) A calendar of Ngadju seasonal knowledge. A report to Ngadju people (Edition 1.2). (CSIRO Sustainable Ecosystems: Perth, WA, Australia) Available at https://publications.csiro.au/rpr/download?pid=csiro:EP111874&dsid=DS15

Oltmans SJ, Levy H II (1992) Seasonal cycle of surface ozone over the western North Atlantic. *Nature* **358**, 392–394. doi:10.1038/358392a0

Paton-Walsh C, Guérette É-A, Emmerson K, Cope M, Kubistin D, Humphries R, Wilson S, Buchholz R, Jones NB, Griffith DWT, Dominick D, Galbally I, Keywood M, Lawson S, Harnwell J, Ward J, Griffiths A, Chambers S (2018) Urban air quality in a coastal city: Wollongong during the MUMBA campaign. *Atmosphere* **9**, 500. doi:10.3390/atmos9120500

Paton-Walsh C, Rayner P, Simmons J, Fiddes SL, Schofield R, Bridgman H, Beaupark S, Broome R, Chambers SD, Chang LT-C, Cope M, Cowie CT, Desservettaz M, Dominick D, Emmerson K, Forehead H, Galbally IE, Griffiths A, Guérette É-A, Haynes A, Heyworth J, Jalaludin B, Kan R, Keywood M, Monk K, Morgan GG, Nguyen Duc H, Phillips F, Popek R, Scorgie Y, Silver JD, Utembe S, Wadlow I, Wilson SR, Zhang Y (2019) A clean air plan for Sydney: an overview of the special issue on air quality in New South Wales. *Atmosphere* **10**, 774. doi:10.3390/atmos10120774

Prober SM, O'Connor MH, Walsh FJ (2011) Australian Aboriginal Peoples' seasonal knowledge: a potential basis for shared understanding in environmental management. *Ecology and Society* **16**, 12. doi:10.5751/ES-04023-160212

Rastogi N, Singh A, Sarin MM, Singh D (2016) Temporal variability of primary and secondary aerosols over northern India: impact of biomass burning emissions. *Atmospheric Environment* **125**, 396–403. doi:10.1016/j.atmosenv.2015.06.010

Rea G, Paton-Walsh C, Turquety S, Cope M, Griffith D (2016) Impact of the New South Wales fires during October 2013 on regional air quality in eastern Australia. *Atmospheric Environment* **131**, 150–163. doi:10.1016/j.atmosenv.2016.01.034

Robinson DL (2011) Australian wood heaters currently increase global warming and health costs. *Atmospheric Pollution Research* **2**, 267–274. doi:10.5094/APR.2011.033

Roös PB (2015) Indigenous knowledge and climate change: settlement patterns of the past to adaptation of the future. *The International Journal of Climate Change: Impacts and Responses* **7**, 13–31.

Rose DB (2000) 'Dingo makes us human: life and land in an Australian Aboriginal culture.' (CUP Archive)

Rose DB (1996) 'Nourishing terrains: Australian Aboriginal views of landscape and wilderness.' (Australian Heritage Commission: Canberra, ACT, Australia)

Simmons JB, Paton-Walsh C, Mouat AP, Kaiser J, Humphries RS, Keywood M, Griffith DW, Sutresna A, Naylor T, Ramirez-Gamboa J (2022) Bushfire smoke plume composition and toxicological assessment from the 2019–2020 Australian Black Summer. *Air Quality, Atmosphere & Health* **15**, 2067–2089. doi:10.1007/s11869-022-01237-5

Tengö M, Hill R, Malmer P, Raymond CM, Spierenburg M, Danielsen F, Elmqvist T, Folke C (2017) Weaving knowledge systems in IPBES, CBD and beyond—lessons learned for sustainability. *Current Opinion in Environmental Sustainability* **26–27**, 17–25. doi:10.1016/j.cosust.2016.12.005

Timbal B (2009) The continuing decline in south-east Australian rainfall – update to May 2009. *CAWCR Research Letters* **2**, 1–8.

Utembe SR, Rayner PJ, Silver JD, Guérette E-A, Fisher JA, Emmerson KM, Cope M, Paton-Walsh C, Griffiths AD, Duc H, Monk K, Scorgie Y (2018) Hot summers: effect of extreme temperatures on ozone in Sydney, Australia. *Atmosphere* **9**, 466. doi:10.3390/atmos9120466

Walsh M, Yallop C (1993) 'Language and Culture in Aboriginal Australia.' (Aboriginal Studies Press)

Wang F, Guo Z, Lin T, Rose NL (2016) Seasonal variation of carbonaceous pollutants in $PM_{2.5}$ at an urban 'supersite' in Shanghai, China. *Chemosphere* **146**, 238–244. doi:10.1016/j.chemosphere.2015.12.036

Williams AG, Chambers SD, Conen F, Reimann S, Hill M, Griffiths AD, Crawford J (2016) Radon as a tracer of atmospheric influences on traffic-related air pollution in a small inland city. *Tellus – B. Chemical and Physical Meteorology* **68**, 30967. doi:10.3402/tellusb.v68.30967

Woodward E (2010) Creating the Ngan'gi Seasons calendar: reflections on engaging Indigenous knowledge authorities in research. *Learning*

Communities: International Journal of Learning in Social Contexts Australia **2**, 125–137.

Woodward E, Marrfurra McTaggart P (2016) Transforming cross-cultural water research through trust, participation and place. *Geographical Research* **54**, 129–142. doi:10.1111/1745-5871.12136

Woodward E, Marrfurra McTaggart P, Yawulminy M, Ariuu C, Daning D, Kamarrama K, Ngulfundi B, Warrumburr M, Wawul M (2009) Ngan'gi seasons calendar. (CSIRO Land and Water) Available at https://www.csiro.au/en/research/indigenous-science/indigenous-knowledge/calendars/ngangi

Woodward E, Jackson S, Finn M, Marrfurra McTaggart P (2012) Utilising Indigenous seasonal knowledge to understand aquatic resource use and inform water resource management in northern Australia. *Ecological Management & Restoration* **13**, 58–64. doi:10.1111/j.1442-8903.2011.00622.x

Woodward E, Hill R, Harkness P, Archer R (2020) Our Knowledge Our Way in caring for Country: Indigenous-led approaches to strengthening and sharing our knowledge for land and sea management. Best Practice Guidelines from Australian Experiences. NAILSMA and CSIRO, Cairns, Qld, Australia.

Zhou T, Wu B, Wang B (2009) How well do atmospheric general circulation models capture the leading modes of the interannual variability of the Asian–Australian monsoon? *Journal of Climate* **22**, 1159–1173. doi:10.1175/2008JCLI2245.1

Data availability. The data that support this study will be shared upon reasonable request to one of the corresponding authors.

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