smoke haze. The exceedance of the health risk values from the threshold limit for the three haze levels suggests that it is harmful to stay in naturally ventilated buildings during the haze period. Consequently, appropriate mitigation measures need to be developed and implemented to decrease human exposure to $PM_{2.5}$ mass concentrations and related health effects during haze episodes.

Size-fractionated PM

Since the carcinogenic health risk or ELCR values estimated for $PM_{2.5}$ exceeded the threshold limit, ELCR values were calculated for size-fractionated PM to get further useful insights. Results obtained from this analysis for the three haze levels for total health risk are illustrated in Fig. 6. Again, an increase in health risk was observed with the increase in haze intensity. Overall, health risk due to exposure to coarse particles was found to be within the threshold limit while submicron sized particles (accumulation and q-UF) showed higher health risk than the threshold value, except for the accumulation mode during light-haze. Furthermore, it is important to note that the health risk was the highest for q-UF particles, followed by accumulation mode particles and then coarse particles. Since these submicron-sized particles are found in higher concentration during haze episodes, their effective removal indoors through mitigation methods such as air filtration is warranted. Suitable mitigation measures such as the use of suitable air cleaners indoors and respirators outdoors can be employed for effective air filtration during smoke haze episodes. However, using effective air cleaners in homes is considered to provide greater health benefits than using respirators outdoors as reported by Qi *et al.* (2017).

Uncertainty analysis for carcinogenic health risk

To refine the health risk assessment and perform extreme value analysis, the uncertainty analysis was conducted with variable exposure parameters for potential carcinogenic health risk assessment for $PM_{2.5}$ as well as size-fractionated aerosols. For this purpose, five input exposure parameters i.e. EF, ED, AT, IR and BW were considered as variables as mentioned before in the methodology section. Moreover, only carcinogenic health risk was considered in the uncertainty analysis as it was found to exceed the threshold limit.

$PM_{2.5}$

The analysis was conducted for the three haze levels for $PM_{2.5}$ for total carcinogenic health risk values at 50^{th} and 95^{th} percentiles, as shown in Fig. 7. Overall, it was observed that the 50^{th} percentile values for health risk exceeded the threshold limit by 2.7, 4.3 and 5.1 times for light-haze, moderate-haze and severe-haze levels, respectively. These values are quite close to the ones obtained in previous section for $PM_{2.5}$ since mean values of parameters distribution were assumed to be the same as constant values assumed in an earlier section. The values calculated for the 95^{th} percentile were found to be 4.3, 9.2 and 11.5 times higher than the threshold limit; all these values are significantly higher than the allowed threshold. The values associated with the 95^{th} percentile showed extreme values and are important for policy making. These results further indicate heightened concerns about public health impacts associated with exposure to $PM_{2.5}$ during smoke haze episodes.

Size-Fractionated PM

In addition to $PM_{2.5}$, the uncertainty analysis in health risk was also conducted for size-fractionated PM, and the obtained results are shown in Fig. S14. The results showed that 50^{th} and 95^{th} percentiles health risks were elevated by several folds for the three particles modes under the three levels of haze. Again, the patterns showed the highest health risk for q-UF particles followed by accumulation mode and then coarse mode particles. It is noteworthy that the 95^{th} percentile health risk was observed to be higher than the threshold limit for the severe-haze case in coarse mode, indicating that coarse mode particles can also cause deleterious health effects in the case of extreme values analysis. The uncertainty analysis provides more realistic evaluation of health risk, highlighting the need for implementation of effective mitigation efforts to reduce exposure of occupants in naturally ventilated buildings to PM, especially q-UF particles during smoke haze episodes.

CONCLUSIONS

Ambient air quality in SEA was severely affected during the 2015 haze episode with a 5-fold increase in the 24 h mean $PM_{2.5}$ concentration compared to the 24 h mean WHO $PM_{2.5}$ guidelines. Size-fractionated analysis of $PM_{2.5}$ showed that the increment in $PM_{2.5}$ levels was mainly due to higher concentrations of quasi-ultrafine particles. The I/O ratios of size-fractionated PM showed higher values for smaller-sized particles during the haze episodes compared to larger particles. This observation indicates that exposure to such PM may pose severe health impacts since small particles contain relatively higher levels of toxic elements than coarse particles. The estimation of deposited dose of PM in the human respiratory system showed that as the particle size decreased from $PM_{2.5}$ to

$PM_{<0.25}$, the contribution from head to alveolar regions to the total deposited dose increased, suggesting that higher concentrations of ultrafine particles can lead to their deeper penetration, thereby causing harmful health impacts during haze events. Total elemental analysis was performed for the 24 selected elements. EF and PDF analyses were used to differentiate sources of PM. Results showed that Cr, Mn Fe and Ni mainly originated from crustal sources while other elements such as Cd, Cu, Pb and Zn are mainly associated with non-crustal sources. Total potential carcinogenic health risk results estimated during the severe-haze period, based on bioavailable toxic elemental concentrations in $PM_{2.5}$, exhibited exceedance from the threshold limit by 5.2 times for constant exposure parameters based analysis for adults. The exceedance was observed to be 11.5 times higher compared to the allowed threshold for the extreme value (95th percentile) analysis conducted for health risk considering the uncertainty or the variability associated with exposure parameters. Moreover, the results obtained for size-fractionated health risk revealed that the health risk increased with the decrease in particle size with accumulation and quasi-ultrafine particles exceeding the threshold limit.

Overall, it was observed that the potential health risk increases with the increase in haze intensity. However, it should be noted that the health risk exceeded from the threshold limit for the three haze levels, implying that remaining in naturally ventilated environments may not be safer during haze events. Therefore, effective mitigation of indoor exposure to PM is much needed during the occurrence of transboundary smoke haze episodes. Mitigation measures such as the use of portable air cleaners with sufficient CADR (clean air delivery rate) indoors and suitable respirators equipped with micro-ventilators in outdoor environments during haze period can help achieve good health benefits. Additionally, the current study considers only toxic elements for potential health risk assessment since they make a significant contribution to the total health risk. However, organic components in PM such as polycyclic aromatic hydrocarbons (PAHs), nitrated-PAHs and quinones may also contribute toward the overall toxicity of PM and therefore should also be included in the overall health risk assessment. Consequently, more comprehensive studies focused on PM chemical speciation together with the use of simulated lung fluids containing antioxidants in place of water as the leaching agent and a comparative evaluation of various mitigation strategies are warranted to improve our understanding of the potential health effects of haze aerosols and to recommend a suitable indoor PM exposure mitigation method. Such studies will be helpful for policymakers to make appropriate decisions for maintaining good IAQ and minimizing public health impacts of haze aerosols.

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REFERENCES

Adamson, I.Y.R., Prieditis, H., Hedgecock, C. and Vincent R. (2000). Zinc is the toxic factor in the lung response to an atmospheric particulate sample. *Toxicol. Appl. Pharmacol.* 166: 111-119.

Agency for Toxic Substances and Disease Registry (ATSDR) (2017). Toxic Substances Portal http://www.atsdr.cdc.gov/toxprofiles/index.asp, Last Access: 10 July 2017.

Apte, J.S., Marshall, J.D., Cohen, A.J. and Brauer, M. (2015). Addressing global mortality from ambient $PM_{2.5}$. *Environ. Sci. Technol*. 49: 8057–8066.

Azarmi, F. and Kumar, P (2016). Ambient exposure to coarse and fine particle emissions from building demolition. *Atmos. Environ.* 137: 62-79.

Balasubramanian, R., Qian, W.B., Decesari, S., Facchini, M.C. and Fuzzi, S. (2003). Comprehensive characterization of $PM_{2.5}$ aerosols in Singapore. *J Geophys Res.* 108: 4523.

Balasubramanian, R. and Qian, W-B. (2004). Characterization and source identification of airborne trace metals in Singapore. *J. Environ. Monit.* 6: 813−818.

Behera, S.N., Betha, R., Huang, X. and Balasubramanian, R. (2015a). Characterization and estimation of human airway deposition of size-resolved particulate-bound trace elements during a recent haze episode in Southeast Asia. *Environ. Sci. Pollut. Res. Int.* 22: 4265–4280.

Behera, S.N., Cheng, J., Huang, X., Zhu, Q., Liu, P. and Balasubramanian, R. (2015b). Chemical composition and acidity of size-fractionated inorganic aerosols of 2013-14 winter haze in Shanghai and associated health risk of toxic elements. *Atmos. Environ.* 122: 259–271.

Behera, S.N., Huang, X. and Balasubramanian, R. (2014). Human health risk associated with exposure to toxic elements in mainstream and sidestream cigarette smoke. *Science of The Total Environ.* 472: 947-956.

Betha, R., Behera, S.N. and Balasubramanian, R. (2014). 2013 Southeast Asian smoke haze: fractionation of particulate-bound elements and associated health risk. *Environ Sci Technol.* 48: 4327–4335.

Betha, R., Pradani, M., Lestari, P., Joshi, U.M., Reid, J.S. and Balasubramanian, R. (2013). Chemical speciation of trace metals emitted from Indonesian peat fires for health risk assessment. *Atmos. Res.* 122: 571–578.

Birmili, W., Allen, A.G., Bary, F. and Harrison, R.M. (2006). Trace metal concentrations and water solubility in size-fractionated atmospheric particles and influence of road traffic. *Environmental Science & Technology* 40: 1144–1153.

Cassee, F.R., Heroux, M.-E., Gerlofs-Nijland, M.E. and Kelly, F.J. (2013). Particulate matter beyond mass: recent health evidence on the role of fractions, chemical constituents and sources of emission. *Inhal. Toxicol.* 25: 802-812.

Chen, A., Cao, Q., Zhou, J., Yang, B., Chang, V.W.-C. and Nazaroff, W.W. (2016). Indoor and outdoor particles in an air-conditioned building during and after the 2013 haze in Singapore. *Building and Environment* 99: 73–81.

Chiu, W.A. and Slob, W. (2015). A Unified Probabilistic Framework for Dose–Response Assessment of Human Health Effects. *Environ. Health Perspect.* 123: 1241–1254.

Choi, D.H. and Kang, D.H. (2017). Infiltration of Ambient $PM_{2.5}$ through Building Envelope in Apartment Housing Units in Korea. *Aerosol and Air Quality Research* 17: 598–607.

Draxler, R.R. and Hess, G.D. (1998). An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. *Aust. Meteorol. Mag.* 47: 295–308.

Draxler, R.R. and Rolph, G.D. (2015). HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website Silver Spring, MD, NOAA Air Resources Laboratory. http://ready.arl.noaa.gov/HYSPLIT.php, Last Access: 15 August 2017.

Gentry, R., Franzen, A., Landingham, C.V., Greene, T. and Plotzke, K. (2017). A global human health risk assessment for octamethylcyclotetrasiloxane (D4). *Toxicology Letters* 279: 23–41.

Haber, S., Yitzhak, D. and Tsuda, A. (2003). Gravitational deposition in a rhythmically expanding and contracting alveolus. *J. Appl. Physiol.* 95: 657–671.

Ham, W.A., Ruehl, C.R. and Kleeman, M.J. (2011). Seasonal variation of airborne particle deposition efficiency in the human respiratory system. *Aerosol. Sci. Technol.* 45: 795−804.

Han, Y., Qi, M., Chen, Y., Shen, H., Liu, J., Huang, Y., Chen, H., Liu, W., Wang, X., Liu, J., Xing, B. and Tao, S. (2015). Influences of ambient air $PM_{2.5}$ concentration and meteorological condition on the indoor $PM_{2.5}$ concentrations in a residential apartment in Beijing using a new approach. *Environ. Pollut.* 205:307-314.

Hinds, W.C. (1999). *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, second ed., John Wiley & Sons, INC., New York.

Huang, X., Betha, R., Tan, L.Y. and Balasubramanian, R. (2016). Risk assessment of bioaccessible trace elements in smoke haze aerosols versus urban aerosols using simulated lung fluids. *Atmos. Environ.* 125: 505-511.

Ingham, D.B. (1984). Diffusion of aerosols from a stream flowing through a short cylindrical pipe. *J. Aerosol. Sci.* 15:637−641.

International Business Times (IBT) (2016). Singapore and Indonesia haze: Interactive before-and-after photos show dramatically reduced visibility, http://www.ibtimes.co.uk/singapore-indonesia-haze-interactive-before-after-photos-show dramatically-reduced-visibility-1521643, Last Access: 24 February 2018.

Jahn, H.J., Kraemer, A., Chen, X.C., Chan, C.Y., Engling, G. and Ward, T.J. (2013). Ambient and personal $PM_{2.5}$ exposure assessment in the Chinese megacity of Guangzhou. *Atmos. Environ.* 74: 402–411.

Jenkins, P.L., Phillips, T.J., Mulberg, E.J. and Hui, S.P. (1992). Activity patterns of Californians: Use of and proximity to indoor pollutant sources. *Atmos. Environ.* 26: 2141–2148.

Ji, W. and Zhao, B. (2015). Contribution of outdoor-originating particles, indoor-emitted particles and indoor secondary organic aerosol (SOA) to residential indoor $PM_{2.5}$ concentration: a model-based estimation. *Build. Environ*. 90: 196-205.

Jiang, N., Guo, Y., Wang, Q., Kang, P., Zhang, R. and Tang, X. (2017). Chemical Composition Characteristics of $PM_{2.5}$ in Three Cities in Henan, Central China. *Aerosol and Air Quality Research* 17: 2367–2380.

Kalaiarasan, G., Balakrishnan, R.M., Sethunath, N.A. and Manoharan, S. (2017). Source Apportionment of $PM_{2.5}$ Particles: Influence of Outdoor Particles on Indoor Environment of Schools Using Chemical Mass Balance. *Aerosol and Air Quality Research* 17: 616–625.

Karthik, K.R.G., Baikie, T., Mohan Dass, E.T., Huang, Y.Z. and Guet, C. (2017). Understanding the Southeast Asian haze. *Environ. Res. Lett.* 12: 084018.

Karthikeyan, S., Balasubramanian, R. and Iouri, K. (2006a). Particulate air pollution from bushfires: human exposure and possible health effects. *J. Toxicol. Environ. Health, Part A* 69:1895-1908.

Karthikeyan, S., Joshi, U.M. and Balasubramanian, R. (2006). Microwave assisted sample preparation for determining water-soluble fraction of trace elements in urban airborne particulate matter: evaluation of bioavailability. *Anal ChimActa* 576: 23–30.

Kumar, P. and Goel, A. (2016). Concentration dynamics of coarse and fine particulate matter at and around the signalised traffic intersections. *Environ. Sci. Process Impacts* 18: 1220-1235.

Lai, C.H., Chen, K.S. and Wang, H.K. (2009). Influence of rice straw burning on the levels of polycyclic aromatic hydrocarbons in agricultural county of Taiwan. *J. Environ. Sci.* 21: 1200−1207.

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

Liberda, E.N., Tsuji, L.J.S. and Peltier, R.E. (2015). Mining in subarctic Canada: airborne $PM_{2.5}$ metal concentrations in two remote First Nations communities. *Chemosphere* 139: 452–460.

Lippmann, M. and Chen, L.C. (2009). Health effects of concentrated ambient air particulate matter (CAPs) and its components. *Crit. Rev. Toxicol*. 39: 865–913.

Lippmann, M., Ito, K., Chen, L.C., Hwang, J.S. and Maciejczyk, P. (2007). Cardiovascular effects of nickel in ambient air. *Environ. Health Perspect.* 114:1662–1669.

Lu, S., Feng, M., Yao, Z., Jing, A., Yufang, Z., Wu, M., Sheng, G., Fu, J., Yonemochi, S., Zhang, J., Wang, Q. and Donaldson, K. (2011). Physicochemical characterization and cytotoxicity of ambient coarse, fine, and ultrafine particulate matters in Shanghai atmosphere. *Atmos. Environ.* 45:736-744.

Lu, S., Zhang, W., Zhang, R., Liu, P., Wang, Q., Shang, Y., Wu, M., Donaldson, K. and Wang, Q. (2015). Comparison of cellular toxicity caused by ambient ultrafine particles and engineered metal oxide nanoparticles. *Part. Fibre Toxicol.* 12: 5.

Lu, X., Wu, X., Wang, Y., Chen, H., Gao, P. and Fu, Y. (2014). Risk assessment of toxic metals in street dust from a medium-sized industrial city of China. *Ecotoxicology and Environmental Safety* 106: 154–163.

Manousakas, M., Papaefthymiou, H., Eleftheriadis, K. and Katsanou, K. (2014). Determination of water-soluble and insoluble elements in $PM_{2.5}$ by ICP-MS. *Sci. Total Environ.* 493: 694-700.

Martins, L.D., Martins, J.A., Freitas, E.D., Mazzoli, C.R., Goncalves, F.L.T., Ynoue, R.Y., Hallak, R., Albuquerque, T.T.A. and de Fatima, A.M. (2010). Potential health impact of ultrafine particles under clean and polluted urban atmospheric conditions: a model-based study. *Air Qual. Atmos. Health* 3: 29-39.

Mason, B. (1966). *Principles of geochemistry*, John Wiley & Sons, New York, pages 41-49.

Massey, D.D., Kulshrestha, A. and Taneja, A. (2013). Particulate matter concentrations and their related metal toxicity in rural residential environment of semi-arid region of India. *Atmos. Environ.* 67: 278-286.

Megido, L., Suarez-Pena, B., Negral, L., Castrillon, L., Suarez, S., Fernandez-Nava, Y. and Maranon, E. (2016). Relationship between physico-chemical characteristics and potential toxicity of PM10. *Chemosphere* 162: 73-79.

Megido, L., Suarez-Pena, B., Negral, L., Castrillon, L., Suarez, S. and Fernandez-Nava, Y. (2017). Suburban air quality: Human health hazard assessment of potentially toxic elements in PM10. *Chemosphere* 177: 284-291.

Misra, C., Singh, M., Shen, S., Sioutas, C. and Hall, P.M. (2002). Development and evaluation of a personal cascade impactor sampler (PCIS). *Journal of Aerosol Science* 33: 1027–1047.

National Environmental Agency (NEA) (2015). Singapore haze, http://www.haze.gov.sg/haze-updates/historical-psi-readings, Last Access: 24 February 2018.

Nichol, J. (1998). Smoke haze in Southeast Asia: a predictable recurrence. *Atmos. Environ.* 32: 2715–2716.

Oberdorster, G. (2001). Pulmonary effects of inhaled ultrafine particles. *Int. Arch. Occup. Environ. Health* 74: 1-8.

Othman, J., Sahani, M., Mahmud, M. and Sheikh Ahmad, M.K. (2014). Transboundary smoke haze pollution in Malaysia: inpatient health impacts and economic valuation. *Environ. Pollut.* 189: 194-201.

Pongpiachan, S. (2015). Incremental Lifetime Cancer Risk of $PM_{2.5}$ Bound Polycyclic Aromatic Hydrocarbons (PAHs) before and after the Wildland Fire Episode, *Aerosol and Air Quality Research*, In Press (http://aaqr.org/ArticlesInPress/AAQR-15-01-SISEASIA-0011_proof.pdf).

Pongpiachan, S. and Iijima, A. (2016). Assessment of selected metals in the ambient air PM_{10} in urban sites of Bangkok (Thailand). *Environ. Sci. Pollut. Res.* 23:2948 – 2961.

Pongpiachan, S. and Paowa, T. (2014). Hospital out-and-in-patients as Functions of Trace Gaseous Species and Other Meteorological Parameters in Chiang-Mai, Thailand. *Aerosol and Air Quality Research* 15: 479-493.

Pongpiachan, S., Choochuay, C., Chonchala, J., Kanchai, P., Phonpiboon, T., Wongsuesat, S., Chomkhae, K., Kittikoon, I., Hiranyatrakul, P., Cao, J. and Thamrongthanyawong, S. (2013). Chemical Characterisation of Organic Functional Group Compositions in $PM_{2.5}$ Collected at Nine Administrative Provinces in Northern Thailand during the Haze Episode in 2013. *Asian Pacific Journal of Cancer Prevention* 14: 3653-61.

Pongpiachan, S., Hattayanone, M. and Cao, J. (2017). Effect of agricultural waste burning season on PM 2.5-bound polycyclic aromatic hydrocarbon (PAH) levels in Northern Thailand. *Atmospheric Pollution Research* 8: 1069-1080.

Pongpiachan, S., Tipmanee, D., Khumsup, C., Kittikoon, I. and Hirunyatrakul, P. (2015). Assessing risks to adults and preschool children posed by $PM_{2.5}$-bound polycyclic aromatic hydrocarbons (PAHs) during a biomass burning episode in Northern Thailand. *Science of the Total Environment* 508: 435-444.

Pope III, C.A. and Dockery, D.W. (2006). Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manage. Assoc.* 56: 709–742.

Qi, M., Zhu, X., Du, W., Chen, Y., Chen, Y., Huang, T., Pan, X., Zhong, Q., Sun, X., Zeng, E.Y., Xing, B. and Tao, S. (2017). Exposure and health impact evaluation based on simultaneous measurement of indoor and ambient $PM_{2.5}$ in Haidian, Beijing. *Environmental Pollution* 220: 704–712.

Reddington, C.L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y.Y., Arnold, S.R., et al. (2014). Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia. *Environ. Res. Lett.* 9: 094006.

Russell, A.G. and Bert, B. (2009). A focus on particulate matter and health. *Environ. Sci. Technol.* 43: 4620–4625.

Ryu, S.Y., Kwon, B.G., Kim, Y.J., Kim, H.H. and Chun, K.J. (2007). Characteristics of biomass burning aerosol and its impact on regional air quality in the summer of 2003 at Gwangju, Korea. *Atmos. Res*. 84: 362–373.

Schwerizer, C., Edwards, R., Bayer-Oglesby, L., Gauderman, W., Ilacqua, V., Jantunen, M., Lai, H.K., Nieuwenhuijsen, M. and Künzli, N. (2007). Indoor time-microenvironment-activity patterns in seven regions of Europe. *J. Exposure Sci. Environ. Epidemiol.* 17: 170–181.

See, S.W., Balasubramanian, R. and Wang, W. (2006). A study of the physical, chemical and optical properties of ambient aerosol particles in Southeast Asia during hazy and nonhazy days. *Journal of Geophysical Research* 111: D10S08.

See, S.W., Balasubramanian, R., Rianawati, E., Karthikeyan, S. and Streets, D.G. (2007). Characterization and source apportionment of particulate matter≤2.5 μm in Sumatra, Indonesia, during a recent peat fire episode. *Environ Sci Technol.* 41: 3488–3494.

Segalin, B., Kumar, P., Micadei, K., Fornaro, A. and Gonçalves, L.T. (2017). Size-segregated particulate matter inside residences of elderly in the Metropolitan Area of Sao Paulo, Brazil. *Atmos. Environ.* 148: 139-151.

Seinfeld, J.H. and Pandis, S.N. (1998). *Atmospheric Chemistry and Physics: from Air Pollution to Climate Change*, John Wiley & Sons, Inc, New Jersey.

Shao, K., Allen, B.C. and Wheeler, M.W. (2017). Bayesian Hierarchical Structure for Quantifying Population Variability to Inform Probabilistic Health Risk Assessments. *Risk Analysis* 37: 1865–1878.

Sulong, N.A, Latif, M.T., Khan, M.F., Amil, N., Ashfold, M.J., Wahab, M.I.A., Chan, K.M., Sahani, M. (2017). Source apportionment and health risk assessment among specific age groups during haze and non-haze episodes in Kuala Lumpur, Malaysia. *Science of the Total Environment* 601–602: 556–570.

The Strait Times (2015). Haze crisis set to be 'one of the worst on record', http://www.straitstimes.com/asia/haze-crisis-set-to-be-one-of-the-worst-on-record, Lasr Access: 22 February 2018.

Today (2015). $PM_{2.5}$ levels hit 471 as haze situation worsens, http://www.todayonline.com/world/asia/pm25-levels-hit-471-haze-situation-worsens, Last Access: 26 February 2018.

United States Environmental Protection Agency (USEPA) (2017). Integrated Risk Information System (IRIS) http://www.epa.gov/iris/, Last Access: 5 July 2017.

Urbancok, D., Payne, A.J.R. and Webster, R.D. (2017). Regional transport, source apportionment and health impact of PM_{10} bound polycyclic aromatic hydrocarbons in Singapore's atmosphere. *Environmental Pollution* 229: 984–993.

USEPA (1992). Guidelines for Exposure Assessment https://www.epa.gov/sites/production/files/2014-11/documents/guidelines_exp_assessment.pdf, Last Access: 8 August 2017.

Velascoa, E. and Rastan, S. (2015). Air quality in Singapore during the 2013 smoke-haze episode over the Strait of Malacca: Lessons learned. *Sustainable Cities and Society* 17: 122–131.

Verma, V., Fang, T., Guo, H., King, L., Bates, J.T., Peltier, R.E., Edgerton, E., Russell, A.G. and Weber, R.J. (2014). Reactive oxygen species associated with water-soluble $PM_{2.5}$ in the southeastern United States: spatiotemporal trends and source apportionment. *Atmos. Chem. Phys.* 14: 12915–12930.

Viana, M., Rivas, I., Querol, X., Alastuey, A., Alvarez-Pedrerol, M., Bouso, L., Sioutas, C. and Sunyer, J. (2015). Partitioning of trace elements and metals between quasi-ultrafine, accumulation and coarse aerosols in indoor and outdoor air in schools. *Atmos. Environ.* 106: 392−401.

WHO (2013). *Review of Evidence on Health Aspects of Air Pollution - REVIHAAP Project*, World Health Organization, Copenhagen.

Zhang, L. and Yu, C.P. (1993). Empirical equations for nasal deposition of inhaled particles in small laboratory - Animals and humans. *Aerosol. Sci. Technol.* 19: 51−56.

Zhang, Z.-H., Khlystov, A., Norford, L.K., Tan, Z.-K. and Balasubramanian, R. (2017). Characterization of traffic-related ambient fine particulate matter ($PM_{2.5}$) in an Asian city: Environmental and health implications. *Atmos. Environ.* 161**:**132–143.

Zhou, J., Chen, A., Cao, Q., Yang, B., Chang, V.W.-C. and Nazaroff, W.W. (2015). Particle exposure during the 2013 haze in Singapore: Importance of the built environment *Building and Environment* 93: 14–23.

List of Table Titles

Table 1. Total non-carcinogenic health risk estimates for indoors and outdoors of $PM_{2.5}$ for the three levels of haziness.

Element	RfD (mg kg^{-1} day^{-1})	HI for $PM_{2.5}$					
		Light-Haze		Moderate-Haze		Severe-Haze	
		Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Al	1.40×10^{-3}	7.42×10^{-5}	4.97×10^{-5}	9.82×10^{-5}	6.62×10^{-5}	1.07×10^{-4}	9.47×10^{-5}
As	3.01×10^{-4}	3.26×10^{-5}	1.30×10^{-5}	5.33×10^{-5}	2.64×10^{-5}	5.45×10^{-5}	2.90×10^{-5}
Be	5.71×10^{-6}	1.42×10^{-5}	2.72×10^{-6}	9.77×10^{-5}	1.99×10^{-5}	1.90×10^{-6}	2.80×10^{-6}
Cd	5.71×10^{-6}	2.32×10^{-4}	7.81×10^{-5}	2.18×10^{-4}	1.03×10^{-4}	4.26×10^{-4}	3.12×10^{-4}
Co	5.71×10^{-6}	1.32×10^{-4}	7.46×10^{-5}	1.33×10^{-4}	7.31×10^{-5}	1.04×10^{-4}	8.37×10^{-5}
Cr	2.86×10^{-5}	1.20×10^{-3}	8.68×10^{-4}	2.02×10^{-3}	1.22×10^{-3}	2.59×10^{-3}	1.35×10^{-3}
Cu	4.02×10^{-2}	1.09×10^{-6}	6.81×10^{-7}	1.36×10^{-6}	7.67×10^{-7}	3.29×10^{-6}	2.17×10^{-6}
Mn	1.43×10^{-5}	2.99×10^{-3}	1.21×10^{-3}	4.13×10^{-3}	2.10×10^{-3}	5.05×10^{-3}	3.47×10^{-3}
Ni	2.06×10^{-2}	2.77×10^{-6}	1.62×10^{-6}	3.03×10^{-6}	1.73×10^{-6}	1.84×10^{-6}	1.61×10^{-6}
Pb	3.52×10^{-3}	2.20×10^{-6}	4.99×10^{-7}	1.73×10^{-6}	7.87×10^{-7}	2.62×10^{-6}	1.85×10^{-6}
Zn	3.00×10^{-1}	7.83×10^{-7}	3.87×10^{-7}	1.05×10^{-6}	5.16×10^{-7}	2.03×10^{-6}	1.31×10^{-6}
Σ=		**4.69×10^{-3}**	**2.30×10^{-3}**	**6.76×10^{-3}**	**3.61×10^{-3}**	**8.35×10^{-3}**	**5.35×10^{-3}**
Total Health Risk		**6.99×10^{-3}**		**1.04×10^{-2}**		**1.37×10^{-2}**	

Table 2. Total carcinogenic health risk estimates for indoors and outdoors of $PM_{2.5}$ for the three levels of haziness.

Element	SF (kg day mg^{-1})	ELCR for $PM_{2.5}$					
		Light-Haze		**Moderate-Haze**		**Severe-Haze**	
		Indoor	**Outdoor**	**Indoor**	**Outdoor**	**Indoor**	**Outdoor**
As	15.1	1.48×10^{-7}	5.92×10^{-8}	2.42×10^{-7}	1.20×10^{-7}	2.48×10^{-7}	1.32×10^{-7}
Be	8.4	6.83×10^{-10}	1.30×10^{-10}	4.68×10^{-9}	9.56×10^{-10}	9.13×10^{-11}	1.34×10^{-10}
Cd	6.3	8.35×10^{-9}	2.81×10^{-9}	7.86×10^{-9}	3.70×10^{-9}	1.53×10^{-8}	1.12×10^{-8}
Co	31.5	2.37×10^{-8}	1.34×10^{-8}	2.39×10^{-8}	1.31×10^{-8}	1.87×10^{-8}	1.51×10^{-8}
Cr	42	1.45×10^{-6}	1.04×10^{-6}	2.43×10^{-6}	1.46×10^{-6}	3.11×10^{-6}	1.62×10^{-6}
Ni	0.84	4.79×10^{-8}	2.80×10^{-8}	5.24×10^{-8}	2.99×10^{-8}	3.18×10^{-8}	2.78×10^{-8}
Pb	0.042	3.26×10^{-10}	7.37×10^{-11}	2.56×10^{-10}	1.16×10^{-10}	3.88×10^{-10}	2.74×10^{-10}
Σ=		**1.67×10^{-6}**	**1.15×10-6**	**2.76×10^{-6}**	**1.63×10^{-6}**	**3.43×10^{-6}**	**1.81×10^{-6}**
Total Health Risk		**2.82×10^{-6}**		**4.39×10^{-6}**		**5.24×10^{-6}**	

List of Figure Captions

Fig. 1. Haze map and backward trajectory analysis using HYSPLIT model for severe-haze level on 23 October 2015. The haze map is reproduced from weblink http://asmc.asean.org/home/ (with permission from ASEAN Specialized Meteorological Centre (ASMC)).

Fig. 2. $PM_{2.5}$ mass concentration under different levels of haziness for indoors and outdoors with its comparison to the WHO guideline. B, C, D and E are stages in PCIS which refer to $PM_{1.0-2.5}$, $PM_{0.5-1.0}$, $PM_{0.25-0.5}$ and $PM_{<0.25}$, respectively.

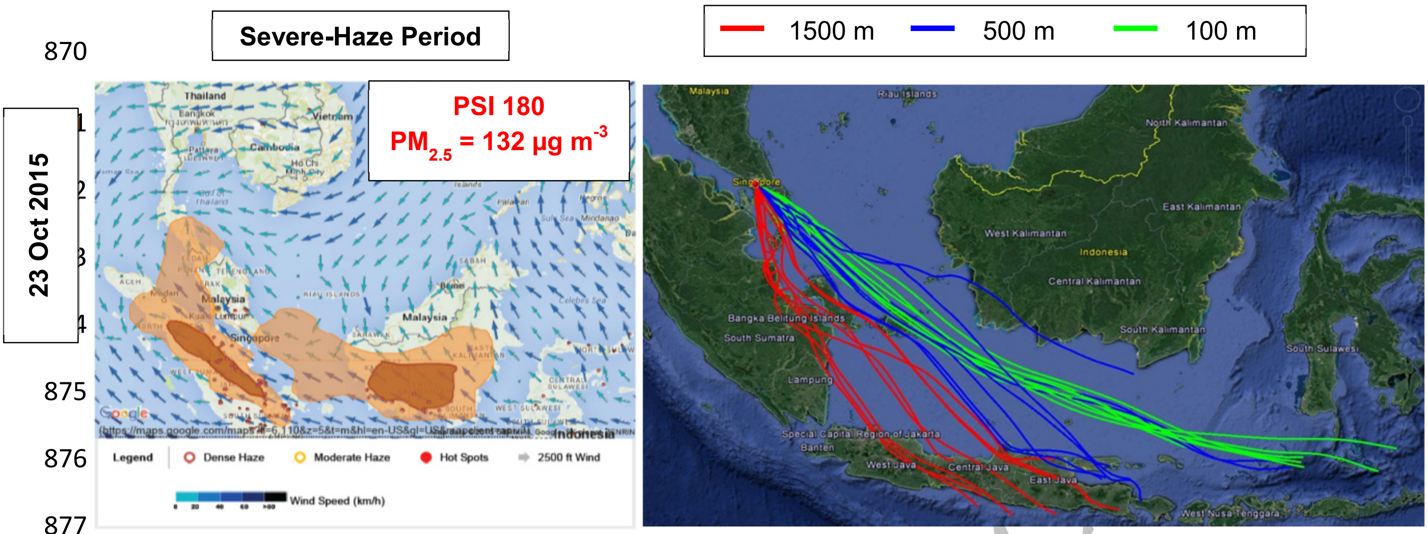
Fig. 3. Indoor and outdoor PM concentrations in various sizes under different levels of haze as per PSI values. A, B, C, D and E are $PM_{>2.5}$, $PM_{1.0-2.5}$, $PM_{0.5-1.0}$, $PM_{0.25-0.5}$ and $PM_{<0.25}$, respectively.

Fig. 4. Average I/O ratios in various sizes. A, B, C, D and E are $PM_{>2.5}$, $PM_{1.0-2.5}$, $PM_{0.5-1.0}$, $PM_{0.25-0.5}$ and $PM_{<0.25}$, respectively.

Fig. 5. Deposited dose in the three zones of respiratory system for size-fractionated PM under three haze levels for indoors and outdoors. L, M and S refer to light-haze, moderate-haze and severe-haze levels, respectively.

Fig. 6. Total carcinogenic human health risk for indoors and outdoors for size-fractionated aerosols (coarse, accumulation and q-UF) for adults and its comparison with threshold value for different levels of haziness.

Fig. 7. Uncertainty analysis for total carcinogenic human health risk for $PM_{2.5}$ for indoors and outdoors and its comparison with threshold value for different levels of haziness.



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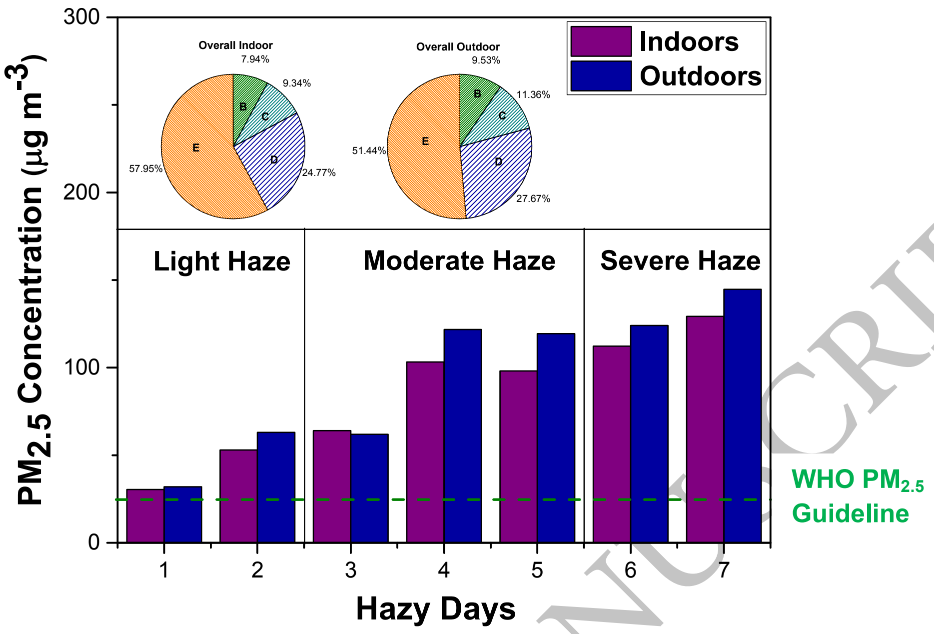

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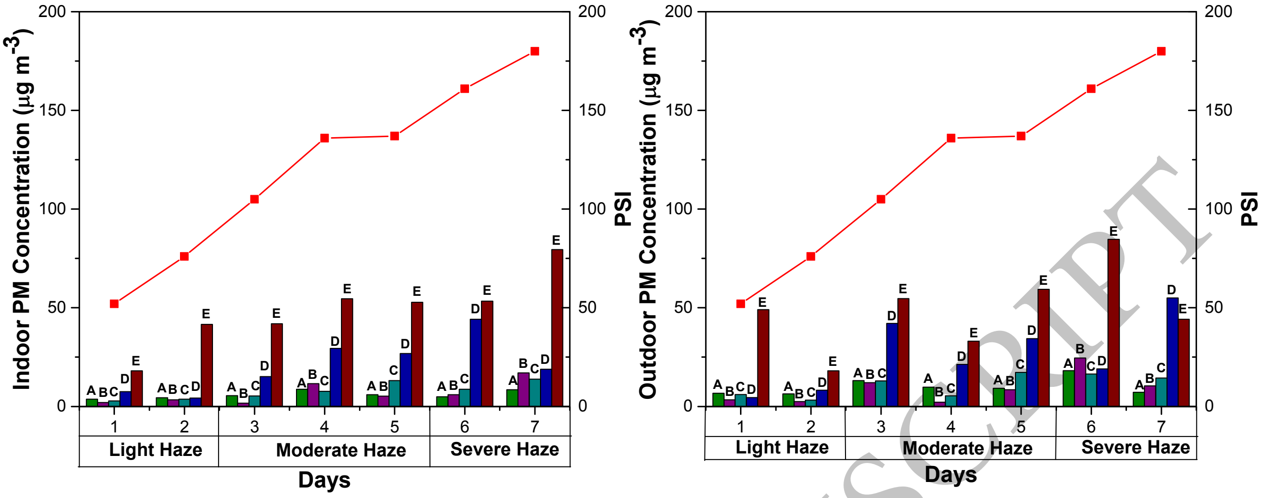

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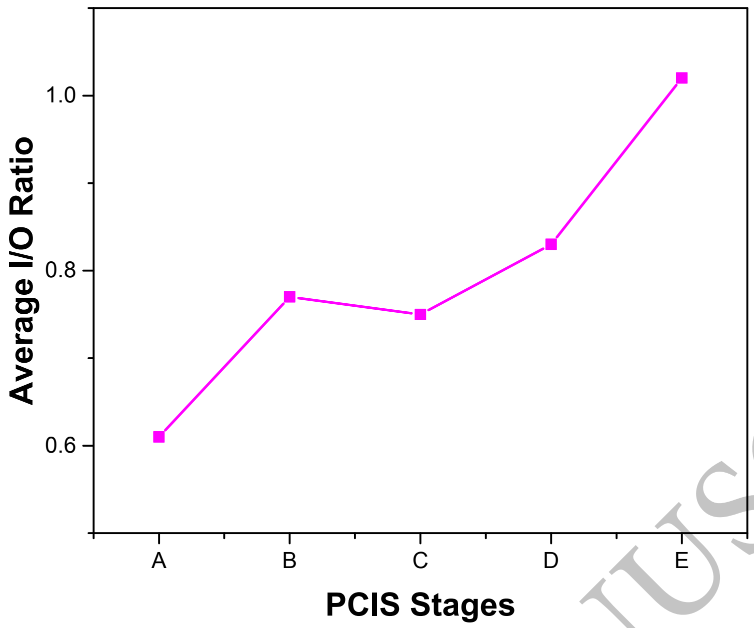

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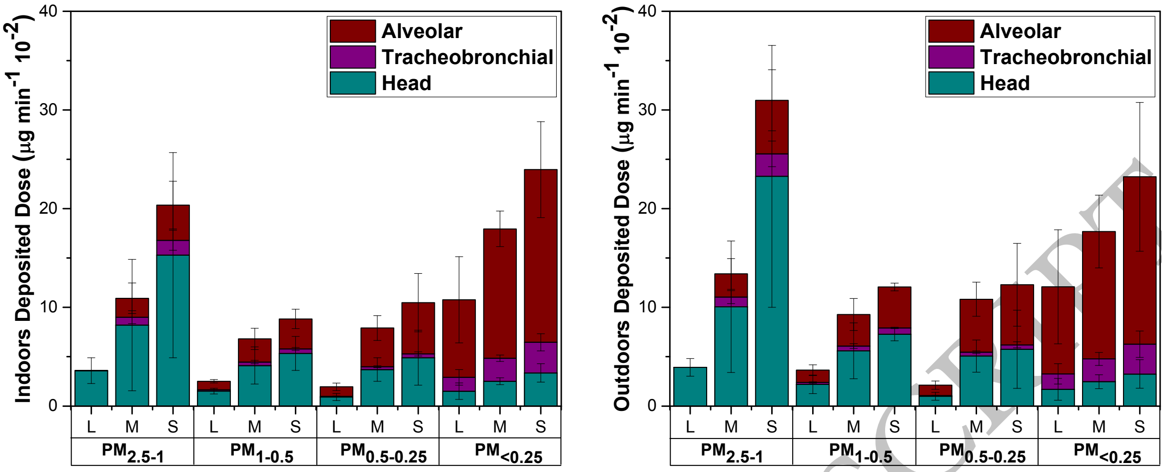

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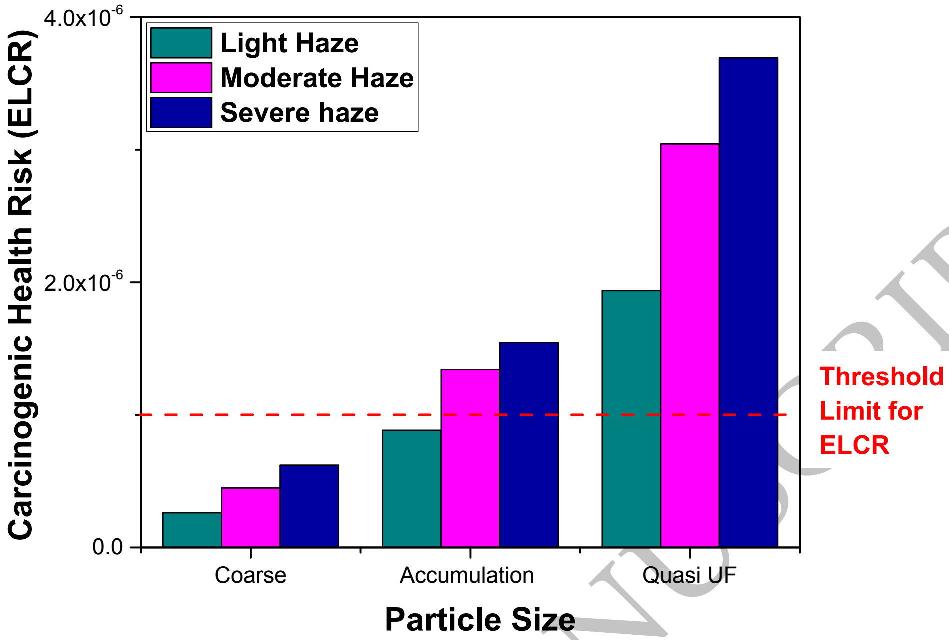

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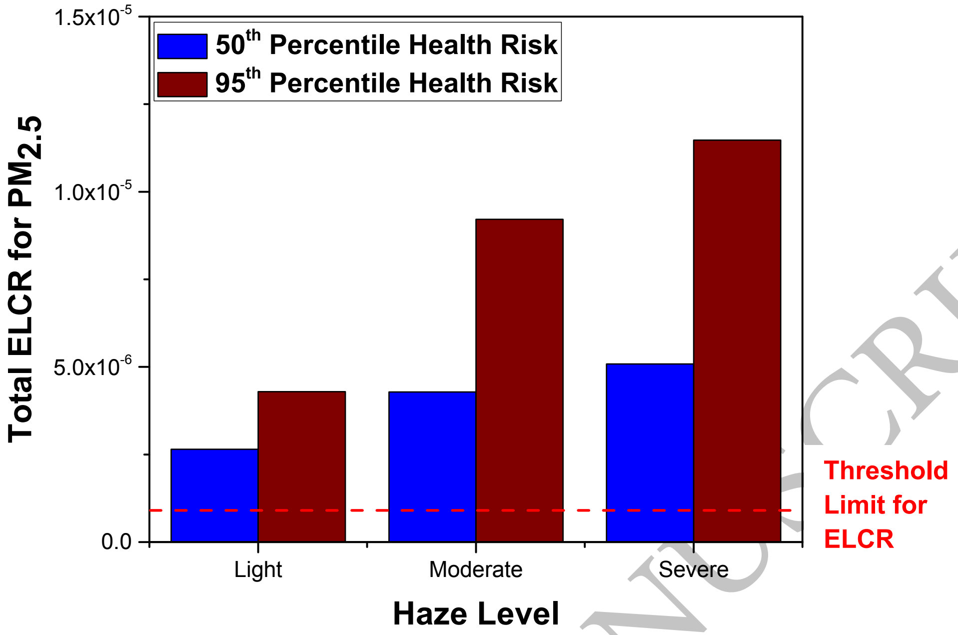

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