Atmos. Chem. Phys. Discuss., 10, 22623–22652, 2010
www.atmos-chem-phys-discuss.net/10/22623/2010/
doi:10.5194/acpd-10-22623-2010


Atmospheric Chemistry and Physics Discussions



# Observation of new particle formation in subtropical urban environment

**H. C. Cheung, L. Morawska, and Z. D. Ristovski**

International Laboratory of Air Quality and Health, Queensland University of Technology, G.P.O. Box 2434, Brisbane QLD 4001, Australia

Received: 20 August 2010 – Accepted: 14 September 2010 – Published: 1 October 2010

Correspondence to: L. Morawska (l.morawska@qut.edu.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.







## Abstract

The aim of this study was to characterise the new particle formation events in subtropical urban environment Southern Hemisphere. The study measured the number concentration of particles and its size distribution in Brisbane, Australia during 2009. The variation of particle number concentration and nucleation burst events were studied and the particle growth rate was characterised which was first reported in urban environment of Australia. The annual average $N_{UFP}$, $N_{Aitken}$ and $N_{nuc}$ were $9.3\times10^3$, $3.7\times10^3$ and $5.6\times10^3$ cm$^{-3}$, respectively. Weak seasonal variation in number concentration was observed. Local vehicle emission was major contributor of the pollution observed in the morning which was dominated by the Aitken mode particles, while particle formed by secondary formation process was contributed to the particle number concentration in the afternoon. 65 nucleation burst events were identified during the study period. Nucleation burst events were classified into two groups with and without particle growth after the burst of nucleation mode particles observed. Average particle growth rate of the nucleation events was 4.6 nm hr$^{-1}$ (ranged from 1.79–7.78 nm hr$^{-1}$). Case studies of the nucleation burst events were characterised including i) the nucleation burst with particle growth which was associated with the particle precursor emitted from local vehicle emission, ii) the nucleation burst without particle growth which was due to the transport of industrial emissions from the coast to Brisbane city, and iii) interplay between the above two cases which demonstrated the impact of the vehicle and industrial emissions on the variation of particle number concentration and its size distribution during the same day.

## 1 Introduction

Understanding the formation process of atmospheric particles is vital because of the significant impact of particulate matter on human health and climate change (Charlson et al., 1992, Donaldson et al., 1998). Atmospheric particles can be formed by





ACPD
10, 22623–22652, 2010



nucleation process via a number of different mechanisms (e.g., Kulmala, 2003; Kulmala et al., 2004), such as binary nucleation (involving $H_2SO_4$ and water vapour), ternary nucleation (involving $NH_3$, $H_2SO_4$ and water vapor) and ion-induced nucleation for charged particles, depending on the environmental conditions. To date, numerous studies have been conducted in different locations, in order to investigate particle formation processes in different environmental settings, including the free troposphere (e.g., Weber et al., 2001), boreal forests (e.g., Vehkamäki et al., 2004) and coastal areas (e.g., O'Dowd et al., 1999; Lee et al., 2008). However, most of these studies focused on particle formation in rural settings and colder climates, with very few studies conducted in subtropical urban environments, especially in the Southern Hemisphere (Kulmala et al., 2004). A limited number of studies were conducted in continental (e.g., Woo et al., 2001) and coastal (Rodríguez et al., 2008; Fernández-Camacho et al., 2010) urban areas. These urban studies demonstrated the influence of urban emission on particle number concentration, as well as on new particle formation. The few examples include studies on particle formation associated with natural emissions from a Eucalypt forest in South-East Australia (Ristovski et al., 2009; Suni et al., 2008), which concluded that natural emissions were in fact a source of particle formation. In addition, new particle formation was observed in the coastal area of Eastern Australia (Johnson et al., 2005; Modini et al., 2009), the result of which showed that new particles were formed by the condensation of sulphate and/or organic vapours onto sulphate clusters to form an observable particle. Guo et al. (2008) conducted a short-term intensive study on particle formation in the rural environment of Eastern Australia, in which particle formation was suggested to be influenced by the photochemical processes of the urban air plume. The findings of Guo et al. (2008) provided an insight to the impact of urban pollution on nucleation processes. For the urban environment, Mejía et al. (2009) characterised the favourable atmospheric conditions for nucleation burst events in a coastal urban area of Brisbane, which is the only nucleation study to be conducted in an urban area in the Southern Hemisphere to date. The study showed that the nucleation events mostly occurred during the summer and it also suggested





ACPD
10, 22623–22652, 2010



cleaner air masses of a local origin mixing with traffic emission after the events. However, Mejía et al. (2009) did not investigate the nucleation growth process after the nucleation burst events, and thus particle formation parameters, such as particle growth rate, are not available for the urban environment in Southern Hemisphere.

To further investigate the characteristics of the particle formation processes in a subtropical urban environment, we conducted a one year-long measurement of the size distribution of particles in the size range 4–110 nm, at an urban area of Brisbane, Australia. The aim of this study was to characterise the temporal variation of particle number concentration, and to explain the controlling factors that influenced new particle formation processes in the subtropical urban environment.

## 2 Methodology

### 2.1 The topography and meteorology of Brisbane region

Brisbane is the capital city of the state of Queensland, Australia, located at 27′30° S and 153° E. Brisbane city is surrounded by mountains from south to north, and faces the Pacific Ocean to the East. It is the fastest growing urban region in Australia (2 million inhabitants) and the major economic activity of Brisbane can be divided into two sectors. The first sector includes finance services, higher education, information technology and government administration services. This sector is mainly located in the central business district (CBD) of Brisbane, while the second sector, which includes the oil refinery, paper milling, metalwork and shipping industries, is located at the lower reaches of Brisbane River, approximately 18 km NE of the CBD. In addition, the international and domestic airports are located approximately 15 km NE of the CBD. Thus, the major pollution sources affecting the CBD region are vehicle emissions generated in the inner city, and industrial emissions transported from the airports and lower reaches of Brisbane River.





ACPD
10, 22623–22652, 2010



Morawska et al. (1998) provided a description of the wind patterns in the Brisbane region, which are mostly governed by synoptic flows from the SE. A NE sea breeze is also a daily feature throughout the year. In addition, an overnight SW drainage flow from the mountain range to the West carries air parcels from the plateau region and the Western coastal plain towards the city. On the rare occasion when gradient winds blowing from the NW, the combination of the light synoptic NW flow and the overnight SW drainage flow can sufficiently delay the onset of the sea breeze to cause recirculation of the city emissions, leading to photochemical smog events.

### 2.2 The QUT study site

The measurements were conducted at the International Laboratory of Air Quality and Health (ILAQH), Queensland University of Technology (QUT), which is within the CBD of Brisbane (Fig. 1). The monitoring site is about 10 m a.g.l. on the top floor of a QUT campus building, located to the SE of the city centre, with a major highway, the Pacific Motorway, situated along the SW side of the campus. Therefore, the pollution associated NE winds could be attributed to industrial emissions (from the airport, oil refinery and Port of Brisbane), while the pollution associated with S to NW winds could be attributed due to local vehicle emissions.

### 2.3 Measurement techniques

The size distribution of UFPs was measured at the QUT monitoring site from January to December 2009. Particle size distribution in the range 4–110 nm was measured by a Scanning Mobility Particle Sizer (SMPS) system, which consisted of two parts, an Electrostatic Classifier (EC) (TSI 3080) and a Condensation Particle Counter (CPC) (TSI 3781). The EC was equipped with a nano-differential mobility analyser, which can separate the poly-disperse particles into selected mono-disperse particles according to their particle mobility. The number concentration of the mono-disperse particles was then counted by the CPC. Each ambient sample was drawn into the SMPS system





ACPD
10, 22623–22652, 2010



from outside the building through a 0.635 cm (inner diameter) conductive tube and a sampling duration of 5 min was adopted for each particle size distribution sample.

In this study, the size distribution data was classified into three groups, i) ultrafine particles (UFP), including particles ranging from 4–110 nm; ii) Aitken mode with particles, which ranged from 30–110 nm; and iii) nucleation mode particles, which were <30 nm. In addition to the above particle measurements, meteorological parameters, including wind speed and direction, temperature and relative humidity (RH) were monitored at Kangaroo Point (1 km East of QUT) by the Queensland Bureau of Meteorology. It should be noted that global solar radiation was measured at Brisbane Airport (about 15 km North-East of QUT).

### 2.4 Data processing and analysis

In this study, the raw particle size distribution and meteorological data were synchronised into 10 min averaged data for data analysis and figure plotting. Some data were removed from the database based on several criteria such as i) zero value for particle concentration; ii) particle concentration higher than $5\times10^5$ cm$^{-3}$; and iii) data collected during instrument malfunction. Correlations between the parameters were tested using the Pearson-product moment correlation test with a 95% confidence level ($p<0.05$). The linearity of the tested parameters was indicated by Pearson's coefficient, $r$, with a perfect linear correlation between two parameters indicated by an $r$ value close to 1. For the temporal analysis between the particle number concentration and photochemical activity, temperature data was applied in this study instead of solar radiation, since temperature data has higher time resolution compared to that of solar radiation (10 min vs. daily).





ACPD
10, 22623–22652, 2010



## 3 Results and discussion

### 3.1 Overall results

The overall average concentration of ultrafine particles ($N_{UFP}$), Aitken mode ($N_{Aitken}$) and nucleation mode ($N_{nuc}$) measured in this study were $9.3\times10^3$, $3.7\times10^3$ and $5.6\times10^3$ cm$^{-3}$, respectively. Similar values of $N_{Aitken}$ and $N_{nuc}$ were obtained in the urban areas of Helsinki, Finland, which were $4.0\times10^3$–$6.5\times10^3$ cm$^{-3}$ and $5.5\times10^3$–$7.0\times10^3$ cm$^{-3}$, respectively (Hussein et al., 2004). The $N_{UFP}$ measured in Brisbane was relatively lower than in other coastal urban areas, including the Yangtze River Delta, China (Gao et al., 2009) and Huelva and Santa Cruz de Tenerife, Spain (Rodríguez et al., 2008; Fernández-Camacho et al., 2010), which were $28.5\times10^3$ and $22.0$–$26.3\times10^3$ cm$^{-3}$, respectively.

The results of this study were also compared to those of a previous study conducted in the Brisbane urban region from 1995 to 2000 (Mejía et al., 2007). The $N_{UFP}$ and $N_{nuc}$ measured in this study were about 8% and 60% higher than those measured by Mejía et al. (2007), being $8.6\times10^3$ cm$^{-3}$ (for particles in the size range 15–100 nm) and $3.5\times10^3$ cm$^{-3}$ (for particles in the size range 15–30 nm), respectively. In relation to $N_{nuc}$, it should be noted that the nucleation mode particle concentration in this study covered particles in the size range 4–30 nm, and therefore, it is expected to be higher than the earlier result reported by Mejía et al. (2007).

The seasonal variation of particle number concentrations is depicted in Fig. 2. The Pearson's coefficients, $r$, between particle number concentration of different modes and temperature were calculated which ranged from 0.00–0.03, which indicates that there was no statistical seasonal variation in particle concentrations. This result was similar to the result presented by Mejía et al. (2007) for the same study region, however larger variations in particle number concentrations were observed in each mode during the summer season, as reflected by the large interquartile range (see Fig. 2).





ACPD
10, 22623–22652, 2010



Figure 3 shows the diurnal variation of particle number concentration for different modes with the diurnal variations of temperature and relative humidity also plotted. Two peaks were observed for UFP during the day, the first of which occurred from around 06:00 a.m. to 08:00 a.m., possibly due to traffic emissions during the morning peak hours (from around 06:00 a.m. to 08:00 a.m.) in Brisbane urban region (Mejía et al., 2007). The second peak was observed from around 12:00 noon to 03:00 p.m., and this may be due to the formation of new particles (this is discussed in more detail below). During the period of UFP morning peak, Aitken mode particles also peaked, which implies that the particles measured during this period were emitted by diesel and petrol engine emissions, which produce particles in the size range of about 20–130 nm and 20–60 nm, respectively (Morawska et al., 2008). During the period of second UFP peak, a nucleation mode peak was also observed, which implies that new particles were produced during the early afternoon, at a time when the highest level of photochemical activities occurred and were likely to have contributed to the number concentration of UFP.

### 3.2 Relationship between particle number concentrations and meteorological parameters

#### 3.2.1 Temperature and relative humidity

From Fig. 3, it can be seen that temperature and relative humidity displayed an anti-correlation, whereby increases in temperature were associated with decreases in relative humidity. The influences of temperature on particle number concentration were not confirmed in previous studies. Some studies found that high particle concentration was related to relatively high temperatures (e.g., Kim et al., 2002), whilst others found that they were associated with relatively low temperatures (e.g., Olivares et al., 2007). In this study, a weak correlation between particle number concentrations and temperature was observed ($r$=0.36–0.53; $p$<0.01), however higher variations in $N_{UFP}$, $N_{Aitken}$ and $N_{nuc}$ were observed during warmer, low humidity conditions (Figs. 4 and 5). The





ACPD
10, 22623–22652, 2010



highest number concentrations of all particle sizes were associated with temperature around 32 °C. The peaks of $N_{Aitken}$ and $N_{nuc}$ observed in the early afternoon (under high temperature condition) were suggested that contributed by new particle formation processes and the subsequent particle growth to larger particles. In addition, another peak of $N_{Aitken}$ was observed with temperature around 10 °C (see Fig. 4). This result may be due to enhanced coagulation and condensation effects under high humidity conditions.

### 3.2.2 Wind direction and speed

Figure 6 shows the particle number concentration for different particle sizes under different wind directions. For UFP, a sharp peak was associated with ENE wind directions, and a lower broad peak was associated with SSE to WNW wind directions. An interesting result was also obtained when dividing the data into Aitken and nucleation modes. The sharp peak was observed in both of these two modes, however the broad peak was only observed in the Aitken mode. From Fig. 1, it can be seen that the Brisbane Airport, oil refinery and Port of Brisbane were all located to the NE of the monitoring site, whilst the CBD and Pacific Motorway were located to the NW and SW of the monitoring site. Therefore, it is likely that the nucleation mode particles were contributed by the industrial sources located to the NE, while the Aitken mode particles were emitted from both industrial and vehicle emission sources.

In general, a negative correlation was observed between UFP concentration and wind speed, indicated by a Pearson coefficient of $r=-0.97$ ($p<0.01$). Higher particle number concentration was associated with lower wind speeds, which can be explained by the stronger dispersion associated with high wind speeds (Hussein et al., 2006). Similar results were also observed for Aitken and nucleation mode particles.





ACPD
10, 22623–22652, 2010



### 3.3 Particle formation in subtropical urban atmosphere

#### 3.3.1 Classification of nucleation events

The general definition of a nucleation event is a two-phase process involving the burst of observed nucleation particles and the growth of these particles into accumulation mode by condensation and/or coagulation (Kulmala et al., 2004). To illustrate the nucleation event, a banana shape should be observed in the contour plot of particle size distribution. The example of a nucleation event is shown in Fig. 8. Usually the lowest $N_{nuc}$ is observed in the early morning, and then it begins to increase at around 09:00 a.m. The geometric median diameter (GMD) of the measured particles grows into an Accumulation mode during the day and the evolvement of the particle size curve is often compared to a banana shape.

A number of nucleation events were observed during this study, which were classified into different groups (Class Ia/b and II) according to the classification scheme developed by Dal Maso et al. (2005). Class Ia/b events are defined as those events where the particle growth rate can be determined. A typical Class Ia event demonstrates clear and strong particle formation events with little or no pre-existing particles obscuring the observation of the newly formed mode, while a Class Ib event is any other event where the particle growth rate can be determined. Class II events are defined as events where the banana shape still observable, but the data fluctuates to such an extent that formation rate calculation is impractical.

In the urban environment, nucleation burst events have been observed with and without particle growth (Park et al., 2008; Gao et al., 2009). For example, in addition to nucleation events, we occasionally observed increases in nucleation mode particle concentration during the daytime, where the particles did not grow into larger particles (indicated by the near constant GMD value during the event period). We defined this kind of event as a nucleation burst event, and a total of 65 burst events were identified. A more detailed discussion about the occurrence of nucleation events, both with and without particle growth, is provided in Sects. 3.3.2 and 3.4 below.





ACPD
10, 22623–22652, 2010



### 3.3.2 Growth rate during nucleation events

During this study, there were several gaps in the dataset due to instrument malfunction/maintenance. For example, if there were more than 3 h of missing data between 08:00 a.m. to 06:00 p.m. (the period during which the nucleation usually occurs), this was not counted as a valid daily dataset. After the removal of invalid daily datasets, a total of 252 days of data were counted. The number of nucleation events classified as Class Ia, Ib, and II were 4, 13, and 23, respectively. The nucleation events (Class I and II) occurred throughout most of the year, except in November, and only one Class II event was observed in December. Although infrequent nucleation events were observed during November and December, the nucleation bursts (without particle growth) were found to be closely associated with NE wind directions. The mean growth rate for the nucleation events was calculated by the slope of GMD against time during the period of particle growth under 30 nm. The growth rates of Class I events measured in this study ranged from 1.79–7.78 nm $hr^{-1}$ (average 4.6 nm $hr^{-1}$), which is comparable to other urban studies such as those conducted in Atlanta (2.86–22.0 nm $hr^{-1}$) (Woo et al., 2001) and East St. Louis (average 6.7 nm $hr^{-1}$) (Qian et al., 2007).

Figure 9 shows the monthly averaged particle growth rate and solar radiation, as well as the monthly occurrence of nucleation events. This data provided information on the influence of photochemical activity on particle formation in Brisbane. Higher particle growth rate was found to be associated with higher solar radiation and the results showed a positive relationship ($r$=0.83, $p$<0.05) between the particle growth rate of nucleation events and solar radiation. Similar findings were obtained in previous studies, which showed that particle growth rates were associated with the strength of solar radiation (e.g., Kulmala et al., 2004; Vehkamäki et al., 2004).

## 3.4 Case studies of nucleation burst events

In the above sections it was shown that nucleation mode particle concentrations were strongly associated with NE/SW winds. Further analysis of the daily variation of





ACPD
10, 22623–22652, 2010



particles and wind direction showed that nucleation events with particle growth were usually associated with SW winds, while the nucleation burst events without particle growth were associated with NW winds. In this section, case studies relating to types of three nucleation events are discussed, including: i) new particle formation by nucleation processes; ii) a nucleation burst without particle growth; and iii) the interplay between these two situation.

### 3.4.1 Case I – Photochemical formation of nucleation particles

Case I nucleation events were observed during 28–29 April 2009. Significant strong nucleation bursts were found consecutively during these two days (peak 10 min and hourly averaged $N_{nuc}$ during the nucleation events were $47\times10^4$ and $18\times10^4$ cm$^{-3}$, respectively). The time series plots of the particle size distribution and meteorological parameters are illustrated in Fig. 10.

During these two days, the highest temperature was about 30 °C and relative humidity was around 20–40% at noon. Land and sea breeze wind circulation was observed on both days, with a moderate (~4 m s$^{-1}$) SW wind (from inland) dominating in the morning and a moderate NE wind (from the coast) dominating in the afternoon. The variation in concentration of nucleation and Aitken mode particles clearly showed the influence of the nucleation burst on particle number concentrations. In the early morning (06:00–09:00 a.m.) of 28 April 2009, an Aitken mode peak was observed, which could be attributed to traffic emissions during the morning peak hours. At around 10:00 a.m., a sharp peak of nucleation mode particles was observed and the GMD reached the lowest value of the day (~8 nm). The wind direction changed to NE at around 01:00 p.m., and turned back to the SW again after midnight. In terms of GMD, the nucleation mode particles were growing into larger particles (GMD increased from 8 to 57 nm) until around midnight (~03:00 a.m. on 29 April 2009). Another nucleation growth event was observed the following day, on 29 April 2009, with similar meteorological conditions to those which were observed on the previous day. However, the concentration of nucleation particles during the nucleation burst was lower than that





ACPD
10, 22623–22652, 2010



observed on the previous day. This result indicated that the higher number of pre-existing Aitken mode particles in the atmosphere served to diminish the nucleation processes.

### 3.4.2 Case II – Nucleation burst without growth into larger particles

A Case II nucleation event was observed on 11 November 2009. As shown in Fig. 11, the variation in wind direction was similar to that observed during the Case I nucleation events, whereby land and sea breeze circulation was observed, however, the burst of nucleation particles did not appear with the SW wind (associated with local vehicle emissions). Instead, a nucleation burst was observed with the NE wind at ~10:00 a.m. The GMD dropped from ~30 nm to 10 nm and $N_{nuc}$ increased from ~$7.0\times10^3$ to $10.0\times10^4$ cm$^{-3}$ during the nucleation burst, while $N_{Aitken}$ did not show any significant variation, ranging from 2–$5\times10^3$ cm$^{-3}$. This plume disappeared at around 06:00 p.m. and GMD rose to ~25 nm. Based on these findings, it was suggested that the plume was not directly emitted from the local vehicle emissions or ship emission from the Port of Brisbane, since the particles from vehicle and ship emissions are in the range 20–130 nm (Morawska et al., 2008) and 60–120 nm (Sinha et al., 2003), respectively. However, the emissions of $SO_2$ and VOCs from the industrial sources located at the coast could be possible precursors to the formation of new particles by nucleation process. Another possible source of this plume was aircraft emissions from the Brisbane Airport, which is located in a NE direction from the study site. Mazaheri et al. (2009) measured the particle size distribution produced by commercial aircraft at Brisbane Airport and a very distinct peak of nucleation mode particles was observed at around 15 nm. This result was comparable to the average GMD measured during the nucleation burst events in this study, which was 14 nm (ranging from 8–32 nm).





ACPD
10, 22623–22652, 2010



### 3.4.3 Case III – Interplay between new particle formation and nucleation burst events

A Case III nucleation event was observed on 15 March 2009. During this study, it was found that particle formation via nucleation processes was associated with SW winds (Fig. 10) and that the subsequent particle growth (banana shape of particle size distribution) usually followed with the presence of a NE wind. In contrast, the nucleation burst events without particle growth were most commonly related to emission sources from the NE (Fig. 11). In some events, a partial banana shape was observed with a SW wind in the morning, but particle growth was interrupted by a nucleation burst plume from the airport region (Fig. 12).

It can be seen that the nucleation process commenced at 09:00 a.m. and the particles kept growing into Aitken mode particles until 12:00 p.m. (GMD rose from 20 to 35 nm). After 12:00 p.m., the wind direction changed to a NE wind and an air plume enriched with nucleation mode particles was observed, which interrupted the banana shaped progression of the particle size distribution curve. After the interruption, the GMD dropped suddenly to below 20 nm and several similar cases were also observed during the one year study period at QUT. Overall, the results showed that the nucleation mode particles originated from a variety of sources such as vehicle emission in Brisbane CBD and industrial emissions located NE to Brisbane.

## 4 Conclusions

A year long measurement campaign of the size distribution of ultrafine particles was conducted at subtropical urban area of Brisbane, Australia during 2009. The annual average $N_{UFP}$, $N_{Aitken}$ and $N_{nuc}$ were $9.3\times10^3$, $3.7\times10^3$ and $5.6\times10^3$ cm$^{-3}$, respectively. Small seasonal variation in number concentration was observed, with higher particle concentrations during the warmer months. Diurnal variation of $N_{UFP}$, $N_{Aitken}$ and $N_{nuc}$ showed the influence of local vehicle emissions on the particle number concentration





ACPD
10, 22623–22652, 2010



during morning peak hours, and elevated nucleation mode particle levels suggested the contribution of new particle formation during the early afternoon. In relation to wind direction, $N_{Aitken}$ and $N_{nuc}$ were associated with NE winds, which pointed to the emission sources present at the lower reaches of Brisbane river (such as Brisbane Airport, the oil refinery and the Port of Brisbane). A broad peak of $N_{Aitken}$ particles was also observed during SSE to WNW winds, which suggested the influence of local vehicle emissions, with particle size ranging from 30–70 nm. Overall, two major sources of $N_{nuc}$ were identified in this study, which were new particle formation by nucleation and primary nucleation mode particles emitted from aircraft at Brisbane Airport. New particle formation via nucleation process was frequently observed in this study, and the particle growth rate (average 4.6 nm $hr^{-1}$) was positively related to the strength of global solar radiation. The nucleation growth events associated with SW winds were influenced by the precursor emitted from vehicle emission in Brisbane city. An interesting question arose during the course of this study regarding the absence of nucleation particle growth in air masses originating from the coast. It may due to lack of nucleation particles precursor associated with coastal air mass. To tackle this question, a further study on the new particle formation, with parallel measurements of particle chemical composition and gaseous pollutants, is needed.

*Acknowledgements.* This project was supported by the Australian Research Council and Queensland Transport through Linkage Grant LP0882544. We would also like to thank the Queensland Bureau of Meteorology for providing the meteorological data.

## References

Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley Jr., J. A., Hansen, J. E., and Hofmann, D. J.: Climate forcing by anthropogenic aerosols, Science, 255, 423–430, 1992.

Dal Maso, M., Kulmala, M., Riipinen, I., Wagner, R., Hussein, T., Aalto, P. P., and Lehtinen, K. E. J.: Formation and growth of fresh atmospheric aerosols eight years of aerosol size distribution data from SMEAR II, Hyytiälä, Finland, Boreal Environ. Res., 10, 323–336, 2005.





ACPD

10, 22623–22652, 2010



Donaldson, K., Li, X. Y., and MacNee, W.: Ultrafine (nanometre) particle mediated lung injury, J. Aerosol Sci., 29, 553–560, 1998.
Fernández-Camacho, R., Rodríguez, S., de la Rosa, J., Sánchez de la Campa, A. M., Viana, M., Alastuey, A., and Querol, X.: Ultrafine particle formation in the inland sea breeze airflow in Southwest Europe, Atmos. Chem. Phys. Discuss., 10, 17753–17788, doi:10.5194/acpd-10-17753-2010, 2010.
Gao, J., Wang, T., Zhou, X., Wu, W., and Wang, W.: Measurement of aerosol number size distributions in the Yangtze River Delta in China: Formation and growth of particles under polluted conditions, Atmos. Environ., 43, 829–836, 2009.
Guo, H., Ding, A., Morawska, L., He, C., Ayoko, G., Li, Y., and Hung, W.: Size distribution and new particle formation in subtropical Eastern Australia, Environ. Chem., 5, 382–390, 2008.
Hussein, T., Karppinen, A., Kukkonen, J., Härkönen, J., Aalto, P. P., Hämeri, K., Kerminen, V-M., and Kulmala, M.: Meteorological dependence of size-fractionated number concentrations of urban aerosol particles, Atmos. Environ., 40, 1427–1440, 2006.
Hussein, T., Puustinen, A., Aalto, P. P., Mäkelä, J. M., Hämeri, K., and Kulmala, M.: Urban aerosol number size distributions, Atmos. Chem. Phys., 4, 391–411, doi:10.5194/acp-4-391-2004, 2004.
Johnson, G. R., Ristovski, Z. D., Anna, B. D., and Morawska, L.: The hygroscopic behaviour of partially volatilized coastal marine aerosols using the VH-TDMA technique, J. Geophys. Res., 110, D20203, doi:10.1029/2004JD005657, 2005.
Kim, S., Shen, S., Sioutas, C., Zhu, Y., and Hinds, W. C.: Size Distribution and Diurnal and Seasonal Trends of Ultrafine Particles in Source and Receptor Sites of the Los Angeles Basin, J. Air Waste Manag. Assoc., 52(33), 2955–2968, 2002.
Kulmala, M.: How Particles Nucleate and Grow, Science, 302, 1000–1001, 2003.
Kulmala, M., Vehkamäki, H., Petäjä, T., Dal Maso, M., Lauri, A., Kerminen, V.-M., Birmili, W., and McMurry, P. H.: Formation and growth rates of ultrafine atmospheric particles: a review of observations, J. Aerosol Sci., 35, 143–176, 2004.
Lee, Y., Lee, H., Kim, M., Choi, C. Y., and Kim, J.: Characteristics of particle formation events in the coastal region of Korea in 2005, Atmos. Environ., 42, 3729–3739, 2008.
Mazaheri, M., Johnson, G. R., and Morawska, L.: Particle and gaseous emissions from commercial aircraft at each stage of the landing and takeoff cycle, Environ. Sci. Technol., 43, 441–446, 2009.
Mejía, J. F. and Morawska, L.: An investigation of nucleation events in a coastal urban environ-





ACPD
10, 22623–22652, 2010



ment in the Southern Hemisphere, Atmos. Chem. Phys., 9, 7877–7888, doi:10.5194/acp-9-7877-2009, 2009.
Mejía, J. F., Wraith, D., Mengersen, K., Morawska, L.: Trends in size classified particle number concentration in subtropical Brisbane, Australia, based on a 5 year study, Atmos. Environ., 41, 1064–1079, 2007.
Modini, R. L., Ristovski, Z. D., Johnson, G. R., He, C., Surawski, N., Morawska, L., Suni, T., and Kulmala, M.: New particle formation and growth at a remote, sub-tropical coastal location, Atmos. Chem. Phys., 9, 7607–7621, doi:10.5194/acp-9-7607-2009, 2009.
Morawska, L., Bofinger, N. D., Kocis, L., and Nwankwoala, A.: Submicrometer and Supermicrometer Particles from Diesel Vehicle Emissions, Environ. Sci. Technol., 32, 2033–2042, 1998.
Morawaska, L., Ristovski, Z., Jayaratne, E. R., Keogh, D. U., and Ling, X.: Ambient nano and ultrafine particles from motor vehicle emissions: characteristics, ambient processing and implications on human exposure, Atmos. Environ., 42, 8113–8138, 2008.
O'Dowd, C. D., McFiggans, G., Greasey, D. J., Pirjola, L., Hoell, C., Smith, M. H., Allan, B. J., Plane, J. M. C., Heard, D. E., Lee, J. D., Pilling, M. J., and Kulmala, M.: On the photochemical production of new particles in the coastal boundary layer, Geophys. Res. Lett., 26, 1707–1710, 1999.
Olivares, G., Johansson, C., Strom, J., and Hasson, H.-C.: The role of ambient temperature for particle number concentrations in a street canyon, Atmos. Environ., 41(10), 2145–2155, 2007.
Park, K., Park, J. Y., Kwak, J.-H., Cho, G. N., and Kim, J.-S.: Seasonal and diurnal variations of ultrafine particle concentration in urban Gwangju, Korea: observation of ultrafine particle events, Atmos. Environ., 42, 788–799, 2008.
Ristovski, Z. D., Suni, T., Kulmala, M., Boy, M., Meyer, N. K., Duplissy, J., Turnipseed, A., Morawska, L., and Baltensperger, U.: The role of sulphates and organic vapours in growth of newly formed particles in a eucalypt forest, Atmos. Chem. Phys., 10, 2919–2926, doi:10.5194/acp-10-2919-2010, 2010.
Rodríguez, S., Cuevas, E., González, Y., Ramos, R., Romero, P. M., Pérez, N., Querol, X., and Alastuey, A.: Influence of sea breeze circulation and road traffic emissions on the relationship between particle number, black carbon, $PM_1$, $PM_{2.5}$ and $PM_{2.5-10}$ concentrations in a coastal city, Atmos. Environ., 42, 6523–6534, 2008.
Qian, S., Sakurai, H., and McMurry, P. H.: Characteristics of regional nucleation events in urban





ACPD
10, 22623–22652, 2010



East St. Louis, Atmos. Environ., 41, 4119–4127, 2007.
Sinha, P., Hobbs, P. V., Yokelson, R. J., Christian, T. J., Kirchstetter, T. W., and Bruintjes, R.: Emissions of trace gases and particles from two ships in the Southern Atlantic Ocean, Atmos. Environ., 37, 2139–2148, 2003.
Suni, T., Kulmala, M., Hirsikko, A., Bergman, T., Laakso, L., Aalto, P. P., Leuning, R., Cleugh, H., Zegelin, S., Hughes, D., van Gorsel, E., Kitchen, M., Vana, M., Hõrrak, U., Mirme, S., Mirme, A., Sevanto, S., Twining, J., and Tadros, C.: Formation and characteristics of ions and charged aerosol particles in a native Australian Eucalypt forest, Atmos. Chem. Phys., 8, 129–139, doi:10.5194/acp-8-129-2008, 2008.
Vehkamäki, H., Dal Maso, M., Hussein, T., Flanagan, R., Hyvärinen, A., Lauros, J., Merikanto, P., Mönkkönen, M., Pihlatie, K., Salminen, K., Sogacheva, L., Thum, T., Ruuskanen, T. M., Keronen, P., Aalto, P. P., Hari, P., Lehtinen, K. E. J., Rannik, Ü, and Kulmala, M.: Atmospheric particle formation events at Värriö measurement station in Finnish Lapland 1998-2002, Atmos. Chem. Phys., 4, 2015–2023, doi:10.5194/acp-4-2015-2004, 2004.
Weber, R. J., Moore, K., Kapustin, V., Clarke, A., Mauldin, R. L., Kosciuch, E., Cantrell, C., Eisele, F., Anderson, B., and Thornhill, L.: Nucleation in the equatorial pacific during PEM-tropics B: Enhanced boundary layer $H_2SO_4$ but no particle production: NASA global tropospheric experiment Pacific Exploratory Mission in the tropics phase B, Part 1: Measurement and analyses (PEM-Tropics B), J. Geophys. Res., 106, 32767–32776, 2001.
Woo, K. S., Chen, D. R., Pui, D. Y. H., and McMurry, P. H.: Measurements of Atlanta aerosol size distributions: observations of ultrafine particle events, Aerosol Sci. Techn., 34, 75–87, 2001.





ACPD
10, 22623–22652, 2010



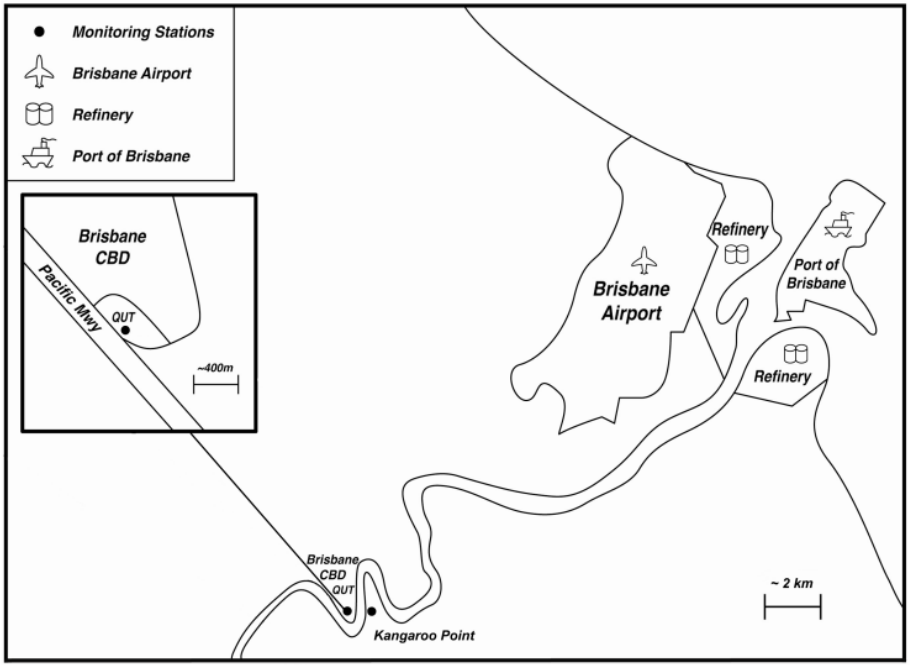


**Fig. 1.** Map of Brisbane.





ACPD
10, 22623–22652, 2010



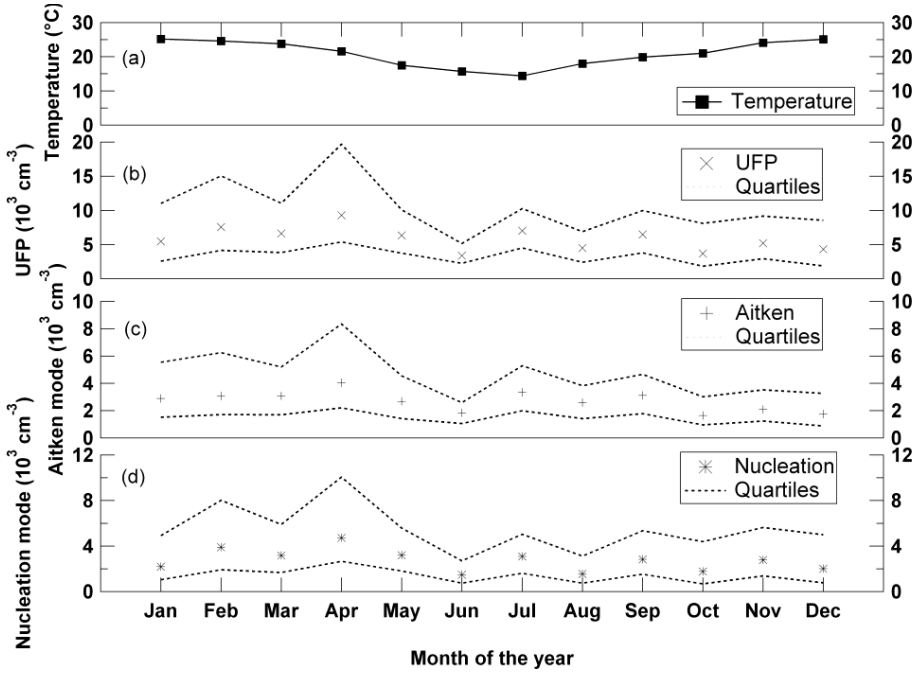


**Fig. 2.** Monthly variations of **(a)** mean temperature, **(b)** particle number concentration of ultrafine (UFP), **(c)** Aitken mode, and **(d)** nucleation modes particles. The median number concentrations and 1st and 3rd quartiles are presented.





ACPD
10, 22623–22652, 2010



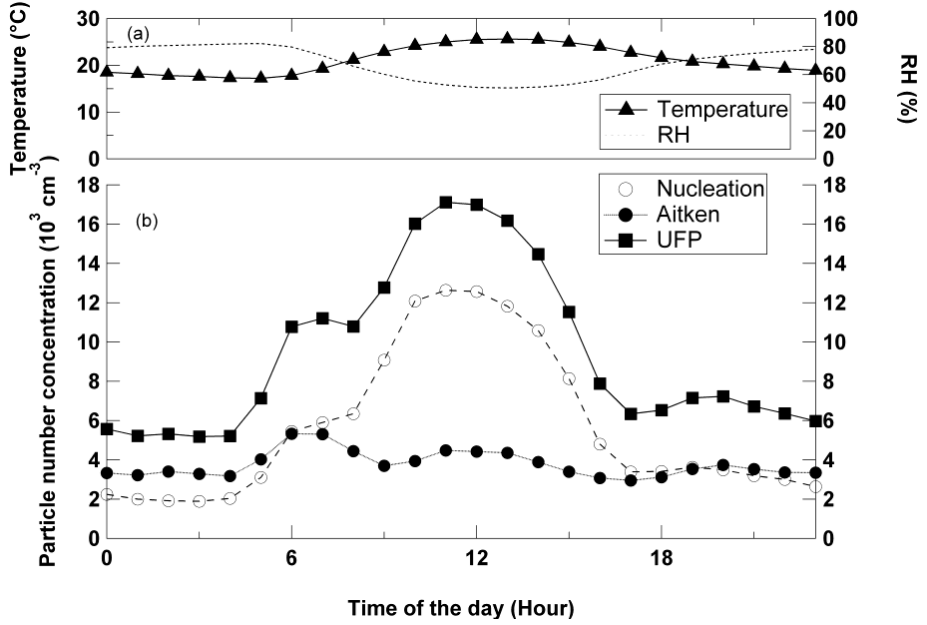


**Fig. 3.** Diurnal variation of **(a)** averaged temperature and RH and **(b)** averaged UFP, nucleation mode and Aitken mode particle concentrations.





ACPD
10, 22623–22652, 2010



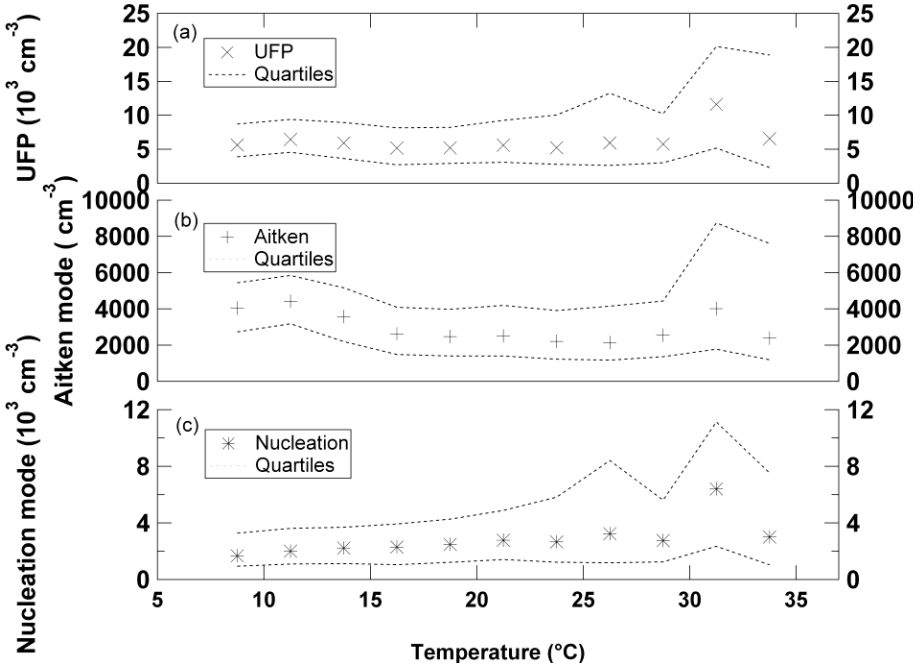


**Fig. 4.** Particle number concentrations of **(a)** ultrafine (UFP), **(b)** Aitken mode, and **(c)** nucleation mode particles and their variation as a function of temperature. The median number concentrations and the 1st and 3rd quartiles are presented.





ACPD
10, 22623–22652, 2010



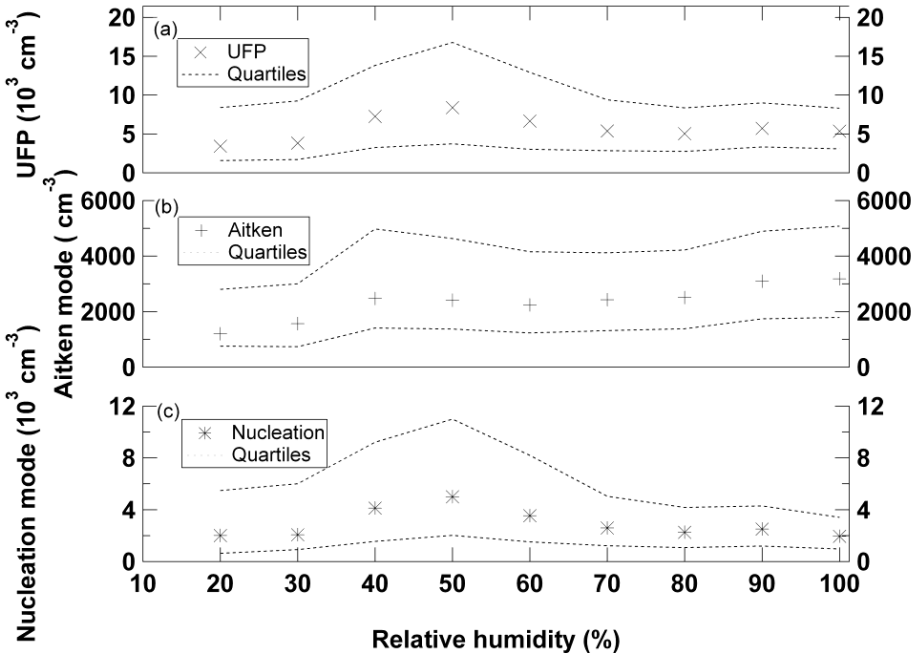


**Fig. 5.** Number concentrations of **(a)** ultrafine (UFP), **(b)** Aitken mode, and **(c)** nucleation mode particles and their variation as a function of relative humidity. The median number concentrations and the 1st and 3rd quartiles are presented.





ACPD
10, 22623–22652, 2010



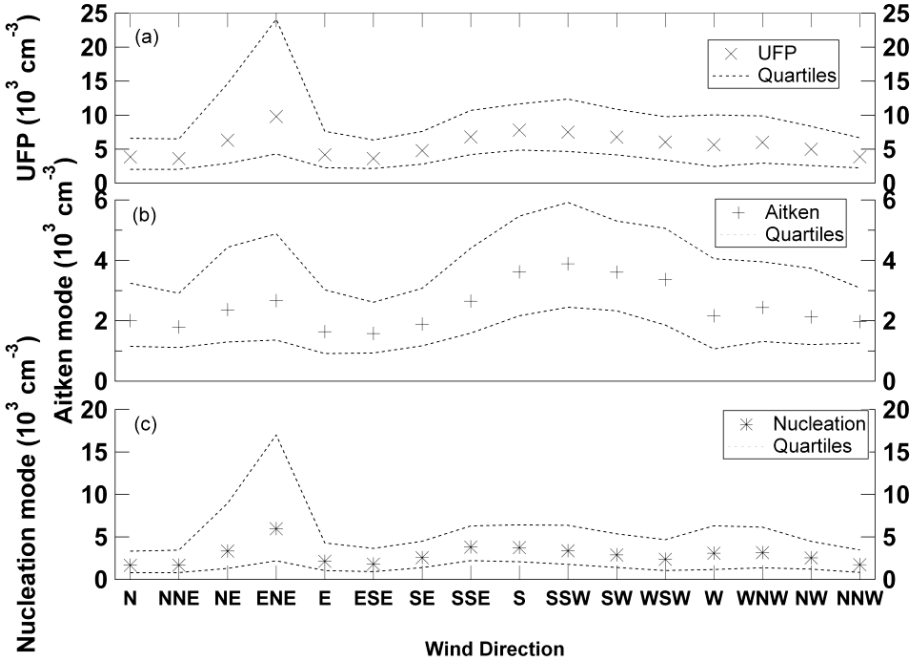


**Fig. 6.** Number concentration of **(a)** ultrafine (UFP), **(b)** Aitken mode, and **(c)** nucleation mode particles and their variation as a function of wind direction. The median number concentrations and the 1st and 3rd quartiles are presented.





ACPD
10, 22623–22652, 2010



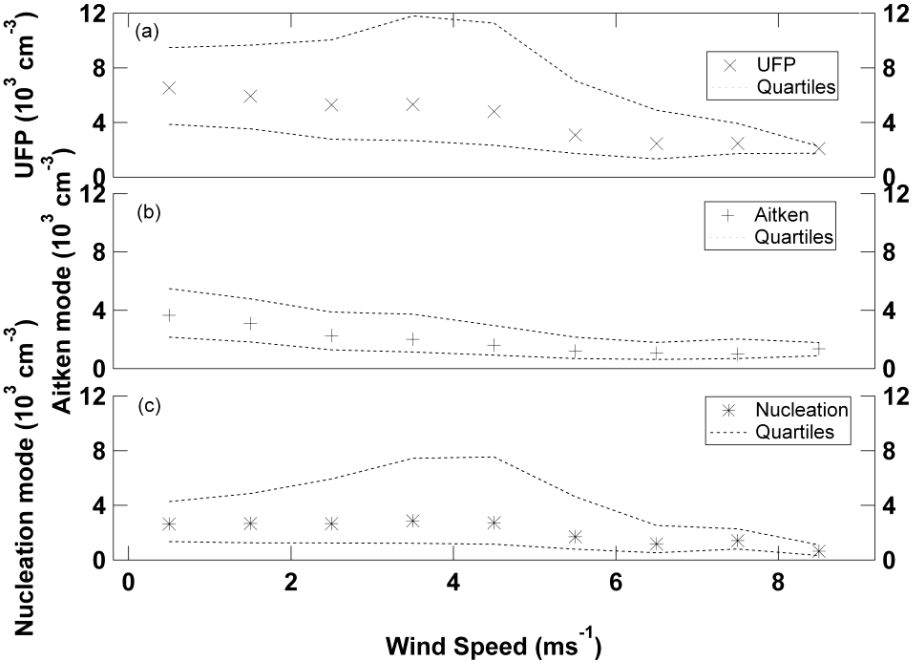


**Fig. 7.** Number concentration of **(a)** ultrafine (UFP), **(b)** Aitken mode, and **(c)** nucleation mode particles and their variation as a function of wind speed. The median number concentrations and the 1st and 3rd quartiles are presented.





ACPD
10, 22623–22652, 2010



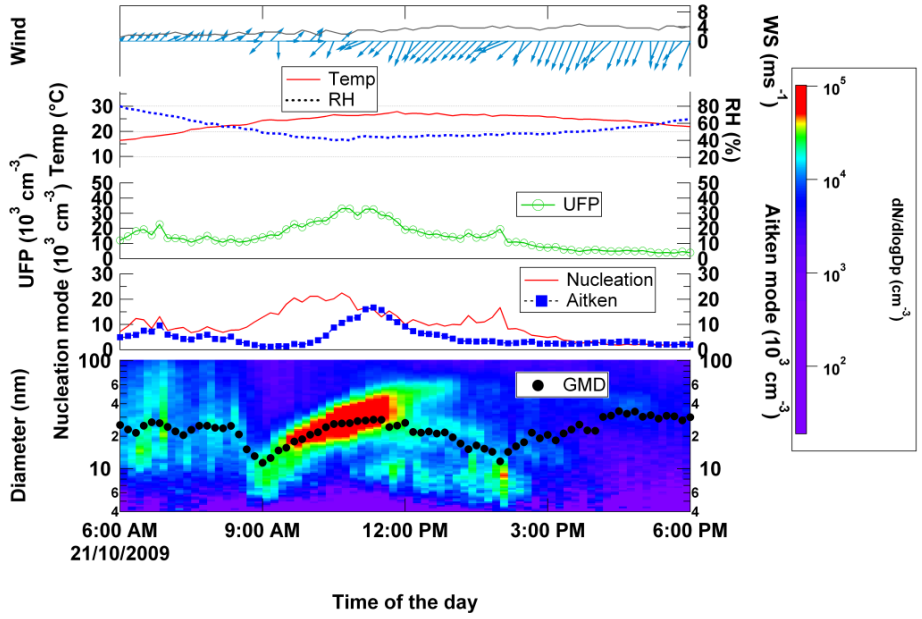


**Fig. 8.** The time series of nucleation events observed at QUT on 21 October 2009. From bottom to top, the parameters are: i) Geometric median diameter (GMD) and contour plot of size distribution; ii) Particle number concentration of nucleation and Aitken mode particles; iii) Particle number concentration of ultrafine particles (UFP); iv) Temperature and relative humidity; and v) wind direction and speed.





ACPD
10, 22623–22652, 2010

Particle formation in subtropical urban environment

H. C. Cheung et al.



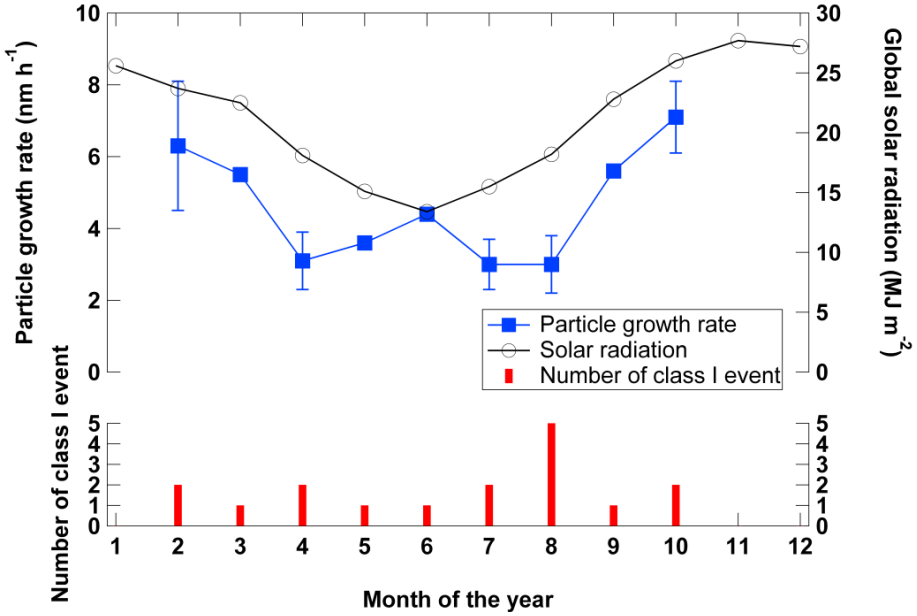


**Fig. 9.** Seasonal variation in particle growth rates and solar radiation.





ACPD
10, 22623–22652, 2010



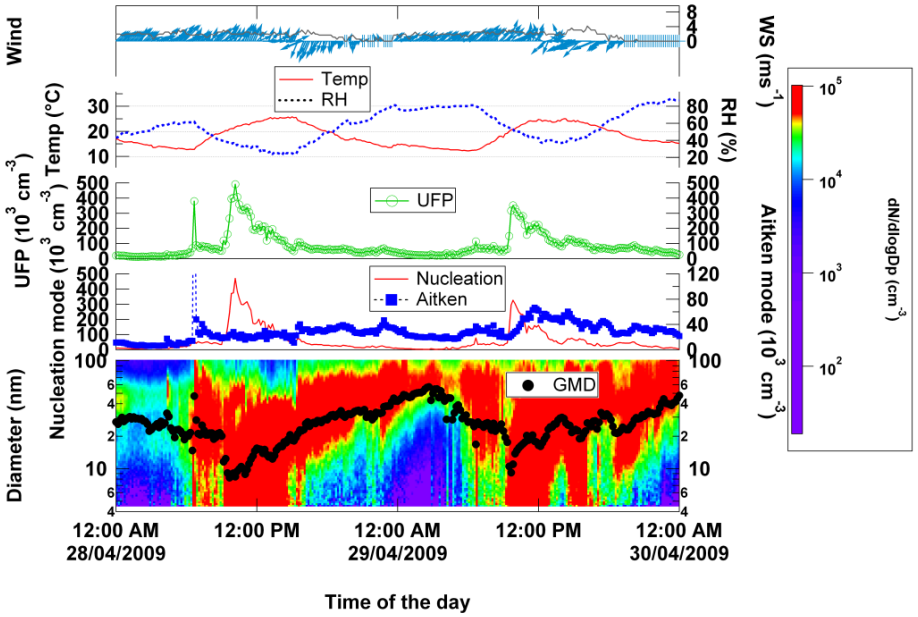


**Fig. 10.** Nucleation events observed on 28–29 April 2009. From bottom to top, the parameters are: i) Geometric median diameter (GMD); ii) Particle number concentration of nucleation and Aitken mode particles; iii) Particle number concentration of ultrafine particles (UFP); iv) Temperature and relative humidity; and v) wind direction and speed.





ACPD
10, 22623–22652, 2010



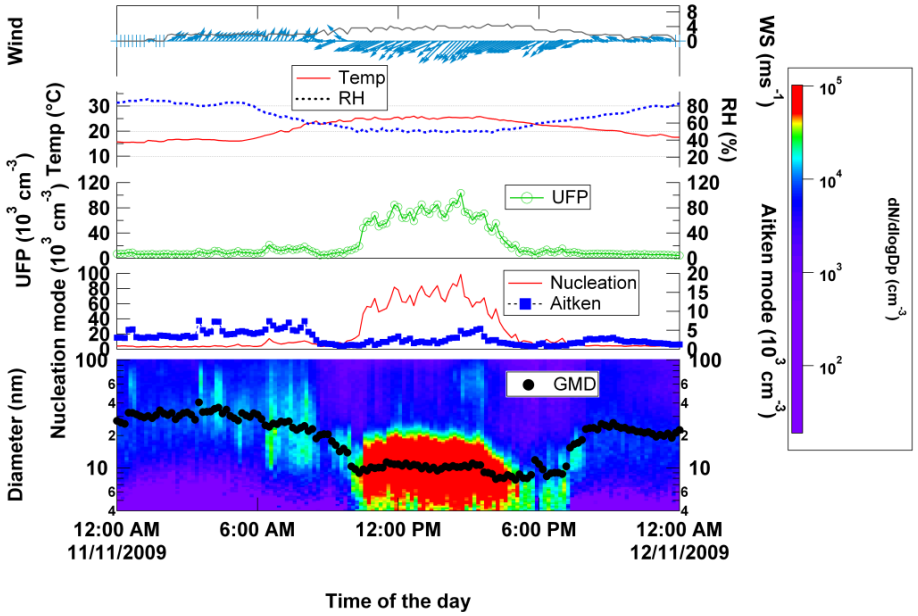


**Fig. 11.** The nucleation bursts measured on 11 November 2009. From bottom to top, the parameters are: i) Geometric median diameter (GMD); ii) Particle number concentration of nucleation and Aitken mode particles; iii) Particle number concentration of ultrafine particles (UFP); iv) Temperature and relative humidity; and v) wind direction and speed.





ACPD
10, 22623–22652, 2010

Particle formation in subtropical urban environment

H. C. Cheung et al.



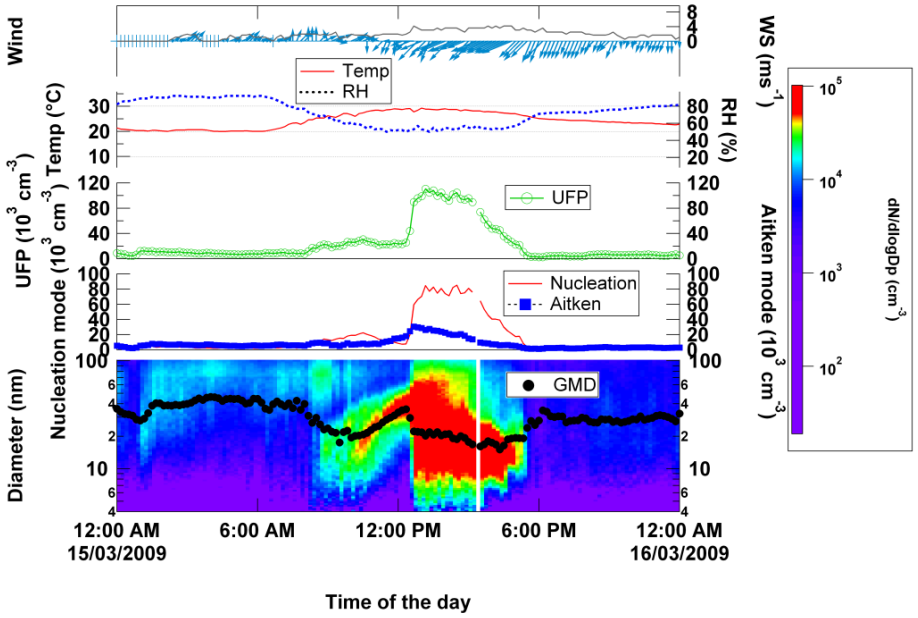


**Fig. 12.** Contour plot of particle size distribution observed on 15 March 2009. From bottom to top, the parameters are: i) Geometric median diameter (GMD) and contour plot of size distribution; ii) Particle number concentration of nucleation and Aitken mode particles; iii) Particle number concentration of ultrafine particles (UFP); iv) Temperature and relative humidity; and v) wind direction and speed.





ACPD
10, 22623–22652, 2010