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$PM_{2.5}$ and aerosol black carbon in Suva, Fiji

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HIGHLIGHTS

- $PM_{2.5}$ in Suva Fiji are generally within WHO guidelines.
- BC in $PM_{2.5}$ are high compared to population size.
- Peak PM levels at night-time are a result of meteorological conditions.
- Back-trajectory analyses indicate low residence times of air parcels within Suva.

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ABSTRACT

Concentrations of particulate air pollution in Suva, Fiji, have been largely unknown and consequently, current strategies to reduce health risk from air pollution in Suva are not targeted effectively. This lack of air quality data is common across the Pacific Island Countries. A monitoring study, during 2014 and 2015, has characterised the fine particulate air quality in Suva, representing the most detailed study to date of fine aerosol air pollutants for the Pacific Islands; with sampling at City, Residential (Kinoya) and Background (Suva Point) sites. Meteorology for Suva, as it relates to pollutant dispersion for this period of time, has also been analysed. The study design enables the contribution of maritime air and the anthropogenic emissions to be carefully distinguished from each other and separately characterised. Back trajectory calculations show that a packet of air sampled at the Suva City site has typically travelled 724 km in the 24-h prior to sampling, mainly over open ocean waters; inferring that pollutants would also be rapidly transported away from Suva. For fine particulates, Suva City reported a mid-week $PM_{2.5}$ of 8.6 ± 0.4 μg/m^3, averaged over 13-months of gravimetric sampling. Continuous monitoring (Osiris laser photometer) suggests that some areas of Suva may experience levels exceeding the WHO $PM_{2.5}$ guideline of 10 μg/m^3, however, compared to other countries, Fiji's $PM_{2.5}$ is low. Peak aerosol particulate levels, at all sites, were experienced at night-time, when atmospheric conditions were least favourable to dispersion of air pollutants. Suva's average ambient concentrations of black carbon in $PM_{2.5}$, 2.2 ± 0.1 μg/m^3, are, however, similar to those measured in much larger cities. With any given parcel of air spending only seven minutes, on average, over the land area of Suva Peninsula, these black carbon concentrations are indicative that significant combustion emissions occur within Suva. Many other communities in the Pacific Islands, as well as in Africa, Asia and South America share similar climate and similar burning practices and as such are likely to experience similar aerosol black carbon loadings. These black carbon levels indicate the need for combustion emissions, particularly those from open burning and diesel usage, to be addressed in air policy.

1. Introduction

The public perception of the southern tropical Pacific Islands, including Fiji, is one of a clean environment. However, there is emerging evidence that substantial emissions from the combustion

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of fossil fuels, industrial and domestic waste burning are resulting in air quality that increases the risk of adverse consequences for human health. The evidentiary basis for ascribing source and atmospheric loadings of pollutants from these sources is, however, very limited for Suva, Fiji's capital city, as it is for all tropical South Pacific Island countries, which are under-represented in scientific literature. The Pacific Island Countries are '*increasingly dependent on fossil fuels*' (Mishra et al., 2009), particularly diesel (Pacific Energy Summit, 2013) and, as such, are suffering greater air pollution from fossil fuel use (Mishra et al., 2009). For Fiji, diesel imports in 2010 were equivalent to 9% of the GDP (Fiji Bureau of Statistics, 2014). In many parts of the developing world, large contributions to air pollution arise from burning of wastes, including wastes associated with agriculture. In Fiji's urban areas, that have waste collection services, approximately 21% of all household waste and green waste is still burned by households (Isley et al., 2016). The same is true for Malaysia (Periathamby et al., 2009). Areas without waste collection burn a much higher proportion of their wastes (McDowall, 2005). Wiedinmyer et al. (2014) conclude, from global emissions modelling, that '*emissions of many air pollutants are significantly underestimated in current inventories because open waste burning is not included*'; and that these emissions from waste burning are particularly significant in developing countries in Asia, Africa and South America. Similarly, Yevich and Logan (2003) estimate that in the world's humid tropical regions, 50% of agricultural residues are burned and that these agricultural wastes form a large proportion of biofuel combustion in Asia, Africa and Southern America which is often not counted in fuelwood usage calculations.

The need for fine particle air quality studies was highlighted at the Global Environment Facility Pacific Alliance for Sustainability Pacific Project inception meeting (Ralgaivau, 2013); involving 14 Pacific Island Countries. Whilst this meeting was intended to address persistent organic pollutants from the burning of wastes, it was recognised at this meeting that fine aerosol particles from combustion also present a significant health risk. This meeting was used to refine the proposal for Suva, through consultation with Pacific Island Country representatives, in order to maximise the benefit of the study to the wider Pacific Island Community. This article presents the findings of the fine particle aerosol characterisation study for Suva.[1]

Emissions from vehicles, burning of wastes and industrial sources are considered to be major contributors to air pollutant emissions in Suva; however, there is no evidence-based data delineating their relative contribution. General public complaints data indicate that air pollution is a significant community concern for Fijians (Government of Fiji, 2007). Using an analysis of complaint volumes along with visual inspections of air quality, the Department of Environment (Government of Fiji, 2007) ranked air pollution sources in order of concern: vehicle emissions, open burning of wastes at dumpsites and backyard burning of household waste, industrial emissions, agricultural burning, incinerators, cooking with open stoves, emissions from shipping vessels and dust from gravel roads. A survey investigating perceptions of air quality in Suva was carried out in 2013 (Isley, 2013), which produced a similar list of pollution sources of concern. This survey reveals that when Suva residents were asked what causes air pollution, 99% of respondents listed vehicle exhaust; 57% listed industrial emissions, 53% open burning by households and 42% incinerators (Isley, 2013). The majority of respondents described the air pollution in Suva as being 'smoke', 'dust' or 'irritates eyes, nose or throat' (Isley, 2013). Combustion-type emissions feature heavily in these public complaints. Fine particles, namely $PM_{2.5}$ (particles with aerodynamic diameter 2.5 μm or less), are commonly associated with emissions from combustion or secondarily formed aerosol particles, as opposed to coarse particles (aerodynamic diameter larger than 2.5 μm), commonly associated with wind-blown dust, crushing and grinding actions or resuspension by vehicle movement (World Health Organisation, 2009). Characterisation of Suva's $PM_{2.5}$ will provide further information about the contributions from combustion emissions.

There has been growing research interest in fine particle air pollution over recent years because of the well-established adverse human health effects from exposures, even at low concentration levels. Lelieveld et al. (2015) report that 3.3 (1.61–4.81) million premature deaths occur annually due to outdoor air pollution, mainly by $PM_{2.5}$. This is in accord with estimates by the World Health Organisation (2014), which also attributed around 7 million deaths in 2012 to the combination of indoor and ambient air pollution. Lim et al. (2012) ranks ambient (outdoor) $PM_{2.5}$ air pollution as ninth on the global leading risk factors for death in 2010. Fine PM is associated with a broad spectrum of acute and chronic illness, such as lung cancer cardiopulmonary disease (World Health Organisation, 2009) and asthma (Kim, 2004). Improving air quality, in particular, reductions in $PM_{2.5}$ concentrations, have been associated with reduced mortality risk (Laden et al., 2006; Pope et al., 2009). Considering this health-based evidence, $PM_{2.5}$ has been selected as the main pollutant of interest in the investigation of Suva's air quality.

Black carbon (BC) aerosol particles are emitted from a range of combustion activities, with diesel engines contributing significantly to total BC emissions (McDonald et al., 2015). BC particles are very small, typically around 50 nm in diameter (Wang et al., 2015). Increased BC exposure has been associated with increased airway inflammation in adult subjects with asthma (Jansen et al., 2005) and an increased BC exposure of 1 $\mu g/m^3$ relates to greater adverse health impacts than from the same increase in $PM_{2.5}$ or PM_{10} (Janssen et al., 2011). Similarly, in a study of six cities in the United States of America, Laden et al. (2000) found that combustion particles in $PM_{2.5}$ from vehicles were associated with increased mortality, whereas fine particulates derived from crustal sources were not associated with increased risk. Straif et al. (2013) classified diesel engine exhaust as carcinogenic to humans, based on an association of diesel exhaust exposure with an increased risk for lung cancer. For this reason, this study also includes measurement of BC in PM.

The association of asthma and respiratory symptom occurrence in Fiji with ambient air quality is yet to be investigated. Flynn (1994b) reported current wheezing rates in Fijian children to be 21% in 1990 for children aged nine to ten years old, living in Suva. In a systematic review of worldwide variations of the prevalence of wheezing symptoms in children, Patel et al. (2008) consider the Fijian wheezing rate to be '*very high*' by worldwide standards. In a ranking of the prevalence of current asthma symptoms in childhood by country (Masoli et al., 2004), Fiji was ranked 16th most prevalent out of 84 countries. Asthma has been linked to air pollution, including fine aerosol PM (Kim, 2004). Use of kerosene and solid fuels for cooking contribute to indoor aerosols (Flynn, 1994a); did not find any association between cooking fuel used and respiratory symptoms or asthma diagnosis in Suva and Nausori of Fiji. Relationship between ambient air quality and Fijian asthma rates has not been studied and further investigation is required to delineate any connections between asthma/respiratory symptoms

[1] Abbreviations used in article: ANSTO, Australian Nuclear Science and Technology Organisation; ASP, Aerosol sampling program cyclone $PM_{2.5}$ gravimetric sampler; HYSPLIT, Hybrid single particle Lagrangian integrated *trajectory* model; LIPM, Laser Integrated plate method; TAPM, Commonwealth Scientific and Industrial Research Organisation air pollution model.

and air quality in Suva.

Suva, the capital city of Fiji, is located on the south-western coast of Viti Levu, the largest of the Fijian islands, as shown on Fig. 1. Prevailing winds are from the east-southeast. The terrain of the area surrounding Suva, shown in Fig. 1, rises steeply to the northwest and the west, whereas the land to the northeast is relatively flat. Along the coast to the west of Suva there are small towns, however the steep terrain inland from the coast is generally forested. The built-up-area of the city extends to the northeast for a distance of approximately 15 km. The area beyond this is a mixture of residential and agricultural landuse. Further to the east are smaller townships and villages surrounded by forested area.

If the Suva city area alone is considered, the population was 85,691 people in the most recent census (Fiji Bureau of Statistics, 2007). The adjacent metropolitan area is considered by many as part of Suva; this includes the separate local government areas of Lami (20,529), Nasinu (84,446) and Nausori (47,604), as shown on Fig. 1. The total population of the larger area was 241,270 in 2007, representing 29 per cent of the national population (Fiji Bureau of Statistics, 2007). In 2004, United Nations Habitat estimated the informal urban settlement population in Suva (squatter areas commonly referred to as 'settlements') to be 82,000 (UN Habitat 2004).

Fiji experiences a tropical marine climate with only slight seasonal variation in temperature. A summary of Suva's meteorology, from Fiji Bureau of Meteorology (2015) and Australian Government (2016b) is given in Table 1. Suva receives, on average, 2705 mm of rainfall per year, over 254 rain days. In terms of historical average (2000–2012), March is the wettest month, with 330 mm over 21 rain days, July is the driest month, with 124 mm over 19 rain days. March is also the warmest month with average maximum temperature of 31 °C and average minimum temperature of 24 °C. July is the coolest month with average maximum and minimum temperatures of 26 °C and 20 °C respectively. The annual average maximum and minimum temperatures for Suva are 28 °C and 22 °C respectively.

2. Method

In order to assess air quality within the city of Suva, Fiji, aerosol concentrations of $PM_{2.5}$ were measured at three locations within the city; Suva city centre, Kinoya, and at Suva Point (Fig. 1). The period of air quality monitoring in Suva commenced 15th October 2014 and concluded 23rd October 2015. The City site, located at approximately 18 m height and 20 m elevation, on top of a four level building on the west coast of the Suva peninsula, provides information on the exposures of people as they travel and work in the city. The Suva bus terminal, city markets, an industrial area and shipping port activities all lie within 1 km of this City site. Suva Point is located on the east of the peninsula, on the University of the South Pacific lower campus, 4 km east-southeast of the City site and is mainly characterised by winds from the ocean; hence providing data for a site less affected by emissions from the Suva city area. Kinoya is a more densely populated inland residential area, 6 km northeast from the city centre, and 1.5 km northwest of two diesel-fuelled power plants. Kinoya displays less windy conditions than the other sites, impeding the dispersal of air pollutants.

Due to the proximity of the port, bus terminal and industry, $PM_{2.5}$ levels at the City site would show some influence from localised activities. Any given location in a busy city is likely to have localised influences, however this site was selected for three main reasons. Firstly, meteorological data, collected and quality-controlled by the Australian Bureau of Meteorology (Australian Government, 2016b); is obtained from instruments affixed to the same tower (on the same building) as the air samplers for this study. Secondly, the location of this building on the western side of the city area of Suva means that air pollutant emissions from activities in the city area were likely to be detected. Thirdly, as pollutant concentration from vehicle emissions decreases with height above street level (Wang et al., 2008), the location of the sampler on top of a building (18 m height) allows some dispersion of traffic exhaust before air reaches the sampler, hence a more representative urban concentration may be determined.

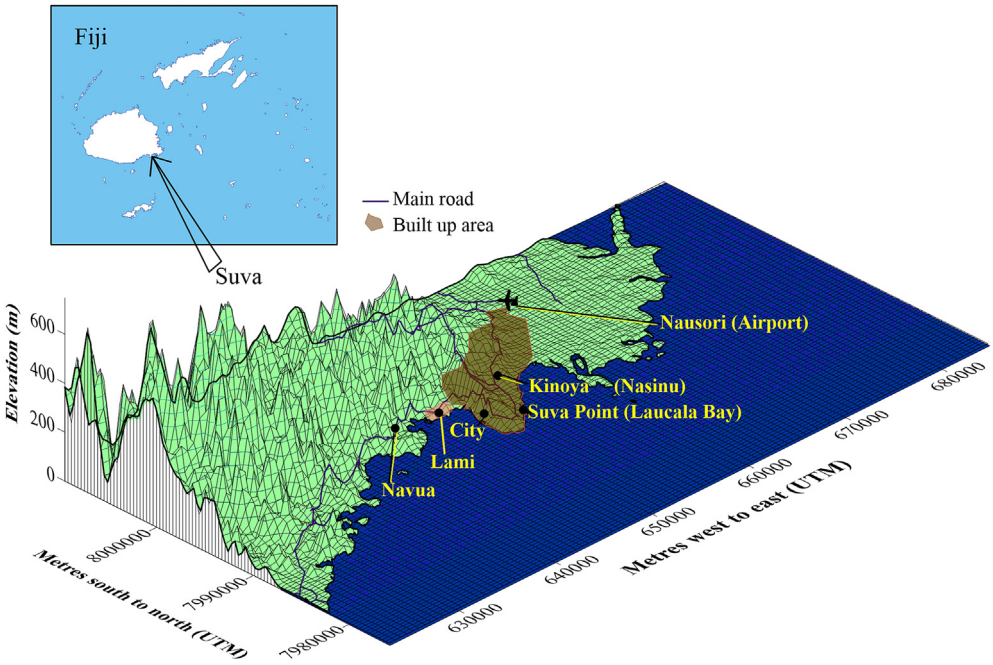

Fig. 1. Location and terrain height: Suva is located on Viti Levu, the largest of the Fijian islands, Steep terrain to the northwest and west is generally forested; land to the northeast is relatively flat and along the coast west of Suva are small towns. The built-up-area of Suva extends northeast for 15 km. Exaggerated vertical scale, elevation data source: Jarvis et al. (2016).

Table 1
Monthly air quality and meteorological summary for Suva. Fine particle air quality data ($PM_{2.5}$) were collected at Suva City in 2014 and 2015. Historical averages for Laucala Bay use data from *2000 to 2012*. Rainfall and humidity data are from Fiji Bureau of Meteorology (2015). Temperature data are for Suva City, from Australian Bureau of Meteorology (Australian Government, 2016b).

	2014			2015										Avg
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	
Monthly ASP air quality measurements (μg/m^3)														
$PM_{2.5}$ Suva City	6.8 ± 0.5	6.5 ± 0.8	7.8 ± 0.6	7.6 ± 1.0	5.6 ± 0.6	5.8 ± 0.7	8.0 ± 0.6	7.2 ± 1.3	7.6 ± 2.0	6.9 ± 0.7	6.8 ± 1.2	8.4 ± 1.0	17.1 ± 2.5	7.4 ± 0.3
BC Suva City	1.8 ± 0.2	1.4 ± 0.2	2.3 ± 0.3	2.3 ± 0.3	2.2 ± 0.3	2.2 ± 0.3	3.2 ± 0.3	2.0 ± 0.4	2.1 ± 0.8	1.8 ± 0.2	1.6 ± 0.9	2.4 ± 0.4	4.9 ± 0.6	2.2 ± 0.1
Monthly rainfall (mm)														
Laucala Bay	218.5	59.5	579.7	292.1	273.1	188.8	85.9	126.2	55.5	48.4	132.5	127.9	98.3	175.9
Nausori Airport	225.9	97.4	735.6	312.5	311.4	172.7	152.2	150.6	75.8	69.8	138.3	170.8	122.9	201.4
Historical average	*205.6*	*219.0*	*269.4*	*314.8*	*247.6*	*329.7*	*296.2*	*219.5*	*156.3*	*124.1*	*138.4*	*184.3*	*205.6*	*225.0*
Number of rain days per month														
Laucala Bay	19	23	21	21	23	17	23	22	19	14	22	17	15	20
Historical average	*21*	*21*	*24*	*24*	*21*	*23*	*23*	*21*	*20*	*19*	*19*	*18*	*21*	*21*
Monthly average temperature (°C)														
Suva City	24.9	26.0	26.5	27.4	28.3	28.2	26.8	25.1	24.1	23.5	23.0	23.6	24.9	25.6
Historical maximum	*27*	*29*	*30*	*30*	*31*	*31*	*29*	*28*	*27*	*26*	*26*	*27*	*27*	*28*
Historical minimum	*21*	*22*	*23*	*23*	*23*	*24*	*23*	*21*	*21*	*20*	*20*	*20*	*21*	*21*
Monthly average relative humidity (%)														
Laucala Bay	79	77	79	78	78	78	76	79	83	80	78	83	73	78
Nausori Airport	81	77	79	82	82	80	77	81	83	83	80	85	73	80

One Australian Nuclear Science and Technology Organisation (ANSTO) Aerosol Sampling Program (ASP) $PM_{2.5}$ low volume cyclone sampler provides the basis for gravimetric analysis to determine $PM_{2.5}$ concentrations at the City site. The ASP $PM_{2.5}$ sampler used in this study was built by ANSTO according to the US EPA IMPROVE (Interagency Monitoring of Protected Visual Environments) system used across North America in their National Parks air monitoring program (Malm et al., 1994; Cohen, 1996; Cohen et al., 1996). Data obtained using IMPROVE samplers at three sites were found to be not significantly different to paired collocated data from US EPA Federal Reference Method samplers (Pitchford et al., 1997). Additionally, Keywood (1999) determined that the ASP $PM_{2.5}$ inlet was within the performance requirements of US and Australian reference standards. $PM_{2.5}$ data collected using ASP samplers have been widely used in recent studies (Cohen et al., 2012, 2014; Hallal et al., 2013; Hibberd et al., 2013); with each of these studies using identical laboratory techniques (performed at the same laboratory) for gravimetric analyses and determination of black carbon to the current study. Two Australian field studies, where $PM_{2.5}$ from a total of six sites were sampled for 12 months each, show good correlation between Beta Attenuation Monitors (BAMs) and the ASP (Hibberd et al., 2013, 2016). A sample was collected, on a Teflon filter, each Wednesday and Sunday, for 24-h, from midnight to midnight, with a flowrate of 22 L/min. More frequent samples were collected, for approximately five weeks, during three intensive campaigns. One field blank for the ASP $PM_{2.5}$ sampler was collected for every ten exposed samples. The mass of $PM_{2.5}$ on the sample filters was determined gravimetrically. The filters were weighed before and after the sampling period to determine the particulate mass collected and then divided by the total volume of air that passed through the filter, to obtain the $PM_{2.5}$ concentration. Weighing was performed under controlled temperature (22 ± 2 °C) and relative humidity conditions (50± 10%). Using Rasmussen et al. (2010), this variation in laboratory humidity may potentially contribute an error of up to ± 0.094 μg/m^3 $PM_{2.5}$ concentration, based on average sample mass (239 μg) and volume (31.7 m^3). Other studies (Koistinen et al., 1999; Buonanno et al., 2014) show humidity variation in this range to have negligible effects on the mass of PM collected on Teflon filters. Calibration and quality control reports for this microbalance laboratory (Cohen, 1996), report an accuracy of ±3 μg over a 12 month period; equivalent in this study to an error of ±0.096 μg/m^3 $PM_{2.5}$ concentration.

Black carbon (BC) was determined, on ASP filters, using the Laser Integrated Plate Method (LIPM). Light from a HeNe laser (wavelength 633 nm) is diffused and collimated to give a uniform beam across the Teflon filter. The transmitted signal intensity is measured using a photodiode detector on each filter before and after exposure. The BC concentration is estimated from these two transmission measurements assuming a mass absorption coefficient value of 7 m^2/g for carbon particles, using the method of Taha et al. (2007). This method provided a non-destructive estimation of BC, leaving the filters available for further chemical analyses. There is no generally accepted standard method for BC or EC and Janssen et al. (2012) discuss some of the difficulties with BC measurement using optical methods such as LIPM. Variability in chemical composition of aerosol at different locations and even for the same location may affect optical measurement of BC. LIPM uses a mass absorption efficiency (ε) to calculate BC concentration, however ε depends on particle size distribution and chemical composition and hence may vary over time even for the same site. In response to studies showing the high variability of ε for LIPM and in order to provide an improved BC calculation, calibration for the LIPM method at ANSTO was performed (Taha et al., 2007), based on experimental measurements using both test carbon and ambient aerosol samples. Reflectometer measurements with test carbon (acetylene and candle carbon) supported a mass absorption efficiency of $\varepsilon = 7$; as did refractive index and density calculated from the measured elemental composition of the test carbon samples, a method similar to that used to calibrate Athelometers (Taha et al., 2007). This mass absorption efficiency value was also supported by analysis of eight years of ANSTO aerosol LIPM BC data (650 samples) from an Australian site, using experimentally determined chemical composition data for black carbon (Taha et al., 2007). Comparison to EC determined by the IMPROVE-A thermal optical method for four Australian sites (Hibberd et al., 2016), over 12 months, showed generally good agreement between the two methods, using $\varepsilon = 7$ m^2/g, however the slope of EC v BC (Hibberd et al. (2016) Figs. 1, 3, 4) did not pass through zero; indicating some interference from other light absorbing particles. Comparison to EC

measured by thermal desorption at two Australian sites (Hibberd et al., 2013), for 12 months, showed a good relationship (EC/BC close to 1.0) for the first seven months, however for the final five months, EC/BC > 1, attributed to carbonate interference with EC results.

Three Osiris (Turnkey Instruments Ltd.) samplers were placed in Suva; at the City, Kinoya and Suva Point. The Osiris sampler utilises the principle of low angle forward scattering of light to determine particle concentration. The Osiris samplers recorded 10-min average concentrations of total suspended particulate (TSP), particulates with equivalent aerodynamic diameter 10 μm or less (PM_{10}), $PM_{2.5}$ and PM_1. Heated inlets were used to precondition the particle sample and account for moisture derived artefacts. The Osiris samplers use a Teflon filter, identical to that used in the ASP, with a flow rate of 0.6 L/min. These filters were weighed on a monthly basis, as per ASP filters, and these measurements were used to calibrate the continuous measurement of TSP over the 12-month sampling period. Ratio of gravimetric filter mass to mass recorded by the Osiris varied from month to month by approximately 6%. For this reason, Osiris data were considered to be approximate, however, these data are very useful for examining variation of $PM_{2.5}$ across a typical day or week. The Osiris units at the City and Kinoya sites experienced periods of data loss due to equipment malfunction, meaning that comprehensive annual averages are not available for these sites. Available data do however indicate the differences between concentrations at each of the sampling sites. Data available are shown in Table 2.

Low-volume samplers, (SKC personal sampling pumps), with flow-rate calibrated to 3 L/min, were used to collect 27 TSP samples on quartz filters, in October 2014 and April 2015, which were also analysed gravimetrically.

A compilation of meteorological data available for Suva have been included in this study. Osiris samplers at Kinoya and Suva Point were fitted with a hemispherical cup anemometer and wind vane (Davis Instruments), to record wind speed and direction. The Australian Bureau of Meteorology (Australian Government, 2016b) monitors air temperature, wind speed and wind direction at the Suva City air sampling site, available as hourly averaged data. Fiji Bureau of Meteorology (2015), records relative humidity and rainfall on a daily basis at Laucala Bay about 1 km from the Suva Point site and Nausori airport, 10 km northeast from the Kinoya site (Fig. 1). The Commonwealth Scientific and Industrial Research Organisation (Hurley, 2008) Air Pollution Model, (TAPM) was also used to simulate meteorology at the Suva Point and Kinoya sites, useful particularly due to the periods of missing data from the Kinoya on-site instruments. Wind direction data for the Suva Point site were also incomplete and TAPM data have been used to supplement these. In order to refine the TAPM simulations, wind speed and direction data from the Suva City site were input to the model. The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al., 2015) has been used to calculate, backwards in time, the path of air parcels arriving in Suva during the sampling period. Back trajectory calculations were carried out, at 3-hourly intervals, for the entire period of air quality monitoring; tracing the path of air parcels for a 24-h period prior to arrival at the Suva City site.

3. Results

ASP samples collected at the City site indicate ambient weekday $PM_{2.5}$ concentrations of 8.6 ± 0.4 μg/m^3 (Table 2). Weekend concentrations were lower at 6.0 ± 0.3 μg/m^3. Black carbon accounts for approximately 30.3± 1.0% of $PM_{2.5}$ in samples from Suva City and shows the same weekday and weekend pattern as $PM_{2.5}$; with weekday and weekend BC concentrations of 2.6 ± 0.2 μg/m^3 and 1.8 ± 0.1 μg/m^3 respectively. For Osiris results, Suva Point demonstrates lower $PM_{2.5}$ than other sites, with levels 2.6 and 3.1 times lower those measured at the City and Kinoya, respectively. Diurnal profiles of $PM_{2.5}$ concentration (Fig. 2) show that aerosol levels are highest overnight, between 18:00 and 05:00, with lowest levels occurring between 11:00 and 14:00. Fig. 3 shows the weekly profile for mean hourly concentration at each site, demonstrating that a similar diurnal pattern is repeated each day. The Kinoya site shows the greatest variation between morning and evening $PM_{2.5}$

Table 2
Summary results from all monitoring sites. Comparison of all data available for the period; $PM_{2.5}$ measured at Suva City by ASP cyclone at 22 L/min; PM fractions (TSP, PM_{10}, $P_{2.5}$ and PM_1) for Suva City, Kinoya (residential) and Suva Point (background); TSP by low volume samplers at or near Suva City, Kinoya and Suva Point and TSP from previous studies are shown here for comparison.

Sampler	Fraction	Date	Sample type	City	Kinoya	Suva Point
				PM concentration in μg/m^3		
ASP	$PM_{2.5}$	13 months Oct 2014–Oct 2015	Gravimetric 24 h n = 112	Weekday 8.6 ± 0.4 Weekend 6.0 ± 0.3	–	–
	BC in $PM_{2.5}$		LIPM on $PM_{2.5}$ sample n = 112	Weekday 2.6 ± 0.15 Weekend 1.7 ± 0.12	–	–
Low-volume sampler	TSP	Oct-14	Gravimetric quartz filter	32.9 ± 4 n = 4	27.3 ± 4 n = 2	22.2 ± 10 n = 3
		Apr-15	3–14 days	33.9 ± 4 n = 4	44.7 ± 2 n = 4	26.8 ± 3 n = 10
Previous studies nearby	TSP	2000–2003 (Garimella and Deo, 2007)	Gravimetric HVAS 7 days	41 ± 4, n = 9 Dec 2000 Suva market, 0.2 km distance	49 ± 11, n = 4 Jul/Aug 2003 Centrepoint, 1 km distance	25 ± 3, n = 15 Jul–Nov 2003 USP campus, 1 km distance
OSIRIS	TSP	*City:* 7 months	Laser photometer	28.4 ± 0.2	44.2 ± 0.4	9.1 ± 0.1
	PM_{10}	Oct 2014–Jan 2015	10 min average	15.2 ± 0.1	21.7 ± 0.3	4.8 ± 0.04
	$PM_{2.5}$	Apr 2015–May 2015		9.7 ± 0.1	11.8 ± 0.1	3.8 ± 0.02
	PM_1	Oct 2015		3.0 ± 0.02	3.6 ± 0.04	1.3 ± 0.01
		Kinoya: 5 months		% contribution to total particulate measured at site		
	$TSP–PM_{10}$	Oct 2014–Nov 2014		*46.6 ± 0.7*	*50.9 ± 0.9*	*47.2 ± 0.9*
	$PM_{10}–PM_{2.5}$	Apr 2015–June 2015		*19.1 ± 0.7*	*22.3 ± 1.3*	*11.0 ± 0.9*
		Suva Point: 13 months				
	$PM_{2.5}–PM_1$	Oct 2014–Oct 2015		*23.8 ± 0.6*	*18.7 ± 0.7*	*27.7 ± 0.6*
	PM_1			*10.4 ± 0.6*	*8.1 ± 1.2*	*14.1 ± 0.6*

Values in italics show the percentage contribution of particulate fraction to total particulate mass for each sampling site.

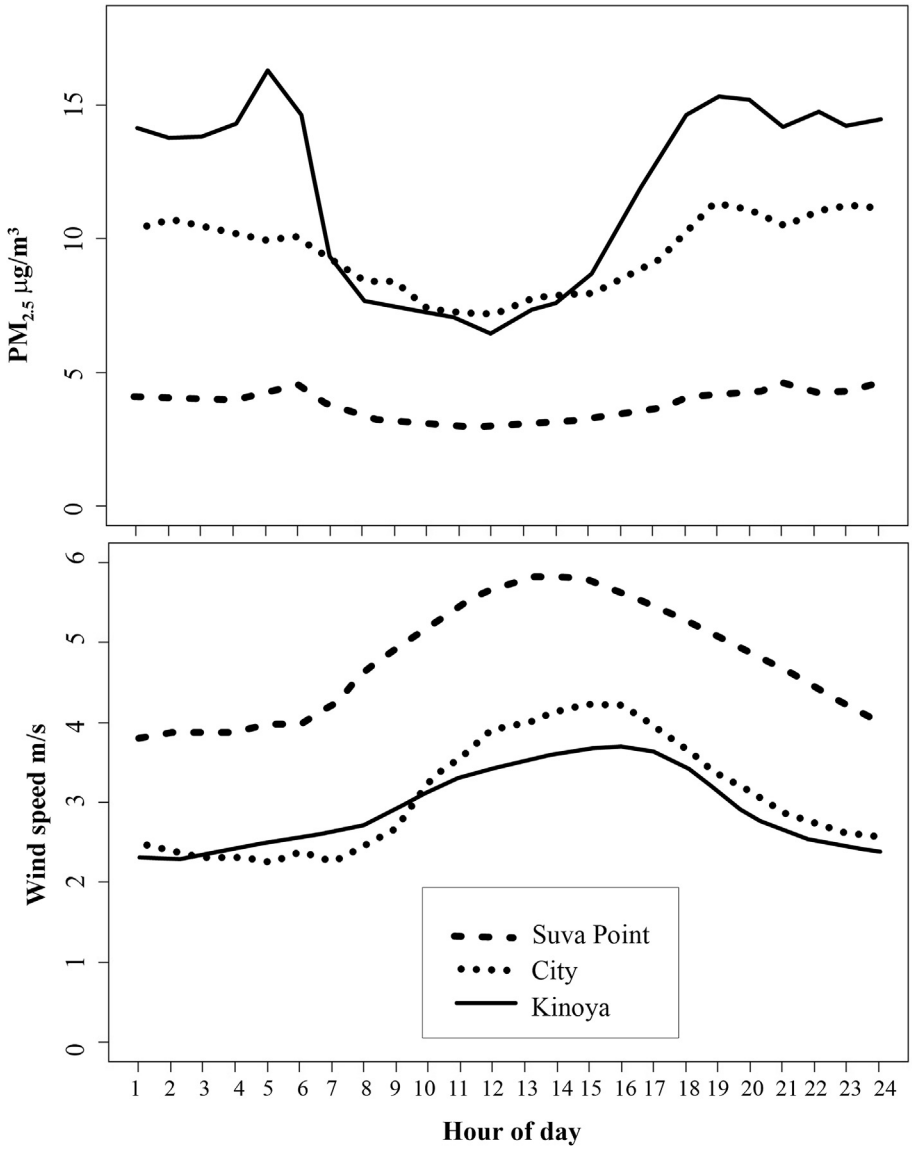

Fig. 2. $PM_{2.5}$ and wind speed by hour of the day in Suva. Peak aerosol levels occur overnight at all sites: Suva City, Kinoya (residential) and Suva Point (background). Conversely, wind speeds are highest during the day.

concentrations. Peak $PM_{2.5}$ concentrations (24.2 µg/m^3) occur at 03:00 on Monday mornings at Kinoya. The highest median concentrations occur at Kinoya on Wednesday evening (23.1 µg/m^3 at 21:00).

The size distribution of particulate matter recorded at each of the sampling sites is shown in Table 2. Kinoya, with TSP measured at 44 ± 0.4 µg/m^3, recorded the highest concentrations in each PM size category. On a percentage basis, across all sites, PM was measured to be comprised of 8%–14% PM_1, 19%–28% PM_1 to $PM_{2.5}$, 11%–22% $PM_{2.5}$ to PM_{10} and 47%–51% PM_{10} to TSP. Of the three sites, Kinoya PM contained the greatest proportion of coarse matter (larger than $PM_{2.5}$). Quartz filter samples (Table 2) reported TSP concentrations of 25.7 ± 5 µg/m^3 for Suva Point; 24 µg/m^3 (October 2014) and 48 µg/m^3 (April 2015) at Kinoya and 33.4 ± 4 µg/m^3 Suva City.

Table 1 shows monthly results for $PM_{2.5}$ measured by ASP at Suva city, alongside monthly data for rainfall, humidity and temperature, including historical data where available. Highest monthly average $PM_{2.5}$ was recorded in October 2015 (12.9 ± 4 µg/m^3) and lowest monthly average $PM_{2.5}$ was recorded in February 2015 (5.6 ± 1 µg/m^3). For BC in $PM_{2.5}$, the highest monthly average was also recorded in October 2015 (4.9 ± 1 µg/m^3) and lowest monthly average BC was recorded in November 2014 (1.4 ± 0.8 µg/m^3). Total rainfall for Suva during the monitoring period was 2201 mm measured at Laucala Bay and 2668 mm measured at Nausori Airport, with average daily rainfall of 6 mm and 7 mm respectively.

Winds recorded by the Australian Bureau of Meteorology (Australian Government, 2016b) at Suva City during the air quality monitoring period were predominantly from the southeast (Fig. 4). Historically, winds at the Suva City site are, likewise, mainly from the southeast, however, the historical data (Fig. 4) shows a greater influence from winds in the northeastern quadrant than was observed during the monitoring period. TAPM simulated data are shown for Kinoya and Suva Point. Southeasterly winds prevailed at all three sites. On an hourly basis, for the Suva City site, highest wind speeds occurred during the day time, from 10:00 to 17:00. Winds during this period are mainly from the southeast, averaging

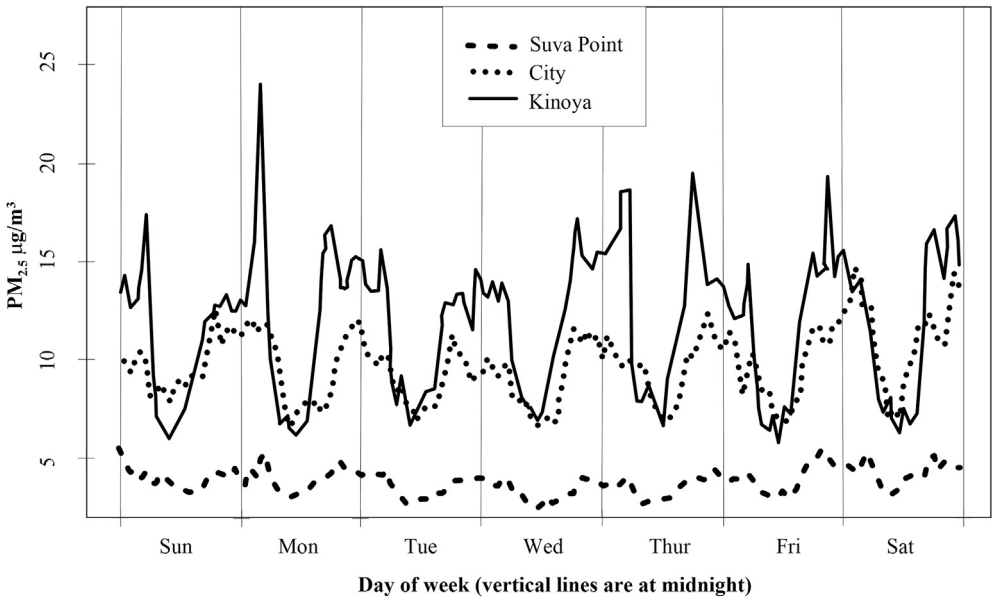

Fig. 3. Mean $PM_{2.5}$ by hour and day of the week for Suva City, Kinoya (residential) and Suva Point (background). Weekly profiles for mean hourly concentration at each site, with vertical grid-lines representing midnight; demonstrate a similar diurnal pattern being repeated each day. Greatest daily variation occurs at Kinoya, with peak $PM_{2.5}$ on Monday mornings.

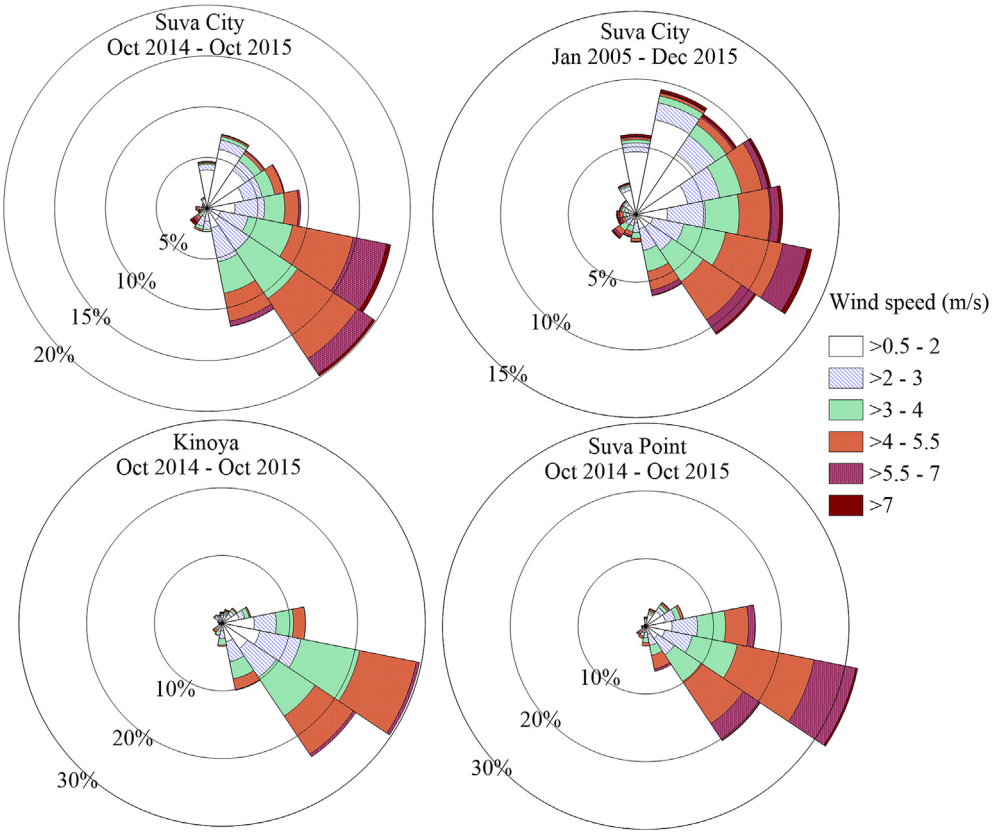

Fig. 4. Windroses for Suva for October 2014 to October 2015, showing frequency of wind speed counts for each direction. Suva City site shows Australian Bureau of Meteorology Data (Australian Government, 2016b); Kinoya and Suva Point show TAPM simulated data.

4.0 m/s and frequently exceeding 5.5 m/s (10% of the time). In the early hours of the morning, midnight to 07:00, this southeasterly component remains; however there is an increase in winds from the northeast (23% of winds) and north (14% of winds). These northerly and northeasterly winds typically have wind speeds below 2 m/s (85% of occurrence). This same pattern of lower wind speeds at night-time is also apparent in diurnal wind speed profiles for the Kinoya and Suva Point sites (Fig. 2). TAPM wind speed has been shown for Kinoya in Fig. 2, as the anemometer at the Kinoya site recorded less than five months of data.

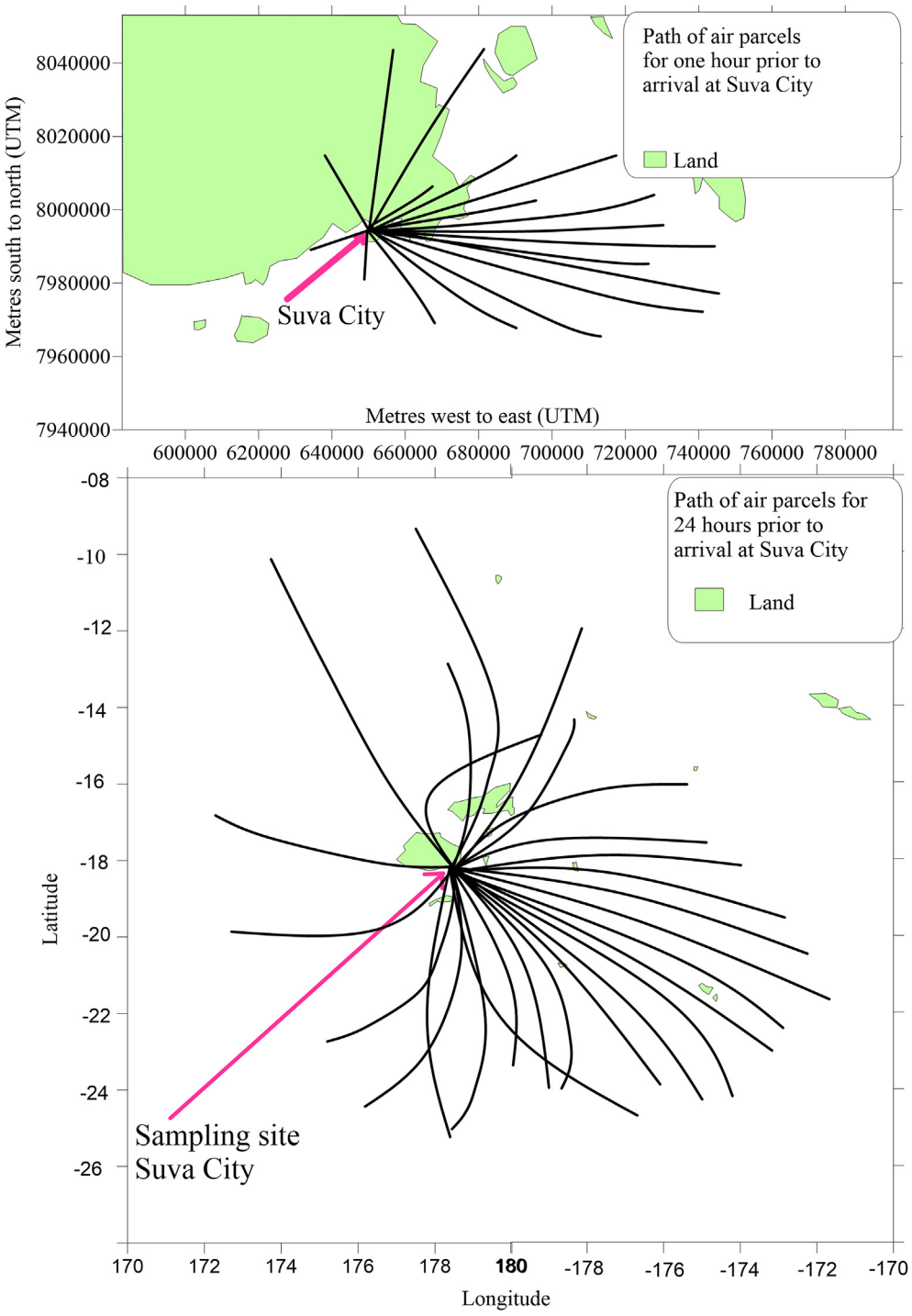

Fig. 5. HYSPLIT back trajectories for Suva City sampling site, showing prevailing south-easterly winds. A typical parcel of air travels over open ocean before arriving in Suva, with a smaller proportion of air parcels arriving from over the land area of Fiji. Air has travelled an average of 41.5 km in the hour prior to arrival in Suva, and 724 km in the past 24-h.

HYSPLIT back-trajectory analyses for one hour and 24 h prior to arrival at the Suva City site are shown in Fig. 5. When time of arrival in Suva was considered for 1-h back trajectories, it showed little difference in the origin of air parcels; with parcels of air arriving between midnight and 03:00, on average, originated from a point 3 km further north than those arriving from 09:00 to 15:00. This represents a 7.2% difference in the origins of these air parcels, considering that they have travelled an average of 41.5 km in this past hour. Typically, a packet of air sampled at the Suva City site has travelled 724 km in the 24-h prior to sampling, mainly over open ocean waters. Air sampled at the Suva City site has typically spent only seven minutes travelling over the land area of Suva Peninsula.

4. Discussion

Meteorological conditions during the period of air quality monitoring were fairly typical of the historical averages; with some slight differences. The annual pattern of ambient air temperature during the monitoring period fits well with historic averages of maximum and minimum temperature for each month. Rainfall

during the monitoring period was, on an annual basis, typical for Suva. During December 2014, higher rainfall was experienced than the historical December average; with drier than average conditions during the period from March 2014 through to July 2015. On the whole, meteorological conditions in Suva during the monitoring period were representative of typical conditions for this location, with prevailing south-easterly winds. No statistical relationship is apparent between $PM_{2.5}$ concentrations measured and rainfall, humidity or temperature during the monitoring period. When Laucala Bay rainfall and ASP $PM_{2.5}$ levels are compared on a daily basis, $r(112) = 0.15$ and $p > 0.05$; similarly, for humidity at Laucala Bay and ASP $PM_{2.5}$, $r(112) = 0.04$ and $p > 0.05$. Also, for air temperature and $PM_{2.5}$, $p > 0.05$. The reduced incidence of winds from the northeast quadrant during the monitoring period, in comparison with historical data, may have resulted in reduced transport of air pollutants from northeastern parts of Suva to the monitoring site in the City. Indeed, from 21st to 23rd October 2015, when winds were from the northeast 73% of the time; compared to 24% over the 2014–2015 monitoring period; ASP $PM_{2.5}$ levels at the City were 13.3 $\mu g/m^3$ to 21.8 $\mu g/m^3$, which is well above the average $PM_{2.5}$ for the monitoring period (7.4 ± 0.3 $\mu g/m^3$).

Continuous monitoring indicates that World Health Organisation (2006) guidelines for $PM_{2.5}$ (10 $\mu g/m^3$ as an annual mean) and Australian Government (2016a) standards (8 $\mu g/m^3$ as an annual mean) may be exceeded in some areas of Suva. A full year of data are not available for Osiris measurements at the City and Kinoya sites and hence an annual mean is not available to compare against these criteria. ASP gravimetric results for $PM_{2.5}$ at the city site indicate that weekday results, 8.6 ± 0.4 $\mu g/m^3$ (Table 2), considered alone, would exceed the Australian guideline, albeit only marginally. Weekend results are significantly lower (Table 2) however, and reduce this average to 7.4 ± 0.3 $\mu g/m^3$ for $PM_{2.5}$ and 2.2 ± 0.1 $\mu g/m^3$ for BC. Most (94%) weekend samples were collected on Sunday. In Suva, Sunday is a day when many businesses and industries do not operate, so it follows that emissions and ambient PM levels would be reduced. The Suva markets are closed on Sunday and public transport services are minimal, with a large portion of the city bus terminal being used for church services. It could therefore be argued that the weekday average concentration is more indicative of typical conditions in Suva City. Weekday results for Suva city provide an indication of the levels that workers and commuters would experience during the working week, when the city is more densely populated.

The World Health Organisation (2016) lists $PM_{2.5}$ and PM_{10} concentrations for 91 countries. These values are listed as a composite of city, and non-city stations for each country. If Fiji were added to the World Health Organisation list, it would be ranked 7th lowest according to $PM_{2.5}$, using gravimetric measurements. Suva's $PM_{2.5}$ concentrations are similar to those reported for New Zealand, or Canada. Suva's $PM_{2.5}$, by world standards, is low, which is not surprising for an isolated island city with a small population. For PM_{10}, Suva would be ranked 11th lowest, using an average of Osiris measurements from Kinoya (residential) and City sites, with similar PM_{10} to Luxembourg and Monaco. By comparison, the world median reported $PM_{2.5}$ concentration was 22 $\mu g/m^3$ and median PM_{10} was 37 $\mu g/m^3$, similar to PM concentrations in Brazil and Russia. Ambient $PM_{2.5}$ concentrations measured in Suva (ASP) comply with current air quality guidelines, however, as reduction in $PM_{2.5}$ concentration is associated with reduced mortality risk (Laden et al., 2006; Pope et al., 2009), there is still good reason to reduce these values where possible.

Particulate measurements at the three sites show relatively low levels of TSP compared to World Health Organisation (2006) guidelines of 90 $\mu g/m^3$, Vrins et al. (2004) note that, for the Osiris, "*due to the low sampling rate, 0.6 L/min, the sampling efficiency for large particles decreases. What is called TSP is actually about PM_{20} and, probably, the sampling efficiency depends on wind speed*". Hence the true TSP concentration is likely to be higher than reported here. In a previous high-volume air sampling study of Suva, Garimella and Deo (2007) reported TSP concentration at the University of The South Pacific (Table 2), approximately 1 km from the Suva Point site, to be 25 ± 3 $\mu g/m^3$, much higher than the 9 ± 0.1 $\mu g/m^3$ reported by the Suva Point Osiris. Considering that the high volume air sampler (HVAS) in the Garimella and Deo study was located on the upper university campus, 1 km further inland than Suva Point, it would have been exposed to pollutant sources such as bus and car emissions and wind-blown dust; to a larger extent than the Suva Point sampler, located on the very east of the peninsula. These samples (Garimella and Deo, 2007) were collected more than ten years prior to this study and so it is also likely that air quality changes have occurred in this time. At Suva market, approximately 0.2 km from the Suva City sampling site, the TSP concentration level reported by Garimella and Deo (2007) was 41 ± 4 $\mu g/m^3$, once again higher than Osiris values at the City (28.4 ± 0.2 $\mu g/m^3$). As well as sampling efficiency differences between the Osiris and HVAS, the City Osiris site was located at 18 m height, compared to the HVAS, which was located at ground level; meaning that highly localised emissions created by passing traffic would have more opportunity to disperse before reaching the Osiris sampler. The Osiris at Suva Point was also located at approximately 8 m height. The HVAS TSP results for Centrepoint, 1 km from the Kinoya site, were 49 ± 11 $\mu g/m^3$, similar to the Kinoya Osiris average of 44 ± 0.4 $\mu g/m^3$. Both the Centrepoint and Kinoya site were located close to ground level.

Low-volume quartz filter samples generally indicated concentrations in line with Osiris measurements. For the Suva Point site, low-volume quartz filter samples reported levels similar to Garimella and Deo (2007); indicating that the Osiris at this site is under-reporting TSP. This may be due to the presence of very coarse PM particles, greater than 20 μm effective aerodynamic diameter, that are not being captured by the Osiris at this site. At the remaining sites, low-volume quartz filter samples generally agreed with Osiris results. This may, therefore, point to localised differences between the sites chosen for the HVAS and Osiris studies, or it may also indicate that the low-volume quartz filter samplers experience similar sampling efficiency constraints to the Osiris monitors. The lower quartz filter result for October 2014 at Kinoya, 27.3 ± 4 $\mu g/m^3$, based on only two samples, is within the variation of daily Osiris TSP averages at this site. For Kinoya, daily average Osiris TSP concentrations range from 1 $\mu g/m^3$ to 112 $\mu g/m^3$ with median of 35.6 $\mu g/m^3$ and standard deviation of 24 $\mu g/m^3$; for October 2014, daily Osiris TSP at Kinoya ranged from 25 $\mu g/m^3$ to 101 $\mu g/m^3$.

Results from the Suva Point site demonstrate that the maritime aerosol arriving in Suva carries a very low PM load, hence the higher concentrations measured at the city and residential (Kinoya) sites show significant influence from land-based emissions within Suva. The Suva Point site demonstrates lower $PM_{2.5}$ than other sites, due to its location upwind of many emission sources in Suva. Windroses for Suva (Fig. 4) show south-easterly winds to prevail. Therefore air at the Suva Point site, on the east of the Suva Peninsula, would show little influence from land-based pollutant sources, as compared with sites on the western side of the peninsula. At Kinoya, mean TSP concentrations were 4.9 times higher than those measured at Suva Point, with $PM_{2.5}$ concentrations being 3.1 times higher. For the City, mean concentrations of all PM fractions were two to three times higher than at Suva Point, showing a significant increase in PM loading as air travels this short distance of 3.8 km across the land area of Suva. As well as being surrounded by residential area, where waste burning activity occurs, the higher concentrations measured at Kinoya reflect the less windy conditions

(Fig. 4) at this site, which impede dispersion of pollutants.

Suva's prevailing south-easterly wind direction is also noted in the back-trajectory calculations (Fig. 5); very little of the air sampled in Suva has come from the north or west. Analysis of trajectories shows that air parcels arriving in Suva during the middle of the night have followed very similar trajectories to those arriving at midday and at other times during the day, with only a 7.2% difference in the average point of origin (one hour before arrival of air in Suva). Average wind speed in Suva City for the monitoring period was 3.1 m/s, with only 3% calm periods (wind speed of 0.5 m/s or less). Residence times of air pollutants in Suva are small, with the typical packet of air arriving in Suva city having travelled over open ocean before arriving at the land area of Suva, then spending an average of only seven minutes travelling across the land area of Suva before arrival at the sampling site. With such short residence times over Suva, formation and accumulation of secondary aerosol particles would be limited.

Diurnal profiles of $PM_{2.5}$ concentration for Suva show that concentrations decrease during the day and increase at night-time, with the most obvious day/night contrast occurring at Kinoya. There are many air pollutant sources, such as road traffic and daytime-operating industries, that have peak emission levels during daylight hours. The daily $PM_{2.5}$ concentration profiles do not show these traffic or daytime emissions to be the dominant influence on $PM_{2.5}$ concentrations. Burning of wastes has been visually observed to frequently occur in the evening and morning in Suva, which may contribute to this observed night-time $PM_{2.5}$ peak, however, little data exist on the temporal patterns of waste burning by households in Suva. The practice of burning wastes, even where waste collection services exist, is a '*culturally entrenched behaviour*' (Mataki, 2011) in all Pacific Island Countries and so similar $PM_{2.5}$ profiles may be anticipated for these countries. The strongest influence on this daily pattern of $PM_{2.5}$ concentration would appear to be meteorology. This diurnal $PM_{2.5}$ pattern appears to be related to wind speeds, which are highest during the day, facilitating rapid dispersal of pollutants; and lowest at night. For 1500 pairs of hourly-averaged $PM_{2.5}$ (city Osiris) and wind speed (City) measurements, $p < 0.05$. Night-time winds also include a greater proportion of winds from the north and north-west than during the day, which may affect the sources of $PM_{2.5}$ that arrive at the sampling site; however, south-easterly winds remain as the predominant wind direction at all hours.

Diurnal $PM_{2.5}$ differences may also be described in terms of atmospheric stability. A simple and commonly-used scheme to describe atmospheric stability is that developed by Pasquill (1961). These describe the tendency of an air parcel to move vertically; and range from Class A, the most unstable, where vertical updrafts tend to develop; to class F, the most stable, where vertical updrafts tend to be suppressed. For Suva City, these stability classes have been calculated for the monitoring period and averaged to give a typical daily occurrence profile. Stability classes were calculated according to the method of Gifford (1961). Cloud cover data, required for these calculations, were obtained for Nausori Airport (Weatherspark, 2016). Whilst Nausori airport is 17 km from the Suva City site, where air temperature, wind speed and wind direction were recorded, this was the nearest station for which cloud cover data were available. The most prevalent stability class, experienced 35% of the time during the monitoring period, is 'D' class, or neutral conditions, which reflect the overcast conditions present much of the time in Suva. These D class stability conditions occur at all hours of the day and night, however they most frequently occur (36% of occurrence) from 14:00 to 19:00. The next most common is 'F' class, or stable conditions, which occur 21% of the time, always at night time, mainly (98% of occurrence) between 18:00 and 06:00. Under F class conditions, pollutants disperse slowly. Ground-level emissions, from burning of wastes, wood-burning for cooking and from vehicles; combined with shallow mixing depths in the night and early morning, are the major reason why $PM_{2.5}$ levels are highest overnight in Suva. Conversely, during daylight hours, the more unstable class A, B and C conditions occur for a combined total of 31% of the time, facilitating rapid dispersal of pollutants.

The Kinoya site shows an unusual peak at 03:00 on Monday mornings (Fig. 3). Data were analysed to ascertain if a one-off event may have greatly influenced average results for this hour. A similar peak occurred for the Suva Point site, on Saturday night, this was strongly influenced by high readings on the evening of 27th December 2014, from 19:00 to 24:00, where 10-min average $PM_{2.5}$ concentrations as high as 233 $\mu g/m^3$ were recorded. It is assumed that a local emission activity, such as a fire, had influenced this particular evening, however this does not represent typical Saturday night $PM_{2.5}$ levels at Suva Point and so these hours (27th December 2014, from 19:00 to 24:00) were removed from calculations. For Kinoya, the highest 2.5% of 10-min $PM_{2.5}$ concentrations were considered; these occurred over 36 separate days, with 94% of these occurring between 17:00 and 06:00. These highest 2.5% of readings were fairly evenly distributed across all days, with $14 \pm 5\%$ occurring each day of the week. Considering only Mondays, the top ten $PM_{2.5}$ measurements occurred on four different Mondays, between 04:10 and 05:30. Therefore this Monday morning peak does not appear to be due to any one particular event, rather, this peak is due to a general pattern of higher levels occurring of a Monday morning. This may be due to localised activities near the monitoring site, such as a nearby resident or business that burns waste or cooks on a wood fire routinely on Monday mornings. Meteorological conditions also play a role in these peak levels at Kinoya, with the highest 2.5% of 10-min $PM_{2.5}$ concentrations occurring mainly under wind-speed conditions of less than 1 m/s, as recorded by the on-site anemometer. Hence a combination of local emissions activities and limited atmospheric dispersion are likely to have combined to create this peak. Night-time levels are significant to exposure as, due to the warm climate, the majority of Fijian households do not close their house windows at night time; hence outdoor, ambient exposures also affect people as they sleep indoors. These indoor air pollution levels require further investigation.

Ambient black carbon concentrations measured in Suva are compared against a variety of other locations, worldwide, in Table 3. Use of differing field and laboratory analysis techniques, to report BC or EC, in different particle fractions, complicates comparison of these data. The (United States Environmental Protection Agency, 2012) discusses these differences, comparing BC and EC data, gained via a variety of techniques, for ten cities in the United States of America (USA) as well as other cities around the world. Overall the United States Environmental Protection Agency (2012) found (p. 255), that ratios of BC/EC were "*typically near 1 (BC/EC = 0.7–1.3)*". Hence it is possible to compare BC and EC, from different studies, but only in an approximate manner. Ratios of BC/EC may also vary for different combustion sources (Holder, 2015). An average of BC data from the United States Environmental Protection Agency (2012) report for the ten cities in the USA is included in Table 3. Much of the data in Table 3 come from Cohen (2011), who reported a multi-year summary (2000–2009) of black carbon concentration in $PM_{2.5}$ measured as part of the ANSTO air sampling program. Hence these data are obtained using the same ASP samplers, Teflon filters and laboratory techniques (LIPM) as were used for Suva. These data represent an average over multiple sites for each country listed, representing mainly city areas; with the inclusion of a smaller number of sites from less densely populated districts as detailed in Cohen (2011). Further data were obtained from the European Union (EU) 'AIRBASE' database (European Environment Agency, 2014), which provided

Table 3
Suva's BC in $PM_{2.5}$ is presented in comparison with other locations. BC and EC data are presented here for various locations. Half of these locations (Cohen, 2011), used the same techniques as the current study, representing a multi-year (2000–2009) average over multiple sites for each country, from mainly city areas; with the inclusion of a smaller number of sites from less densely populated districts. Other locations may be compared only in an approximate manner, due to differences in field and laboratory techniques.

Location	BC	$PM_{2.5}$	Carbon measurement
Australia urban	0.81 ± 0.02	5.56 ± 0.09	BC in $PM_{2.5}$ (Cohen, 2011)
London urban	0.86 ± 0.02	–	EC in PM_{10} (Jones and Harrison, 2005)
EU rural	1.61 ± 0.90	–	Various methods
EU kerbside	3.15 ± 0.28	–	(European Environment Agency, 2014)
London kerbside	3.38 ± 0.03	–	EC in PM_{10}
Belfast urban	1.10 ± 0.02	–	(Jones and Harrison, 2005)
New Zealand urban	1.22 ± 0.02	4.9 ± 0.2	BC in $PM_{2.5}$ (Cohen, 2011)
USA 10 cities BC average over 10 cities	1.26 ± 0.20	–	Various methods (United States Environmental Protection Agency, 2012)
Barcelona urban	1.9 ± 0.2	25.0 ± 0.8	EC in $PM_{2.5}$ (Viana et al., 2006)
Germany urban	2.03 ± 0.16	–	EC in $PM_{2.5}$ or PM_{10} (European Environment Agency, 2014)
Suva Fiji urban	**2.2 ± 0.1**	**7.4 ± 0.3**	**This study: BC in $PM_{2.5}$**
Indonesia urban	2.99 ± 0.03	26.7 ± 0.1	BC in $PM_{2.5}$ (Cohen, 2011)
Korea urban	3.25 ± 0.02	15.7 ± 0.1	
Paskistan urban	3.39 ± 0.04	15.7 ± 0.1	
Malaysia urban	4.76 ± 0.01	49.8 ± 0.2	
China urban	5.08 ± 0.02	26.7 ± 1.6	

annual summaries of available air quality data throughout the EU. These data included a composite of BC and EC measurements, reported in either $PM_{2.5}$ or PM_{10} and are summarised into data representing rural sites ('EU rural') and data collected within 10 m of roads in highly trafficked urban areas ('EU kerbside'). Germany was the only country in the AIRBASE data set to report 'urban background' levels, shown in Table 3, representing a composite of EC in $PM_{2.5}$ or PM_{10} at seven sites across Cottbus, Frankfurt and Bernau (2008–2012). It is surprising that these German data, from larger, more industrialised cities, provide the closest match to BC concentrations in Suva. Suva's BC is around half of that reported for China and similarly, lower than many other highly populated urban centres in; Malaysia, Barcelona Spain, Pakistan, Korea and Indonesia; Suva's BC is also low compared with kerbside EC levels in London (Jones and Harrison, 2005) and the EU. It is noteworthy that Suva's BC levels are higher than those reported in urban USA, London England, Belfast Ireland, New Zealand and Australia. Considering the low residence time of air parcels in Suva (approximately 7 min), these BC concentrations recorded in Suva indicate that significant combustion emissions are occurring within Suva. Black carbon concentrations are significantly lower on weekends than on weekdays (Table 2). As noted above, Suva has decreased transport and industrial activity on Sundays as compared with weekdays. It would appear that these transport and industrial activities that occur with greater intensely on weekdays in Suva contribute significantly to BC concentrations.

5. Conclusion

Whilst the levels of $PM_{2.5}$ in Suva City are within World Health Organisation guidelines, continuous monitoring suggests that the levels in residential areas of Suva may be close to or exceed these guidelines. Although the residence times of air parcels in Suva are small, black carbon concentrations in Suva are close to those of much larger cities, suggesting that combustion emissions in Suva are a significant source of particulate air pollution. These elevated black carbon concentrations warrant continued investigation; due to the variation in BC and EC results between available field and laboratory methods, an alternative measurement method is recommended in order to confirm these BC levels for Suva.

It is likely that other Pacific Island cities are similarly impacted by combustion emissions, which require ongoing investigation. For more inland cities in the developing world, that practice similar combustion activities, yet do not have the benefit of strong maritime winds, $PM_{2.5}$ and black carbon levels are likely to be higher than those measured in Suva. Reducing combustion emissions in Suva would reduce BC and $PM_{2.5}$ concentrations, reducing the health risk from fine particulate exposure in Suva.

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