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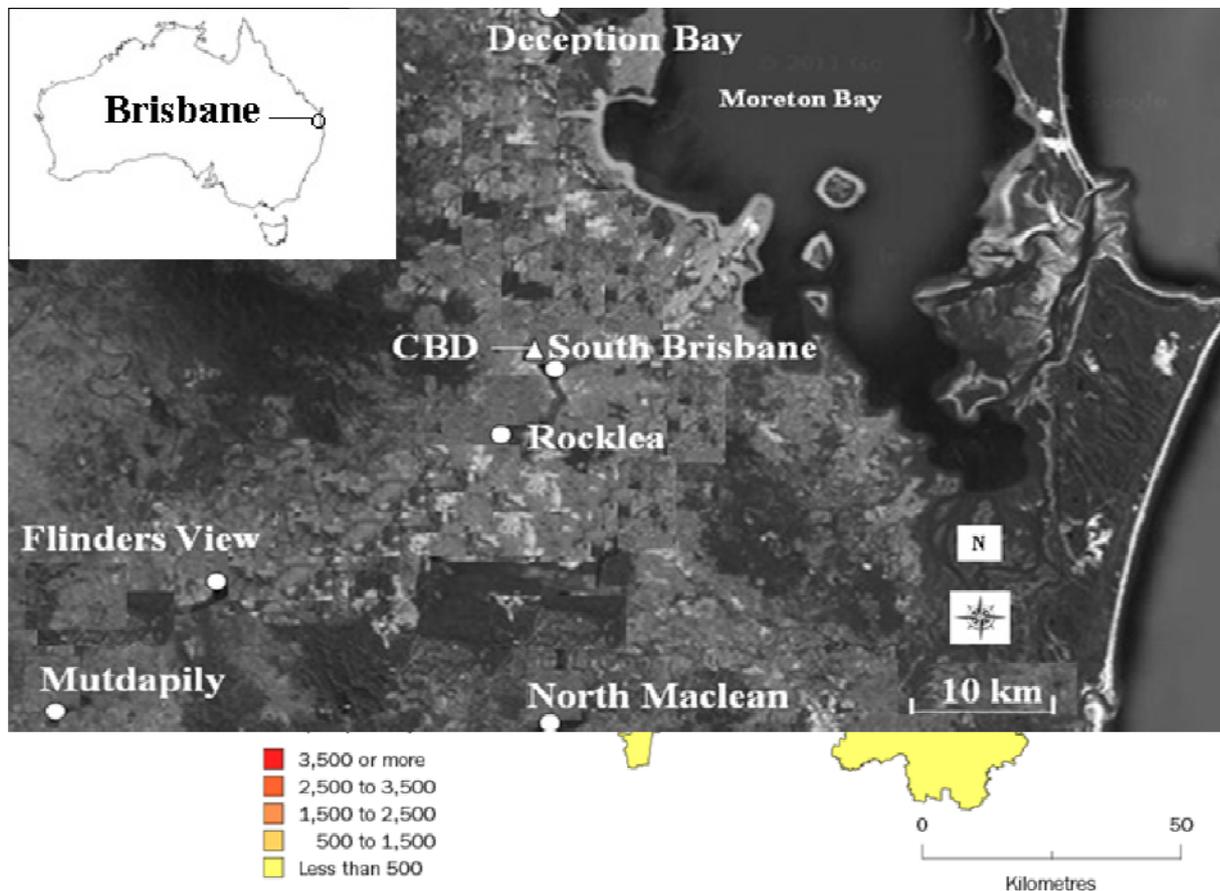
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## Spatial mapping of citywide PBDE levels using an exponential decay model

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## **Abstract**

Passive air samplers (PAS) consisting of polyurethane foam (PUF) disks were deployed at 6 outdoor air monitoring stations in different land use categories (commercial, industrial, residential and semi-rural) to assess the spatial distribution of polybrominated diphenyl ethers (PBDEs) in the Brisbane airshed. Air monitoring sites covered an area ~1143 km<sup>2</sup> and PAS were allowed to accumulate PBDEs in the city's airshed over three consecutive seasons commencing in the winter of 2008. The average sum of five ( $\sum_5$ ) PBDEs (BDEs 28, 47, 99, 100 and 209) levels were highest at the commercial and industrial sites ( $12.7 \pm 5.2$  ng PUF<sup>-1</sup>), which were relatively close to the city center and were a factor of 10 times higher than residential and semi-rural sites located in Outer Brisbane. To estimate the magnitude of the urban 'plume' an empirical exponential decay model was used to fit PAS data vs. distance from the CBD with the best correlation observed when the particulate bound BDE-209 was not included ( $\sum_{5-209}$ ) ( $r^2 = 0.99$ ), rather than  $\sum_5$  ( $r^2 = 0.84$ ). At 95% confidence intervals the model predicts that regardless of site characterization,  $\sum_{5-209}$  concentrations in a PAS sample taken between 4-10 km from the city centre would be half that from a sample taken from the city centre and reach a baseline or plateau (0.6 to 1.3 ng PUF<sup>-1</sup>), approximately 30 km from the CBD. The observed exponential decay in  $\sum_{5-209}$  levels over distance corresponded with Brisbane's decreasing population density (persons/km<sup>2</sup>) from the city center. The residual error associated with the model increased significantly when including BDE-209 levels, primarily due to the highest level ( $11.4 \pm 1.8$  ng PUF<sup>-1</sup>) being consistently detected at the industrial site, indicating a potential primary source at this site. Active air samples collected alongside the PAS at the industrial air monitoring site (B) indicated BDE-209 dominated congener composition and was entirely associated with the particulate phase. This study demonstrates that PAS are effective tools for monitoring citywide regional differences however, interpretation of spatial trends for POPs which are predominantly associated with the particulate phase such as BDE-209, may be restricted to identifying 'hotspots' rather than broad spatial trends.

## ***Introduction***

*Polybrominated diphenyl ethers (PBDEs) have been used globally as flame retardants in many products including computers, electronic equipment, automobiles, plastic products and textiles. The listing of commercial*

*pentabromodiphenyl ether (penta-BDE) and octabromodiphenyl ether (octa-BDE) as persistent organic pollutants (POPs) under the Stockholm Convention has led to their gradual phasing out of production and reduction in use in many countries. For example, Australia ceased importations of the penta-BDE and octa-BDE in mid 2000.<sup>1</sup> However, widespread release to the atmosphere may still occur through volatilization of PBDEs from existing products such as electronic equipment and furniture containing PBDEs.<sup>2-4</sup> Currently no restrictions are in place for imported products to Australia which may contain PBDEs, although it is expected with ongoing international regulatory activity that there will be a gradual decline in the quantities of these chemicals imported in articles.<sup>5</sup> Additional large-scale industrial releases to the atmosphere and broader environment can also occur during recovery and recycling operations of high turnover consumer products containing PBDEs, such as computers and automobiles.<sup>6,7</sup> Regulatory restrictions on penta-BDE and octa-BDE have seen a large decline in their use however, no such restrictions are currently in place for the commercial decabromodiphenyl ether (deca-BDE) mixture. The U.S. Environmental Protection Agency (EPA) recently issued support for phase-out of deca-BDE as well, following commitments from the principal manufacturers and importers to phase-out use by December 31, 2013.<sup>8</sup>*

A key regulatory response by many countries is to monitor PBDEs in the atmosphere, as well as other media, to establish background levels and monitor temporal changes. Knowledge of spatial variation on a smaller scale, particularly of source regions also provides a valuable input for understanding transport and fate processes. Although high-volume active air samplers (AAS) are a conventional tool for POPs sampling in air, they are increasingly being complemented by passive air samplers (PAS) which are cost-effective and simple tools that provide time-integrated estimates of concentrations of POPs such as PBDEs in air.<sup>9, 10</sup> Another advantage when using PAS is they can be deployed at multiple sites and require no maintenance during deployment, making them ideal for spatial mapping of POPs. For these reasons studies have used PAS to

assess POP variability in ambient air on a national,<sup>11</sup> continental<sup>12, 13</sup> and even global scale.<sup>14-16</sup> Other studies have applied PAS on a meso-scale to identify a PBDE concentration gradient between urban and nearby rural ambient air,<sup>17-19</sup> indicative of a general dispersal and fractionation, similar to that reported for numerous other chemicals. The extent of this concentration gradient however, may not be as large due to the diffuse nature of many PBDE emissions such as indoor environments contaminated with PBDEs exchanging air with outdoors. Brisbane, like all the major Australian conurbations are relatively separate, by comparison with Europe or the USA, which reduces the influence of major trans-airshed pollution from anthropogenic sources. For this reason, they can be considered essentially islands of urbanisation with intimate air contact with nearby farming and forestry areas, ideal for understanding fate processes and distribution of semi-volatile organic compounds (SVOCs) over the local area. The primary aim of this study was to identify if different atmospheric PBDE source types are associated with different land use categories in an urban environment. The performance of the PAS for spatial mapping PBDEs, including the predominantly particulate bound BDE-209 was additionally evaluated using parallel active air sampling.

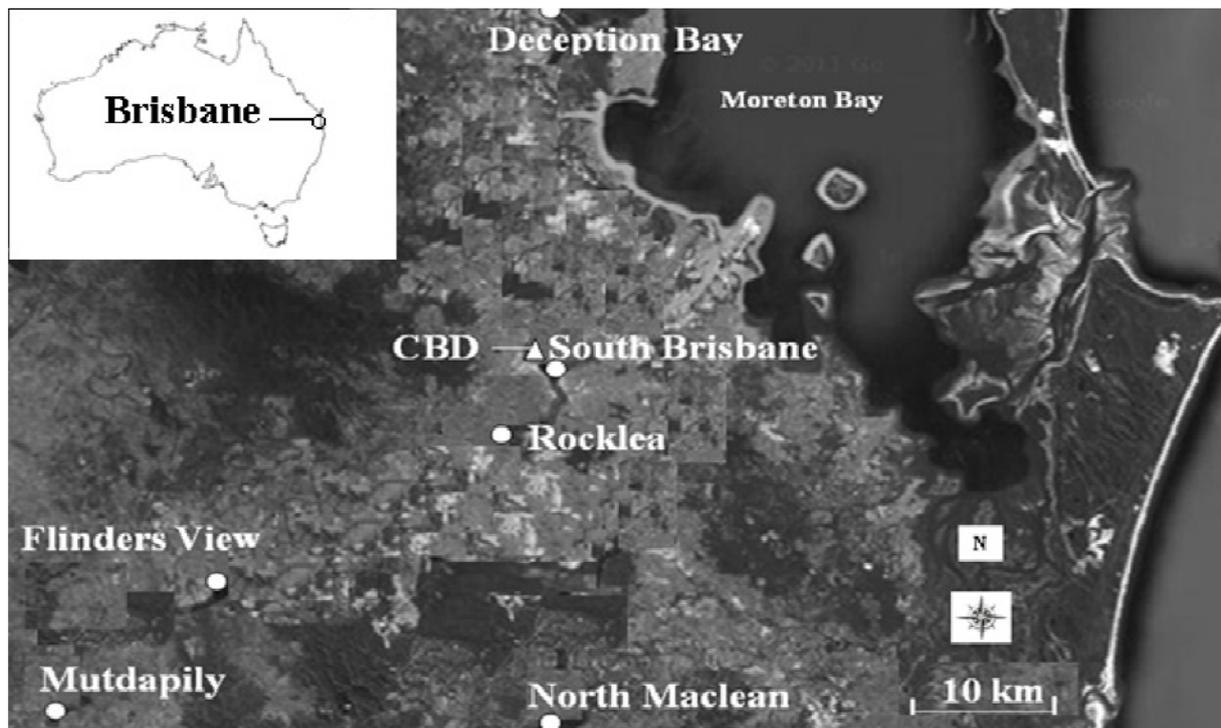
## **Materials and methods**

### **Sampling Sites**

Brisbane is located in the south-east region of Queensland, Australia and has a population of approximately 2.0 million with an extended residential area and a relatively small industrial base. The populated area extends approximately 40 km along the coastline to the north and south of Brisbane, and 35 km to the west, to the city of Ipswich. The Brisbane airshed is located approximately between 27°S to 28°S latitude and 152.5°W to 153.5°W longitude on the east coast of Australia and experiences a typical sub-tropical climate characterized by year-round mild to high temperatures (from 10 to 29 °C) and high rainfalls with an annual average volume of 1150 mm (see ESI Table S1). Presented in Fig. 1 are the six existing Department of Environment and Resource Management (DERM) air monitoring stations which were selected on the basis that each was representative of their surrounding environment (commercial, industrial, residential or semi-rural) and, was a defined distance from the central business district (see Table 1). All stations used in the current study comply with the relevant Australian Standards for the siting of an air monitoring station.

**Table 1** Classification and location of air monitoring sites used in the current study.

Air monitoring site	Area classification	Coordinate reference	Distance from CBD (km)
<b>South Brisbane (A)</b>	Commercial	Lat:- 27.4848 Long: 153.0321	1
<b>Rocklea (B)</b>	Industrial	Lat:- 27.5335 Long: 152.9934	8
<b>Deception Bay (C)</b>	Residential	Lat:-27.1935 Long: 153.0347	31
<b>Flinders View (D)</b>	Residential	Lat:- 27.6528 Long: 152.7745	32
<b>North Maclean (E)</b>	Semi-Rural	Lat:- 27.7708 Long: 153.0302	32
<b>Mutdapily (F)</b>	Semi-Rural	Lat:- 27.7530 Long: 152.6501	50



**Fig. 1** Location of air monitoring sites in relation to CBD used for three seasonal integration periods for deployment of PAS – winter, 2008; winter, 2009 and summer 2009-2010.

The commercial air monitoring site, South Brisbane (A) is approximately 1 km from the central business district (CBD) or city center of Brisbane and typical of the inner city suburbs which have much higher population density than regions further from the city center.<sup>20</sup> The industrial

site (B) is located within one of Brisbane's two main industrial regions, approximately 8 km SW of the CBD and contains a combination of light, general, heavy and extractive industry (see ESI Fig. S1). The site is situated in an open area of the former Department of Primary Industries Animal Husbandry Research Farm and is ~1 km from the nearest industrial or residential area. Two air monitoring sites were selected as representative of a residential environment; Deception Bay (C), located on the foreshore of Deception Bay and Flinders View (D), located inland 30 km SW of the CBD. Semi-rural sites were represented by North Maclean (E) and Mutdapilly (F), approximately 32 km S and 50 km SW of the CBD respectively, and both are surrounded by large tracts of rural land.

### **Sampling Methods - PAS**

PAS consisting of polyurethane foam (PUF) disks were deployed at each site over three periods: winter of 2008 (26 June – 5 August; 40 days), winter-spring 2009 (16 June – 15 October; 121 days) and in the summer of 2009 – 2010 (8 December, 2009 – 4 March, 2010; 86 days). PUF disks (Tisch Environmental TE – 1014; Area =  $3.62 \times 10^{-2} \text{ m}^2$ ; Volume =  $1.95 \times 10^{-4} \text{ m}^3$ ; Sampler density =  $2.36 \times 10^4 \text{ g m}^{-3}$ ) were installed in a stainless steel sampling chamber (“flying saucer” design). The chamber protects the PUF disks from precipitation and ultra-violet –radiation, prevents the sampling of coarse particles, and helps diminish the influence of wind speed on uptake rates.<sup>21</sup> In the initial winter (2008) PAS deployment, two PUF disks were installed in a single chamber at each air monitoring site to assess reproducibility and the analytical error associated with PUF disks. Because results from this first PAS deployment for PAS reproducibility were considered satisfactory, only single PUF disks were installed in each chamber in the following winter-spring (2009) and summer (2009 – 2010) sampling periods. In the final summer (2009 – 2010) sampling period we also co-deployed a second PAS at the industrial air monitoring site because of the high BDE-209 level detected in the winter-spring (2009) PAS deployment. The second PAS was an identical chamber with a single PUF disk installed which was attached to a freestanding tower, approximately 200 metres from the actual air monitoring station (B). This PAS was used to eliminate any potential confounding factors associated with the air monitoring site itself as has previously been reported.<sup>22</sup> PAS chambers were attached to brackets and secured to the safety rails on the roof of the outdoor air monitoring

stations ~3 m in height. PUF disks were pre-extracted using accelerated solvent extraction (ASE) (Dionex, 300) with acetone and hexane (20/80 v/v). They were dried under a stream of nitrogen and stored in cleaned amber glass jars prior to field deployment. At the time of sampling PUF disks were transferred from sample jars to the sampling chamber using gloves. After sampling the PUF disks were placed in their original containers and stored at temperatures below 5 °C until extraction.

## **AAS**

A low-volume AAS was co-deployed alongside the PAS at the industrial air monitoring site (B) in the final summer (2009 – 2010) sampling period. Air samples were collected using a filter-adsorbent active sampling system consisting of a glass fibre filter paper (Whatmann 90mm (GF/A Cat No 1920090)) to collect particle associated PBDEs and a glass cartridge filled with two PUF plugs (length 4.0 cm, diameter 3.5 cm, density 0.026 g cm<sup>-3</sup>) to collect vapor phase PBDEs. The two PUF plugs placed within the glass cartridge were in series with the second PUF plug used to assess any breakthrough of gas-phase. This cartridge was attached to a low volume pump (Gardner Denver V – VTE3) and a gas meter to determine the volume of air sampled. The sampler inlet (~1.5 m high) was oriented vertically upwards with all particle sizes able to be sampled. No bias in particle size collected and by association, POPs associated with different particle size ranges, is therefore expected. The AAS was deployed approximately 3 m from the actual air monitoring station. The first active air sample (748 m<sup>3</sup>) was collected between 15 – 29 January, 2010 and the second active air sample (712 m<sup>3</sup>) was between 6 – 19 February, 2010 with the average hourly sampling rate for both sampling periods approximately 2.2 m<sup>3</sup> h<sup>-1</sup>. Prior to sampling, the filter papers were rinsed with acetone and placed in a furnace at 450 °C for 24 h. Once removed, they were placed in foil envelopes that were previously rinsed with acetone. PUF plugs were pre-extracted using the same method described for PUF disks and stored in cleaned amber glass jars prior to field deployment. All glassware was pre-cleaned, rinsed with acetone and wrapped in foil for transport to the sampling site.

## **Sample analysis**

All samples were spiked with internal standard (<sup>13</sup>C<sub>12</sub>BDEs-28, 47, 99, 153, 154, 183, 197, 207 and 209; Wellington Isotope Laboratories, Canada) prior to extraction. The GMFs, PUF plugs and PUF disks were then extracted by ASE using hexane/toluene (80/20 v/v) and the extracts

purified using acid silica (40% w/w) columns, topped with anhydrous Na<sub>2</sub>SO<sub>4</sub>. BDE-138 was added to samples as the recovery standard immediately prior to analysis by high resolution mass spectrometry (HRMS) (HP 5890 II GC coupled to a VG AutoSpec mass spectrometer; splitless injection; injector temperature 320 °C). The lighter PBDE congeners (BDE-17, -28, -47, -49, -66, -71, -77, -85, -99, -100, -119, -126, -138, -153, -154, -156, -184, -183 and -191) were separated on a Rxi®-1ms column (20 m × 0.18 mm id, 0.18 mm film thickness) with ultra-high purity helium carrier gas; flow rate 1.0 mL min<sup>-1</sup>; temperature program 100 °C for 1 min, 30 °C min<sup>-1</sup> to 200 °C, 30 °C min<sup>-1</sup> to 350 °C and 350 °C for 1 min; total run - time 16 min. The larger molecular weight congeners (BDE-197, 196, 207, 206 and -209) were separated on a Zebron Inferno ZB – 5 HT (5.0 m × 0.25 mm id, 0.1 mm film thickness) flow rate 1.0 mL min<sup>-1</sup>; temperature program 180 °C for 1 min, 10 °C min<sup>-1</sup> to 200 °C, 20 °C min<sup>-1</sup> to 300 °C; total run - time 8 min. The mass spectrometer operating conditions were: ion source and transfer line temperatures 340 °C and 360 °C respectively; ionisation energy 38 eV; electron multiplier voltage set to produce a gain of 10<sup>6</sup>. Resolution was maintained at 5000 (10% valley definition) throughout the sample sequence. Selective Ion Monitoring (SIM) experiments were performed in the electron impact mode with monitoring of the exact masses of appropriate ions for native and labeled compounds. Individual congeners were identified using the GC retention time and ion abundance ratios with reference to internal standards. Criteria used for positive identification and quantification were: (i) retention time within 1 s of the retention time of corresponding <sup>13</sup>C internal standard; (ii) ion ratio ± 20% of the theoretical ion ratio; (iii) signal to noise ratio greater than 3:1. The quantification was performed by means of internal/external standards (isotope dilution).

### **Quality Control**

QA/QC samples included replicate solvent, GMF and PUF disk and plug field and laboratory blanks. The field blank samples were prepared and transported to the sites for each deployment but not exposed and analyzed in the same way as the samples. There was no detectable difference between PBDE levels in the laboratory and field blanks, indicating contamination was negligible during transport and storage. The mean blank concentrations were calculated from the levels detected in both the field and laboratory blanks. The limits of detection (LOD) were defined as the average level in blanks + 3 standard deviations. Blank sampling media (*i.e.* PUF plugs, GMFs and PUF disks) had detectable contamination by congeners BDE-47, BDE-99 and

BDE-209 with the highest level of contamination occurring in the larger volume PUF disks used for PAS. The mean ( $n = 7$ ) blank PUF disk contamination for the sum of congeners BDE-47, -99 and -209 was  $0.5 \text{ ng PUF}^{-1}$  which was 9.8% of the mean PBDE level ( $5.1 \pm 5.8 \text{ ng PUF}^{-1}$ ) detected in PUF disks deployed in the field. Due to the relatively low blank contamination the data has not been blank corrected. Instrument detection limits (IDLs) for the various congeners ranged between ( $5 \text{ pg } \mu\text{l}^{-1}$  and  $25 \text{ pg } \mu\text{l}^{-1}$ ) with the least sensitivity observed for BDE-209. The  $s/n$  ratios for the lowest standards were between 3 and 10. Standards were analyzed at the beginning and end of sample analysis and samples were re-analyzed if the value of standards deviated by  $>10\%$  for the real value. Additional tests for internal standard recoveries were assessed by the use of PUF media and solvent spikes. To elaborate, one PUF disk was spiked with  $10 \mu\text{l}$  of the PBDE calibration mixture and another PUF disk spiked with  $20 \mu\text{l}$  of the  $^{13}\text{C}_{12}$  surrogate mixture. PUF disks were then treated exactly as samples. Solvents spikes were performed in a similar way by spiking these two solutions into  $0.5 \text{ ml}$  toluene and running through the analytical method. Recoveries of PBDEs in this study were between 68 – 84 % in all samples.

### **Modeling spatial distributions of PBDEs**

GraphPad Prism 5 was used to develop an empirical exponential decay model (average amount accumulated in PAS vs. distance from the CBD, using the data acquired from each air monitoring site across three different deployment periods between June 2008 and March 2010. The model performance was assessed in terms of the correlation coefficient ( $r^2$ ) and the absolute sum of squares.

## **Results and Discussion**

### **Determining the error in the analytical method**

In the initial PAS deployment in winter (2008) we installed replicate PUF disks at each monitoring site to determine reproducibility of PAS data. Although 24 PBDE congeners were analyzed for, BDE-28, -47, -99, -100 and -209 were the most consistently detected in the PAS and combined, represented  $\sim 98\%$  of congener composition. Therefore, analysis of PBDE levels for the remainder of this paper is restricted to either the sum of congeners BDE-28, -47, -99, -100 and -209 ( $\sum_5$ ) or exclusive of BDE-209 ( $\sum_5-209$ ). We will also focus on mass ( $\text{ng PUF}^{-1}$ ) to exclude the uncertainty in the sampled volume from the discussion. Presented in Fig. 2 is the

mean and standard deviation of  $\Sigma_5$ -209 concentrations in replicate PUFs deployed in 2008 at each of the monitoring sites. No replicate analysis for BDE-209 levels was possible due to a lack of instrument sensitivity in 2008. Subsequent modifications to the interface of HRGC-HRMS however, enabled the analysis of BDE-209 to be included in 2009 and 2010 samples. Analysis of replicate PAS data including BDE-209 was undertaken in the final summer (2009 – 2010) sampling period and is discussed later in the paper.

**Fig. 2** Variability in the  $\Sigma_5$ -209 levels (ng PUF<sup>-1</sup>) detected in replicate PUF disks installed in the same chamber and deployed at different air monitoring sites between 26 June – 5 August, 2008 (40 days). Presented are the mean and the standard deviation for replicate PUF disks.

To evaluate the variability in the  $\Sigma_5$ -209 levels (ng PUF<sup>-1</sup>) between replicate PUF disks (*i.e.* PUF disks installed in the same chamber) we calculated the % relative standard deviation (%RSD). Due to the very low PBDE levels at rural and residential sites the average %RSD between PUF disks was elevated (38%). As  $\Sigma_5$ -209 levels increased in PAS, the associated %RSD between PUF disks reduced with the %RSD at the commercial site 15%. The %RSD between air monitoring sites was 90%. Linear regression analysis of the  $\Sigma_5$ -209 levels in replicate PUF disks provided a standard error of regression of 1.0 ng PUF<sup>-1</sup> and indicates PAS are suitable for capturing differences in PBDE levels across multiple locations in Brisbane. Full statistical analysis of replicate PUF disks is provided in Supporting Information (see ESI Table S2 and S3).

### **Passive air samples – data for three consecutive seasons**

The  $\Sigma_5$  amounts accumulated in the PUF disks ranged between 0.8 and 16.4 ng PUF<sup>-1</sup>. Sample congener composition was dominated by BDE-209, BDE-47 and BDE-99 with the average BDE-209 level representing ~68 % of the  $\Sigma_5$  mass when detected in the PAS. BDE-47 was the only congener detected in every PAS for each sampling period. As shown in Fig. 3 the more atmospherically mobile PBDE congeners BDE-47 and BDE-99 demonstrate a gradual decrease in levels as each air monitoring site's distance increases from the CBD. In contrast, the BDE-209 levels in PAS were highest at the industrial site (B), rather than the commercial site (A). The

complete PAS dataset and associated QA/AC values for all three sampling periods is presented in Supporting Information (see ESI Table S4).

**Fig. 3** Comparison of the levels ( $\text{ng PUF}^{-1}$ , mean  $\pm$  standard deviation) of the five main PBDEs detected in air at each air monitoring site. BDE-209 data consists of 2 sampling periods only; winter, 2009 and summer, 2009 – 2010.

Analysis of sample congener composition (see Fig. 4) indicates the commercial (A), industrial (B) and residential (C) sites were different due to the relatively large contribution by BDE-209 which was consistently highest at the industrial site ( $11.4 \pm 1.8 \text{ ng PUF}^{-1}$ ). The only other site where BDE-209 was detected in both sampling periods was the commercial site (A) ( $5.9 \pm 6.4 \text{ ng PUF}^{-1}$ ).

**Fig. 4** Comparison of percent contributions of individual congeners to  $\sum_5\text{PBDE}$  concentrations ( $\text{ng PUF}^{-1}$ ).

The general increased variability of BDE-209 was attributed to its exclusive partitioning to the particulate phase. While PAS sample or ‘trap’ aerosols (and hence particle associated POPs) they are subject to increased variability, depending on the profile of the particle load at an air monitoring site.<sup>23,24</sup> For example, Klanova et al.<sup>23</sup> reported that sampling rates of relatively high molecular weight PAHs were found to be reduced to  $\sim 10\%$  of gas phase POPs when coarser aerosols dominated air sampling sites. This finding is particularly relevant for studies which use PAS in urban settings where particle loads may be significantly different between air monitoring sites within the same geographical region, as has previously been identified in Brisbane.<sup>25,26</sup>

### **Assessing the urban and rural gradient**

To investigate the spatial characteristics of urban PDDE levels in Brisbane, an empirical exponential decay model was used to fit the PAS data for  $\sum_5\text{-209}$  concentrations ( $\text{ng PUF}^{-1}$ ) as a function of a site’s distance from the CBD (see Fig. 5). At 95% confidence intervals, the model predicts that regardless of site characterization,  $\sum_5\text{-209}$  concentrations in a PAS sample taken 4-

10 km from the city centre would be half that from a sample taken at the city centre. A baseline or plateau concentration (0.6 to 1.3 ng PUF<sup>-1</sup>) would be reached approximately 30 km from the city center. Complete model results are provided in Supporting Information (see ESI Table S5 and S6). This finding is similar to that from another study in the West Midlands of the UK<sup>19</sup> that reported PBDE concentrations clearly decreased with increasing distance from the city center, supporting the existence of an urban “pulse”. They hypothesized that the high density of indoor environments contaminated with PBDEs due to usage of, for example, furnishings and electronic goods in urban areas, resulted in significant emissions when these sources exchange air with the external environment.<sup>19</sup>

**Fig. 5** Exponential decrease in average  $\sum_5$ -209 concentrations (ng PUF<sup>-1</sup>) in PAS as a function of a sites distance from the center of the city. Data was combined from all 3 sampling periods: winter, 2008; winter, 2009 and summer, 2009 – 2010 to construct the model.

To further investigate the spatial characteristics of the urban PBDE footprint, concentration data were related to Brisbane’s population density (persons km<sup>-2</sup>). Generally, population density is correlated with the distance from the CBD. However, the magnitude of the population density gradient may provide additional insight into the observed PBDE concentration gradient. Inner Brisbane covers a combined area of ~200 km<sup>2</sup> and extends 8 km from the CBD (see ESI Fig. S2 and Table S7). The PBDE gradients are consistent with the population density gradient between both regions and support the exponential decay observed in the model. This suggests the population density gradient will characterize the magnitude of a city’s PBDE plume provided there are no PBDE sources external to the region influencing observed concentrations and no significant point sources within.

To illustrate the latter caveat, inclusion of BDE-209 (*i.e.*  $\sum_5$  totals) in concentration data profiles assessed by the model decreases the significance of the correlation ( $r^2 = 0.84$ ). In addition, the residual error, described by the absolute sum of squares, increases from 0.1 to 28.5. This is a result of the highest BDE-209 level being consistently detected at the industrial site (B) and the large inter-seasonal variation in BDE-209 levels at the commercial (A) and the residential site (D). Whether the predominantly particulate bound BDE-209 follows the same spatial distribution

as the more atmospherically mobile congeners or, is of industrial origin is still unclear, due to the close proximity of these air monitoring sites (*i.e.* Commercial (A) and Industrial (B)) in the study area. In addition, PAS devices are not designed to sample POPs primarily associated with the particulate phase and a more accurate interpretation of the local spatial distribution of BDE-209 would require additional active air sampling.

Previous studies investigating source-receptor relationships within an urban environment and using high-volume AAS have indentified industrial areas as potential source regions which may influence surrounding areas.<sup>27-30</sup> Fugitive PBDE emissions from large industrial point sources are different from diffuse non-point sources, due to the associated kinetic energy during release. Perhaps more importantly, energetic industrial processes may release larger molecular weight congeners,<sup>6, 30</sup> that due to their larger octanol-air partition coefficients ( $K_{OA}$ ) and lower vapor pressures, are restricted in their atmospheric transport to primarily the particulate phase. This in turn may limit the distance they travel from a source site compared to vapour phase material. PBDEs attached to relatively large 10 – 20  $\mu\text{m}$  particles (10 – 20  $\mu\text{m}$  in aerodynamic diameter), are predicted to travel only over modest distances (approximately 5 – 50 km) due to their relatively short atmospheric lifetimes – of the order of minutes to hours.<sup>31</sup> A key industry in the industrial region monitored in this study is a large automotive shredding and metal recycling facility, which is located approximately 1.8 km to the south of the industrial air monitoring station (B) in this study. During the highly energetic shredding process of automobiles, PBDEs are released to air which may contaminate the local area, particularly with BDE-209.<sup>6</sup> The way in which such industrial emissions, particularly heavier congeners that are predominantly associated with the particulate phase, behave and move in the local area and broader city airshed is poorly understood but clearly such sites influence the local air quality.

### **Low-volume active air samples**

As indicated in Table 2 the lower molecular weight (MW) species were exclusively captured in the gas phase (e.g. BDE-28 and -47). The PBDE contents in the second plug were below the LOD for all congeners. The  $\Sigma_5$  concentrations in the gas phase (*i.e.* associated with the PUF plug in active samples) ranged between 3.1 and 4.1  $\text{pg m}^{-3}$  and were dominated primarily by BDE congeners 28, 47 and 99. Congeners BDE-99 and BDE-209 were the only PBDEs detected in the particulate phase (*i.e.* on the GMFs) and concentrations ranged between 2.8 and 7.0  $\text{pg m}^{-3}$ . The

ratio of BDE-99 associated with the particulate phase was ~37% and BDE-209 was only detected on GMFs. BDE-209 dominated AAS sample composition (48% of the total).

**Table 2** Range of PBDE concentrations ( $\text{pg m}^{-3}$ ) in air at the industrial site (B), collected during the summer 2009 – 2010 sampling period. PBDE partitioning behavior is represented by concentrations ( $\text{ng PUF}^{-1}/\text{GMF}^{-1}$ ).

<b>15-29 January, 2010</b> – (14 days) (air volume sampled – 748 $\text{m}^3$ )	<b>BDE-28</b>	<b>BDE-47</b>	<b>BDE-100</b>	<b>BDE-99</b>	<b>BDE-209</b>	<b><math>\Sigma 5</math></b>
PUF plug ( $\text{ng PUF}^{-1}$ )	0.4	1.8	0.1	0.8	nd	
$\text{pg m}^{-3}$	0.5	2.4	0.1	1.1	na	
GMF (ng $\text{GMF}^{-1}$ )	nd	nd	nd	0.4	4.8	
$\text{pg m}^{-3}$	na	na	na	0.5	6.4	
Bulk (vapor + particulate phase, $\text{pg m}^{-3}$ )	0.5	2.4	0.1	1.6	6.4	
<b>6-19 February, 2010</b> – (13 days) (air volume sampled – 712 $\text{m}^3$ )						

PUF plug (ng PUF <sup>-1</sup> )	0.3	1.3	0.1	0.6	nd	
pg m <sup>-3</sup>	0.4	1.8	0.1	0.8	na	
GMF (ng GMF <sup>-1</sup> )	nd	nd	nd	0.4	1.6	
pg m <sup>-3</sup>	na	na	na	0.6	2.2	
Bulk (vapor + particulate phase, pg m <sup>-3</sup> )	0.4	1.8	0.1	1.4	2.2	5.9
PUF plug Blank	nd	0.1	nd	nd	nd	0.1
GMF blank	nd	nd	nd	nd	nd	nd
LOD	na	0.2	nd	na	na	0.1
Mean recovery(%) - <sup>13</sup> C <sub>12</sub> (PUF plugs)	70.3	80.1	na	70.2	65.6	na
Mean recovery(%) - <sup>13</sup> C <sub>12</sub> (GMFs)	85.7	90.3	na	92.1	87.3	na
IDL (pg/μl)	5	5	5	5	25	na

na-not applicable

nd-non detect

<LOD-less than Limit of Detection - calculated as the mean blank value + 3 standard deviations.

These results are similar to gas-particle partitioning model estimates which predict at 25 °C, similar to the temperatures experienced during active air sample collections, the ratio of BDE-99 and BDE-209 associated with aerosols would be 56 and >99% respectively.<sup>32</sup>

The levels reported in this study are similar to the only previous Australian study,<sup>33</sup> also undertaken in Brisbane, which reported PBDE levels urban air using a similar low-volume AAS technique. In that study  $\sum_{26}$  levels ranged between 1.7 and 6.8 pg m<sup>-3</sup> with congener composition also dominated by BDE-209. Similar levels and the dominance of BDE-209 have been reported in urban air studies from Sweden<sup>34</sup> and Japan.<sup>35</sup> In China, Chen et al.<sup>27</sup> reported that the average  $\sum_{11}$ PBDE concentration in an urban site was as high as 353 pg m<sup>-3</sup> with BDE-209 dominating sample congener composition (>70%). Similarly high PBDE levels were reported in urban areas of the U.S. however, sample congener composition was dominated by BDE-47.<sup>36</sup> This difference may indicate the continued use in the U. S. of the penta-BDE product during the sampling period.

### Comparing PAS and AAS data

Active air samples were deliberately collected over longer time periods (*i.e.* approximately 2 weeks) and at low sampling rates (2.2 m<sup>3</sup> hr<sup>-1</sup>) because this air monitoring station is located in a large industrial region and may be subject to increased variability, due to its proximity of large point sources.<sup>30</sup> In addition, variation in local weather conditions during collection of active air samples may influence PBDE levels, particularly congeners which are associated with the particulate phase.<sup>27,37</sup> As mentioned previously, in any comparison of AAS and PAS derived data, there is uncertainty in the proportion of particles in air which is sampled by the PAS.<sup>22-24</sup> Additionally the AAS and PAS data here were collected over different time periods and hence represent different air masses. These factors notwithstanding, in this work, a comparison of AAS and PAS results indicates each identified the same main PBDE congeners in air and in the same decreasing order of concentration, *i.e.* 209, 47, 99, 28 and 100 (Fig. 7). The high molecular

weight BDE-209 dominated both the AAS and PAS sample congener compositions, comprising 48% and 75% of the totals respectively.

**Fig. 7** Comparison of the PBDE congener composition in AAS and PAS samples collected at the industrial air monitoring site (B).

Our results suggest the general increase in the variability of BDE-209 accumulated in PAS means interpretation of spatial distributions of particulate bound congeners on a local scale should be done with caution. The detection of relatively high levels of BDE-209 at the industrial site by PAS was consistent with data from active samples and appears to be a marker for industrial processes/regions. Although increased variability in sampling rates may reduce the PAS capability to estimate particulate bound PBDE concentrations in urban ambient air, they are still useful tools to identify source regions and concentration variability within an urban environment. Finally the magnitude of the urban plume may be predicted using the average population density and the maximum population density of city assuming the dominate  $\Sigma_5$ -209 emissions are indoor environments exchanging air with outdoors.

### **Acknowledgments**

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## Supplementary Material (ESI)

### Supplementary Information

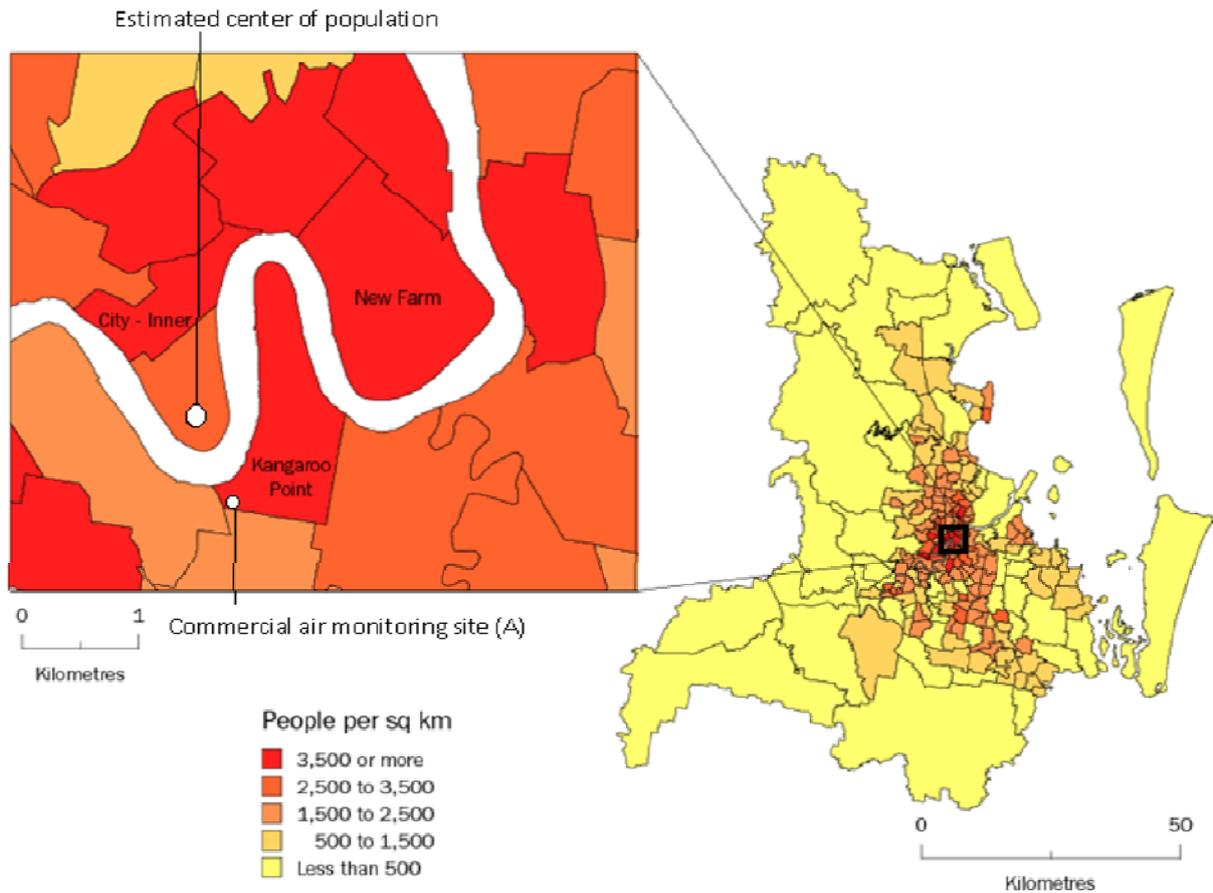
**Figure S1** The location of Brisbane's CBD, the two main industrial regions in Brisbane and, nearby air monitoring sites commercial (A) and industrial (B) used in this study.



Graphic was sourced from the Brisbane City Plan 2000 – Volume 1 Amended 15 April 2011.

Chapter 3, page 39.

**Figure S2** Population spatial distribution map for Brisbane and the calculated center of population for the Brisbane at June 2009. The commercial air monitoring site (A) used in this study is located ~ 1 km from the CBD or estimated center of population.



Graphic accessed at the Australian Bureau of Statistics (ABS) website (13/04/2010)  
<http://www.abs.gov.au/AUSSTATS>

**Table S1** Annual average climate statistics for Brisbane. Data was accessed from the federal Bureau of Meteorology (BOM) website (18/02/2011). <http://www.bom.gov.au>

Climate Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Years (1981-2000)
<b>Temperature</b>														
Mean maximum temperature (°C)	29.2	28.9	27.9	25.9	23.5	20.9	20.5	21.6	23.9	25.5	26.9	28.4	25.3	19
Mean minimum temperature (°C)	21.1	20.9	19.3	16.8	14.3	10.7	9.6	9.9	12.4	15.4	17.8	19.7	15.7	19
Mean temp (°C)	25.2	24.9	23.6	21.4	18.9	15.8	15.1	15.8	18.2	20.5	22.4	24.1	20.5	19
<b>Rainfall</b>														
Mean rainfall (mm)	121.1	159.8	122.3	130.5	129.4	60.4	57.8	40.1	35.3	79.2	97.3	123.8	1158.3	19
<b>Other daily elements</b>														
Mean daily sunshine (hours)	8.5	7.6	7.8	7.2	6.4	7.2	7.3	8.4	8.9	8.5	8.5	8.8	7.9	19
Mean number of clear days	5	4.8	9.5	9.9	8.7	14.1	15.1	16.8	17.4	10.7	6.9	7.4	126.3	19
Mean number of cloudy days	10.7	11.3	9.8	9.7	10.7	7.3	7.4	5.1	4.5	7.8	10.2	9.8	104.3	19
Mean 9am relative humidity (%)	66	69	70	70	74	70	68	63	59	60	61	64	66	19
Mean 3pm relative humidity (%)	60	62	59	59	59	51	50	47	50	56	58	60	56	19
Mean 3pm wind speed (km/h)	21.6	20.9	20	17.8	14.9	15.2	16.2	18.3	21.7	22.5	22.9	22.2	19.5	19

**Table S2** Calculated %RSD values for replicate PUF disks and between air monitoring sites during the winter (2008) sampling period. The  $\sum_5-209$  concentrations (ng PUF<sup>-1</sup>) have been used to calculate the %RSD.

<b>Air monitoring site</b>	<b>%RSD for replicate PUF disks</b>
Rural F	47.1
Rural E	47.1
Residential D	51.4
Residential C	35.4
Industrial B	31.0
Commercial A	14.9
<b>%RSD between monitoring sites</b>	<b>90.0</b>

**Table S3** Linear regression statistics of replicate PUF disks deployed during the winter (2008) sampling period. The  $\sum_5-209$  concentrations (ng PUF<sup>-1</sup>) have been used for regression analysis.

<b>Multiple R</b>	0.91
<b>R Square</b>	0.84
<b>Adjusted R Square</b>	0.80
<b>Standard Error</b>	1.03
<b>Observations</b>	6.00
<i>Observation</i>	<i>Predicted Y</i>
1	0.72
2	0.72
3	1.75
4	2.09
5	2.89
6	6.33

**Table S4** Summary of  $\Sigma_5$  and  $\Sigma_5-209$  amounts (ng PUF<sup>-1</sup>) accumulated in the PUF disks for all 3 sampling periods at all sites together with mean data (highlighted) for all sites.

<b>PBDE congener</b>	<b>BDE-28</b>	<b>BDE-47</b>	<b>BDE-100</b>	<b>BDE-99</b>	<b>BDE-209</b>	<b><math>\Sigma_5</math></b>	<b><math>\Sigma_5-209</math></b>
<i>Winter, 2008 – 26 June to 5 August (40 days)</i>							
<sup>a</sup> Commercial A	0.3	3	0.6	2.4	na	na	6.3
<sup>a</sup> Industrial B	0.2	0.9	0.3	0.7	na	na	2.1
<sup>a</sup> Residential C	nd	1.1	0.3	1.1	na	na	2.5

<sup>a</sup> Residential D	nd	0.5	0.1	0.6	na	na	1.2
<sup>a</sup> Rural E	nd	0.4	0.2	0.4	na	na	1
<sup>a</sup> Rural F	nd	0.4	0.3	0.3	na	na	1
<i>Winter, 2009 – 16 June to 15 October (121 days)</i>							
Commercial A	0.2	2.9	0.4	2.5	10.4	16.4	6
Industrial B	0.1	1.4	0.2	1.9	12.7	16.3	3.6

Residential C	nd	0.4	0.1	0.6	<LOD	1.1	1.1
Residential D	0.1	0.6	0.1	0.6	<LOD	1.4	1.4
Rural E	nd	0.3	0.1	0.4	<LOD	0.8	0.8
Rural F	nd	0.4	0.1	0.4	<LOD	0.9	0.9
<i>Summer, 2009-2010 – 8 December to 4 March (86 days)</i>							
Commercial A	0.2	2.6	0.2	0.9	1.4	5.3	3.9

Industrial B	0.2	1.8	0.1	0.7	10.1	12.9	2.8
Residential C	0.1	0.3	nd	<MDL	<LOD	0.4	0.4
Residential D	0.1	0.7	0.1	0.2	4.9	6.1	1.1
Rural E	0.1	0.6	0.1	0.2	<LOD	1	1
Rural F	nd	0.5	nd	0.2	<LOD	0.7	0.7

*Mean (n=3) PBDE levels – 3 seasons combined*

<b>Commercial A</b>	<b>0.2 ±0.1</b>	<b>2.8±0.2</b>	<b>0.4±0.2</b>	<b>1.9±0.9</b>	<b><sup>b</sup>5.9±6.4</b>	<b>11.2±7.8</b>	<b>5.4±1.3</b>
<b>Industrial B</b>	<b>0.2± 0.1</b>	<b>1.4±0.5</b>	<b>0.2±0.1</b>	<b>1.1±0.7</b>	<b><sup>b</sup>11.4±1.8</b>	<b>14.2±2.4</b>	<b>2.8±0.8</b>
<b>Residential C</b>	<b>0.1</b>	<b>0.6±0.4</b>	<b>0.1±0.2</b>	<b>0.6±0.6</b>	<b>na</b>	<b>1.3±0.5</b>	<b>1.3±1.1</b>
<b>Residential D</b>	<b>0.1±0.1</b>	<b>0.6±0.1</b>	<b>0.1±0.0</b>	<b>0.5±0.2</b>	<b><sup>b</sup>2.5±3.5</b>	<b>3.7±3.4</b>	<b>1.2±0.2</b>
<b>Rural E</b>	<b>0.1±0.01</b>	<b>0.4±0.2</b>	<b>0.1±0.1</b>	<b>0.3±0.1</b>	<b>na</b>	<b>0.9±0.1</b>	<b>0.9±0.1</b>
<b>Rural F</b>	<b>nd</b>	<b>0.4±0.1</b>	<b>0.1±0.2</b>	<b>0.3±0.1</b>	<b>na</b>	<b>0.9±0.1</b>	<b>0.9±0.2</b>

Mean blank (ng PUF <sup>-1</sup> , n=7)	nd	0.1	nd	0.1	0.3	na	na
LOD	na	0.2	na	0.1	0.5	na	na
Mean recovery(%)- <sup>13</sup> C <sub>12</sub> PBDEs PUF	70.5	80.1	na	70.2	50.1	na	na
IDL (pg/μl)	5	5	5	5	25	na	na
na-not applicable nd-non detect <LOD-average level in blanks + 3 × standard deviation <MDL - less than method detection limit, defined as analyte peak with s/n ratio < 3:1 <sup>a</sup> replicate PUFs deployed at each monitoring site (winter, 2008) mean value has been used <sup>b</sup> The mean BDE-209 level is calculated from winter (2009) and summer (2009 – 2010) sampling periods only.							

**Table S5** One phase decay model for  $\Sigma_5$ -209 data.

Best-fit values
Y0
Plateau
K
Half Life
Tau
Span
Y0
Plateau
K
Span
95% Confidence Intervals
Y0
Plateau
K
Half Life
Tau
Span
Degrees of Freedom
R square

Absolute Sum of Squares
Sy.x
K
Number of points

**Table S6** One phase decay model for  $\Sigma_5$ PBDE data.

One phase decay
Best-fit values
Y0
Plateau
K
Half Life
Tau
Span
Std. Error
Y0
Plateau
K
Span
95% Confidence Intervals
Y0

Plateau
K
Half Life
Tau
Span
Degrees of Freedom
R square
Absolute Sum of Squares
Sy.x
Constraints
K
Number of points
Analyzed

$$Y = (Y_0 - \text{Plateau}) * \exp(-K * X) + \text{Plateau}$$

where  $Y_0$  is the Y value when X (distance) is zero. It is expressed in the same units as Y,

Plateau is the Y value at infinite times, expressed in the same units as Y.

K is the rate constant, expressed in reciprocal of the X axis time units. If X is in kilometres, then K is expressed in inverse kilometres.

Tau is the time constant, expressed in the same units as the X axis. It is computed as the reciprocal of K.

Half-life is in the time units of the X axis. It is computed as  $\ln(2)/K$ .

Span is the difference between  $Y_0$  and Plateau, expressed in the same units as your Y values

**Table S7** Estimated Resident Population, Statistical Local Areas, Brisbane

<b>Statistical Local Area</b>	<b>km<sup>2</sup></b>	<b>persons/km<sup>2</sup></b>
Distance from CBD	Inner Brisbane	
2.5	Bowen Hills	1.7
1.0	City - Inner	0.7
1.5	City - Remainder	1.5
3.0	Dutton Park	0.9

1.5	Fortitude Valley	1.4
2.0	Herston	1.7
1.5	Highgate Hill	1.2
1.0	Kangaroo Point	1.3
2.5	Kelvin Grove	1.7
2.5	Milton	1.2
1.2	New Farm	2.0
2.0	Newstead	1.3
2.2	Paddington	2.4
2.5	Red Hill	1.7
0.8	South Brisbane	2.0
1.0	Spring Hill	1.2
1.5	West End	1.9
2.2	Woolloongabba	2.4
1.8	Total Inner Brisbane	28.2
	Northwest Inner Brisbane	
2.2	Albion	1.5
5.0	Alderley	2.4
4.5	Ascot	2.5
4.0	Ashgrove	5.6
4.0	Bardon	5.6
6.0	Chelmer	1.4
5.5	Clayfield	2.9
7.0	Corinda	2.9
5.0	Enoggera	9.2
7.0	Graceville	1.9
5.0	Grange	1.9
5.0	Hamilton	1.7
6.0	Hendra	2.7
6.0	Indooroopilly	7.5
6.5	Kedron	5.2
5.0	Lutwyche	0.9
5.0	Newmarket	1.7
8.0	Nundah	3.6
7.0	St Lucia	3.4
7.5	Sherwood	2.3
6.0	Stafford	3.4
4.5	Stafford Heights	2.9
5.0	Taringa	2.1
3.5	Toowong	5.2
3.5	Wilston	1.4

4.0	Windsor	2.9
6.0	Wooloowin	2.2
	Total Northwest Inner Brisbane	86.8
	Northwest Outer Brisbane	
	Anstead	12.5
	Aspley	6.3
	Bald Hills	14.0
	Banyo	5.1
	Bellbowrie	7.3
	Boondall	10.9
	Bracken Ridge	8.4
	Bridgeman Downs	8.8
	Brighton	6.5
	Brookfield (incl. Brisbane Forest Park)	106.1
	Carseldine	4.6
	Chapel Hill	5.4
	Chermside	3.4
	Chermside West	3.4
	Darra-Sumner	8.0
	Deagon	2.7
	Doolandella-Forest Lake	10.0
	Durack	4.5
	Ellen Grove	5.1
	Everton Park	4.2
	Ferny Grove	3.8
	Fig Tree Pocket	4.2
	Geebung	4.0
	Inala	5.9
	Jamboree Heights	1.3
	Jindalee	2.6
	Karana Downs-Lake Manchester	184.8
	Kenmore	5.2
	Kenmore Hills	4.3
	Keperra	5.5
	McDowall	4.4
	Middle Park	1.5
	Mitchelton	4.4
	Moggill	10.3
	Mount Ommaney	2.1
	Northgate	3.0

	Nudgee	7.8
	Oxley	6.9
	Pinjarra Hills	5.5
	Pinkenba-Eagle Farm	53.2
	Pullenvale	24.3
	Richlands	5.0
	Riverhills	2.2
	Sandgate	4.3
	Seventeen Mile Rocks	5.4
	Taigum-Fitzgibbon	6.3
	The Gap	12.2
	Upper Kedron	9.4
	Virginia	3.2
	Wacol	18.5
	Wavell Heights	3.6
	Westlake	1.9
	Zillmere	3.7
	Total Northwest Outer Brisbane	657.9
	Southeast Inner Brisbane	
4.0	Annerley	2.8
3.0	Balmoral	1.3
3.5	Bulimba	2.1
5.0	Camp Hill	4.6
7.0	Cannon Hill	4.6
7.0	Carindale	9.5
6.5	Carina	5.0
6.7	Carina Heights	3.4
3.5	Coorparoo	5.3
1.5	East Brisbane	2.0
3.5	Fairfield	1.2
5.0	Greenslopes	2.9
3.0	Hawthorne	1.4
5.0	Holland Park	3.3
5.5	Holland Park West	2.6
6.0	Moorooka	4.1
5.0	Morningside	5.4
4.0	Norman Park	3.0
5.0	Tarragindi	4.5
5.0	Yeerongpilly	2.7
2.5	Yeronga	3.0

	Total Southeast Inner Brisbane	74.5
	Southeast Outer Brisbane	
	Acacia Ridge	9.1
	Algester	3.9
	Archerfield	4.7
	Belmont-Mackenzie	12.4
	Burbank	30.0
	Calamvale	6.5
	Chandler-Capalaba West	13.6
	Coopers Plains	3.9
	Eight Mile Plains	7.7
	Gumdale-Ransome	9.8
	Hemmant-Lytton	39.7
	Kuraby	4.7
	Lota	2.0
	MacGregor	2.7
	Manly	2.0
	Manly West	5.0
	Mansfield	6.1
	Moreton Island	173.9
	Mount Gravatt	2.7
	Mount Gravatt East	4.6
	Murarrie	7.6
	Nathan	5.3
	Pallara-Heathwood-Larapinta	18.6
	Parkinson-Drewvale	12.7
	Robertson	1.9
	Rochedale	14.3
	Rocklea	9.1
	Runcorn	6.6
	Salisbury	4.7
	Stretton-Karawatha	13.1
	Sunnybank	4.5
	Sunnybank Hills	6.5
	Tingalpa	9.4
	Upper Mount Gravatt	4.2
	Wakerley	4.9
	Willawong	8.1
	Wishart	4.8
	Wynnum	6.1

	Wynnum West	5.4
	Total Southeast Outer Brisbane	492.8
	Caboolture	
	Bribie Island	106.0
	Burpengary-Narangba	38.1
	Caboolture Central	57.4
	Caboolture East	151.4
	Caboolture Hinterland	495.6
	Caboolture Midwest	305.8
	Deception Bay	31.3
	Morayfield	38.4
	Total Caboolture	1224.0
	Ipswich City	
	Ipswich (C) - Central	206.2
	Ipswich (C) - East	119.7
	Ipswich (C) - North	74.8
	Ipswich (C) - South-West	471.1
	Ipswich (C) - West	218.4
	Total Ipswich City	1090.2
	Logan City	
	Beenleigh	7.7
	Bethania-Waterford	12.6
	Browns Plains	28.0
	Carbrook-Cornubia	34.6
	Daisy Hill-Priestdale	14.9
	Eagleby	13.8
	Edens Landing-Holmview	6.6
	Greenbank-Boronia Heights	52.5
	Jimboomba-Logan Village	635.2
	Kingston	8.0
	Loganholme	14.6
	Loganlea	11.3
	Marsden	15.5
	Mt Warren Park	4.3
	Park Ridge-Logan Reserve	21.9
	Rochedale South	6.1
	Shailer Park	8.0
	Slacks Creek	9.6
	Springwood	4.7

	Tanah Merah	1.7
	Underwood	4.1
	Waterford West	5.3
	Wolffdene-Bahrs Scrub	28.0
	Woodridge	10.7
	Total Logan City	959.6
	Pine Rivers	
	Albany Creek	9.9
	Bray Park	4.5
	Central Pine West	54.4
	Dakabin-Kallangur-M. Downs	23.1
	Griffin-Mango Hill	43.2
	Hills District	17.3
	Lawnton	9.3
	Petrie	6.7
	Strathpine-Brendale	17.9
	Moreton Bay (R) Bal	588.3
	Total Pine Rivers	774.6
	Redcliffe	
	Clontarf	6.3
	Margate-Woody Point	4.2
	Redcliffe-Scarborough	9.3
	Rothwell-Kippa-Ring	18.4
	Total Redcliffe	38.1
	Redland City	
	Alexandra Hills	13.6
	Birkdale	11.5
	Capalaba	18.9
	Cleveland	11.8
	Ormiston	4.5
	Redland Bay	46.9
	Sheldon-Mt Cotton	65.4
	Thorneside	2.5
	Thornlands	21.7
	Victoria Point	13.4
	Wellington Point	7.6
	Redland (C) Bal	319.2
	Total Redland City	537.1

	<b>Total Brisbane</b>	<b>5964</b>
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In summary the method used to calculate centers of population by the Australian Bureau of Statistics (ABS) is based on the centroid and population of each Census Collection Districts (CD). To calculate the center of population for an area, the latitude and longitude coordinates of the centroid of each CD in that area are multiplied by the CD's estimated resident population to obtain weighted latitudes and longitudes for each CD. These are summed to obtain a weighted latitude and longitude coordinate for the area, and then divided by the total population of the area to obtain a single latitude and longitude coordinate. At June, 2009 the center of population in Brisbane was just south of the central business district (CBD)