Chemosphere 226 (2019) 616–624

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

# Air quality changes after Hong Kong shipping emission policy: An accountability study

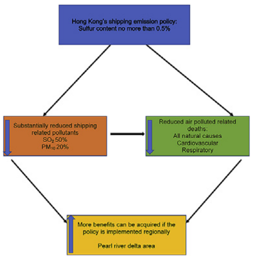
Tonya G. Mason [a], King Pan Chan [a], C. Mary Schooling [a], Shengzhi Sun [c], Aimin Yang [a], Yang Yang [a], Benjamin Barratt [b], Linwei Tian [a, *]

[a] *School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong, China*
[b] *MRC-PHE Centre for Environment and Health & NIHR GSTFT/KCL Biomedical Research Centre, Analytical and Environmental Sciences Division, Faculty of Life Sciences & Medicine, King's College London, London, UK*
[c] *Department of Epidemiology, Brown University School of Public Health, Providence, RI, USA*

## HIGHLIGHTS

- Shipping emission policy resulted in a reduction in $SO_2$ at the main shipping port in Hong Kong by almost 50%.
- Other benefits included a reduction in $PM_{10}$ by 20%.
- The policy reduced air pollution related deaths.
- Full benefits of the policy can only be accomplished if it is enforced regionally and not just in Hong Kong.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 30 November 2018
Received in revised form
25 March 2019
Accepted 26 March 2019
Available online 29 March 2019

Handling Editor: R Ebinghaus

*Keywords:*
Shipping emission policy
Interrupted time series
Segmented regression analysis
CUSUM
Sulfur dioxide
Kwai chung

## ABSTRACT

*Background:* On July 1st 2015, Hong Kong became the first city in Asia to implement a policy regulating sulfur dioxide ($SO_2$) in shipping emissions. We conducted an accountability study assessing the improvement in ambient air quality and estimating the effect on health outcomes of the policy.
*Method:* We used interrupted time series (ITS) with segmented regression to identify any change in ambient concentrations of $SO_2$ in contrast to other ambient pollutants (particulate matter <10 μm in diameter ($PM_{10}$), nitrogen dioxide ($NO_2$) and ozone ($O_3$)) at 10 monitoring stations in Hong Kong from 2010 to 2017. We validated these findings using cumulative sum control (CUSUM) charts. We used a validated risk assessment model to estimate effects of changes in air quality on death for natural causes, cardiovascular and respiratory diseases.
*Results:* Mean monthly concentrations of $SO_2$ fell abruptly at the monitoring station closest to the main shipping port (Kwai Chung (KC)) by $-10.0\ \mu gm^3$ p-value = 0.0004, but not elsewhere. No such changes were evident for the other pollutants ($PM_{10}$, $NO_2$, $O_3$). CUSUM charts confirmed a change in July 2015. Estimated deaths avoided per year as a result of the policy were 379, 72, 30 for all natural causes, respiratory and cardiovascular diseases respectively.
*Conclusion:* Implementation of the shipping emission policy in Hong Kong successfully reduced ambient $SO_2$, with the potential to reduce mortality. However, to gain full benefits, restrictions on shipping emissions need to be implemented throughout the region.

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* Corresponding author.
*E-mail address:* linweit@hku.hk (L. Tian).

https://doi.org/10.1016/j.chemosphere.2019.03.173

## 1. Introduction

Globally, shipping emissions contribute significantly to air pollution, especially in areas situated around the coastline. About 70% of shipping emissions occur within 400 km of land (Endresen et al. 2003)(Viana et al. 2014) exposing populations to anthropogenic emissions of particular matter (PM) and of sulfur and nitrogen oxides (Eyring et al., 2005) (Corbett et al. 2007). Shipping emissions account for approximately 15% of global anthropogenic nitrogen oxides and 5–8% of global sulfur oxides (Eyring et al., 2005) (Corbett et al. 2007). $SO_2$ has been known to cause cardiorespiratory health effects due to its ability to be a respiratory irritant and a bronchoconstrictor—resulting in cardiovascular abnormalities (Kan et al., 2010). Many studies have linked air pollution from $SO_2$ to adverse health effects for both morbidity and mortality for cardiorespiratory diseases (Katsouyanni et al., 1997b; Stieb et al., 2002, 2003), including a 4 city study (Hong Kong, Shanghai, Wuhan and Bangkok) done in Asia —in 2010 (Kan et al., 2010). Throughout time, sulfur rich fuels have proven to affect morbidity and mortality rates for cardiovascular and respiratory diseases however reduction in air pollution from these sulfur-rich fuels have resulted in lower cardiorespiratory deaths and hospital admissions (Dockery et al., 2013; Hedley et al., 2002; Stallings-Smith et al., 2013; Wong et al., 1998).

Hong Kong has the fourth busiest shipping port in the world and serves as a major hub port for South Asian Pacific region and the Mainland of China (Ng et al., 2013). Ship exhaust is one of the major sources of sulfur dioxide ($SO_2$) emissions in Hong Kong, contributing about 36% of ambient $SO_2$ concentrations, measured by monitors located close major shipping ports (Kwai Chung and Tsing Yi) (Yau et al., 2012). Lai et al. recently showed an annual excess death rate due to marine emissions in Hong Kong, to be 9–20 times higher than those in the Pearl River Delta (PRD) regions (Lai et al., 2013). In 2012 the civic exchange department in Hong Kong, reported: $SO_2$ emissions from ocean going vessels was responsible for 519 premature deaths per year in the Pearl River Delta region, with majority of these deaths occurring in Hong Kong (385 avoidable deaths) (Kilburn et al., 2012). This is an indication that due to the heavy shipping traffic and a shipping route within close proximity to densely populated areas, in Hong Kong, marine pollution has become of major public health concern. Studies from the current decade have approximated about 3.8 million people living close marine ports in Hong Kong are directly exposed to shipping emissions that are high in $SO_2$ and other shipping related pollutants such as $NO_x$ and $PM_{10}$ (Kilburn et al., 2012; Lai et al., 2013; Ng, 2013).

Regulatory frameworks have been introduced to reduce the sulfur content of marine fuel internationally (International Maritime Organization 2015) and regionally (North-West Ports Clean Air Strategy) (San Pedro Bay Ports Clean Air Action Plan.). Implementation of such policies improve air quality and has the potential to reduce cardiopulmonary and lung cancer related mortality (Velders et al., 2011) (Winebrake et al., 2009). In a global city with the fourth busiest port in the world, we took advantage of the introduction of a shipping emission policy, implemented on July 1st· 2015, requiring all ocean going vessels (OGV) to switch to fuel with a sulfur content not exceeding 0.5% at berth (Environmental Protection Department 2015), to assess the effects on air quality and to estimate the effects on mortality. In this study, we used interrupted time series (ITS) to quantify changes in $SO_2$ concentration and cumulative sum (CUSUM) charts to confirm that the timing of the changes coincided with the policy implementation in Hong Kong. We similarly assessed the changes in $PM_{10}$, $O_3$ and $NO_2$ to assess the specificity of any changes and the changes by proximity to the port. We also estimated effects on deaths based on the excess risk associated with a 10$\mu gm^3$ change in air pollutants.

## 2. Method

### 2.1. Locations

Fig. 1 displays a map of Hong Kong with the 10 monitoring stations including the major shipping port, Kwai Chung (KC), where most container vessels berth. KC is also a hot spot for $SO_2$ emissions from container vessels (Ng et al., 2013). Monitoring stations at Tai Po (TP), Yuen Long (YL) and Tap Mun (TPM) are furthest from the port, and were considered as control stations (see Fig. 1).

### 2.2. Air pollutants

$SO_2$ was the main pollutant considered. $PM_{10}$, $O_3$ and$NO_2$ were considered as control outcomes because they would not be expected to change significantly as a result of the shipping emission policy on reducing the sulfur content in fuel. Daily concentrations of $SO_2$, $PM_{10}$, $NO_2$ and $O_3$ were obtained from 10 of the 16 monitoring stations in Hong Kong, from January 1st, 2010 to December 31 t h, 2017. 3 roadside stations and 3 general stations with extensive missing data (Tseung Kwan O, Tuen Mun, and Kwun Tong) were excluded from the study. Exposure to shipping air pollution is better represented by general monitoring stations than road side stations (Huang et al., 2017). Most of Hong Kong's population lives within 5 km of the 10 general monitoring stations in this study (Huang et al., 2017). All stations are operated by the Hong Kong Environmental Protection Department (HKEPD) who uses automatic analyzers at each monitoring station to obtained hourly ambient air pollution concentration readings.

### 2.3. Air quality assessment

Two complimentary methods were used to assess the impact of the implementation of the shipping emission policy on air quality overall and by monitoring station. The first method, ITS is a study design, commonly used for evaluating interventions (Dennis et al., 2013). It is known as one of the strongest quasi-experimental designs because the design automatically controls for base line and secular trends (Dennis et al., 2013). Segmented regression is the statistical method used for ITS, which allows us to visually and statistically assess air quality before (January 2013–June 2015) and after (July 2015–December 2017) the implementation of the policy, in terms of an abrupt and gradual changes (Nistal-Nuño, 2017) (for more information see supplementary appendix A).

The shipping policy was represented in the model below using an indicator variable ($\beta_2$) which was assigned the value of 0 for the pre-intervention period, and 1 for post intervention. This variable estimated any abrupt changes detected in the mean concentration ($\mu gm^3$) of the air pollutants. Other variables included were: the outcome of interest (monthly mean concentration of air pollutants ($\mu g/m^3$)), represented by $Yt$; the base line period ($\beta_0$) which provided the mean of the outcome at the beginning of the study period (time = 0); time, a continuous variable from the beginning of the study period (2013) to the end (2017); ($\beta_1$), which captured the mean monthly trend of air pollutants ($\mu gm^3$) before the policy, allowing us to account for long term trends in the outcome of interest over time and an interaction term ($\beta_3$) between the policy and time which detected any gradual changes after the policy, in comparison to before. Random variability not explained by the model was represented by $\varepsilon_t$ (error term at time t)

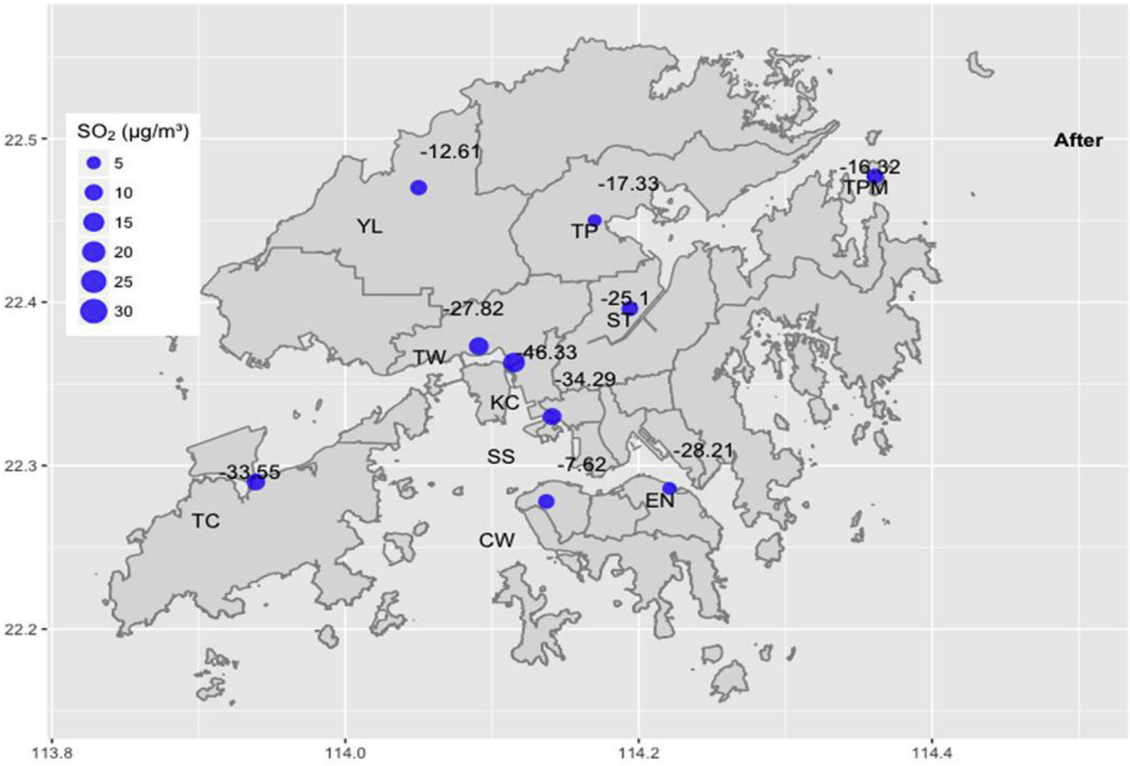

**Fig. 1.** Spatial map of Hong Kong showing $SO_2$ declining percent concentration change, at the 10 monitoring stations, 2 years after the shipping emission policy.

$$Yt = \beta_0 + \beta_1 \times time_t + \beta_2 \times \text{intervention}_t + \beta_3 \times \text{timeafterinterventiont} + \beta_t \quad (1)$$

The Durbin-Watson statistic test was used to test for serial autocorrelation between the error terms in the model (Wagner et al., 2002), with the Cochrane-Orcutt estimator used to correct for autocorrelation. The validity of the ITS model was further assessed by running three additional models, using three false shipping policy periods: 6 months, 12 months and 24 months before the intervention (Stallings-Smith et al., 2013).

The second method, CUSUM charts, were used to verify that a change had occurred at the time of the policy implementation during the period January 1 s, 2010–June 30 t h, 2017. The method was developed initially for industrial purposes and recently the technique has been adapted and used to detect changes in air pollution concentrations (Barratt et al., 2007; Carslaw et al., 2016; Chelani, 2011). In order to apply the technique to detect any changes in the air pollutants for our study, the following procedure was applied: The pre-implementation period (base period), January 1 s, 2010 to June 30 t h, 2015 was used for the calculation of the reference mean and standard deviation. The CUSUM method proposed by Lucas and Crosier (1982) (Barratt et al., 2007) was then applied to individual observations in our time series to calculate the deviations of observations away from the reference mean. Any increase or decrease in mean concentration of the pollutants away from the reference mean were detected by the upper (UDB) and lower (LDB) boundaries on the chart, where the reference value (K) was set to 0.5, as this is the appropriate choice for K in detecting when a 1-sigma shift in the process mean, and it has been shown that sensitivity to detecting shifts away from the mean increases when a smaller reference value is used (Barratt et al., 2007). Confidence limit $(\pm h\sigma_x)$ was also set for the CUSUM charts to indicate when a 1-sigma shift in the process mean has occurred (Barratt et al., 2007). The value of the parameter h is generally set to 4 or 5. We selected h = 4 as it has been widely used in previous studies pertaining to air pollution concentration change (Barratt et al., 2007; Chelani 2011). Detailed description of the CUSUM method charts has been published elsewhere (Barratt et al., 2007; Chelani 2011; Jones et al., 2012; Carslaw et al., 2006). Air pollution concentrations were deseasonalized using the seasonal decomposition time series by Loess (STL) function prior to analysis. All analyses were carried out using the software package R 3.4.2. The R package “qcc” was used for the CUSUM analysis (R Core Team 2016).

### 2.4. Health impact assessment

The health impact of the implementation of the shipping emission policy was based on a previously established relation between changes in air quality $(10ugm^{-3})$ and the mortality rate from all natural causes, cardiovascular diseases and respiratory disease in Hong Kong (Lai et al., 2013). Mortality rates for Hong Kong for 2010–2016 were taken from vital statistics (CHP). Excess deaths due to air pollution from $SO_{2,}$ $PM_{10}$ $NO_2$ and $O_3$ were compared for the periods 2010–2014 versus 2015–2016 as well as 2010 versus 2016. If the excess risk was negative 0 deaths were assumed (Lai et al., 2013), as occurred for $O_{3.}$. The model is described in detail in Appendix B.

## 3. Results

### 3.1. Air quality changes after implementation of the policy

Table 1 shows the average ambient concentrations for $SO_2$, $PM_{10}$ $NO_2$ and $O_3$ at the 10 selected monitoring stations, for two and a half years before and after the policy implementation. The port monitoring station (KC) had the highest levels of $SO_2$ before the

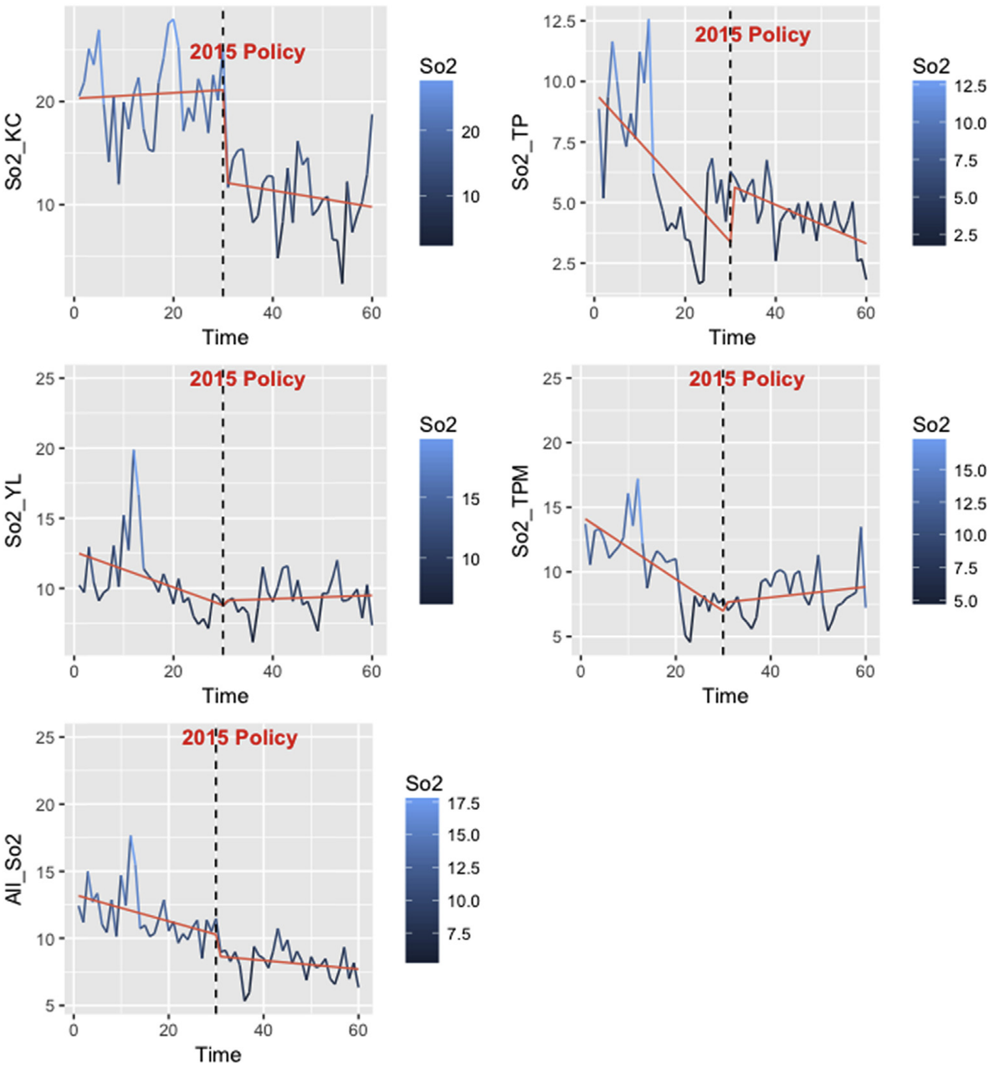

**Fig. 2.** Time series plot of monthly mean concentrations of $SO_2$ at KC, TP, YL, TPM, and all of Hong Kong.

**Table 1**
Mean concentrations of $SO_2$, $PM_{10}$, $NO_2$ and $O_3$ at the 10 general monitoring stations 2.5 years before and after implementation of the shipping emission policy (2013–2017).

| Monitoring stations | Name | $SO_2$ ($\mu gm^3$) | | | $PM_{10}$ ($\mu gm^3$) | | | $NO_2$ ($\mu gm^3$) | | | O3 ($\mu gm^3$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | | Pre | Post | % | Pre | Post | % | Pre | Post | % | Pre | Post | % |
| Port | KC | 21.0 | 11.0 | **−50.0** | 42.0 | 34.0 | −20.0 | 68.0 | 58.0 | −14.0 | 33.0 | 37.0 | 10.0 |
| Control | TP | 5.9 | 4.6 | −21.0 | 41.0 | 32.0 | −23.0 | 46.0 | 36.0 | −22.0 | 49.0 | 49.0 | −0.57 |
| | YL | 11.0 | 9.3 | −12.0 | 52.0 | 39.0 | −25.0 | 52.0 | 43.0 | −17.0 | 37.0 | 40.0 | 8.8 |
| | TPM | 10.0 | 8.2 | −21.0 | 45.0 | 33.0 | −28.0 | 11.0 | 10.0 | −8.9 | 74.0 | 72.0 | −2.4 |
| Other | TW | 16.0 | 11.0 | −29.0 | 43.0 | 32.0 | −25.0 | 60.0 | 46.0 | −24.0 | 35.0 | 38.0 | 8.2 |
| | CW | 9.9 | 8.9 | −11.0 | 46.0 | 33.0 | −27.0 | 50.0 | 42.0 | −17.0 | 41.0 | 48.0 | 17.0 |
| | EN | 6.6 | 4.6 | −31.0 | 40.0 | 31.0 | −21.0 | 54.0 | 44.0 | −19.0 | 40.0 | 54.0 | 34.0 |
| | SS | 14.0 | 8.7 | −37.0 | 44.0 | 34.0 | −24.0 | 68.0 | 56.0 | −17.0 | 33.0 | 37.0 | 12.0 |
| | ST | 10.0 | 7.1 | −29.0 | 40.0 | 30.0 | −25.0 | 44.0 | 38.0 | −15.0 | 49.0 | 48.0 | −1.9 |
| | TC | 13.0 | 8.6 | −33.0 | 41.0 | 33.0 | −18.0 | 46.0 | 37.0 | 20.0 | 45.0 | 45.0 | 0.13 |

intervention and the largest reduction in $SO_2$ concentration after the policy was implemented. Changes in the other pollutants and at other monitoring stations were less marked.

Table 2 shows that the fall in $SO_2$ at the port monitoring station (KC) when the policy was implemented was abrupt but not gradual (illustrated graphically in Fig. 2). No changes in $PM_{10}$, $NO_2$ or $O_3$ were evident at KC. Table 2 also shows no such abrupt (or gradual) change in $SO_2$ at the non-shipping control stations (TP, YL and TPM). However, abrupt declines also occurred at two other monitoring stations close to the port, with a gradual decline at one other station (Appendix C), although the CUSUM charts indicated the decline might have started before the policy change (Appendix D). No decline in $SO_2$, $PM_{10}$, $NO_2$ or $O_3$ were evident for Hong Kong although the possibility of a small abrupt change in $SO_2$ cannot be excluded. After controlling for seasonality, autocorrelation was still present in the error terms based on the Durbin-Watson (DW)

**Table 2**
Estimates of the abrupt and gradual changes in $SO_2$, $PM_{10}$, $NO_2$ and $O_3$ at the port (KC) monitoring station after implementation of the shipping emission policy.

| Station | Air Pollutant | Change | Beta | se | t-values | p-values |
|---|---|---|---|---|---|---|
| **KC** | | | | | | |
| | $\mathbf{SO_2}$ ($\mu$gm$^3$) | Abrupt | −10.0 | 2.7 | −3.8 | 0.0004 |
| | | Gradual | −0.081 | 0.17 | −0.46 | 0.65 |
| | $\mathbf{PM_{10}}$ ($\mu$gm$^3$) | Abrupt | −7.8 | 5.4 | −1.4 | 0.16 |
| | | Gradual | 0.54 | 0.34 | 1.6 | 0.12 |
| | $\mathbf{NO_2}$ ($\mu$gm$^3$) | Abrupt | −4.8 | 4.9 | −0.98 | 0.33 |
| | | Gradual | 0.004 | 0.31 | 0.014 | 0.99 |
| | $\mathbf{O_3}$ ($\mu$gm$^3$) | Abrupt | −1.5 | 4.7 | −0.33 | 0.74 |
| | | Gradual | −0.31 | 0.28 | −1.1 | 0.28 |
| **All of HK** | | | | | | |
| | $\mathbf{SO_2}$ ($\mu$gm$^3$) | Abrupt | −1.6 | 0.91 | −1.8 | 0.084 |
| | | Gradual | 0.071 | 0.055 | 1.3 | 0.20 |
| | $\mathbf{PM_{10}}$ ($\mu$gm$^3$) | Abrupt | 3.6 | 4.6 | 0.77 | 0.44 |
| | | Gradual | 0.14 | 0.28 | 0.52 | 0.61 |
| | $\mathbf{NO_2}$ ($\mu$gm$^3$) | Abrupt | 5.4 | 2.7 | 2.0 | 0.049 |
| | | Gradual | −0.24 | 0.16 | −1.5 | 0.14 |
| | $\mathbf{O_3}$ ($\mu$gm$^3$) | Abrupt | 0.92 | 3.8 | 0.25 | 0.81 |
| | | Gradual | 0.15 | 0.23 | 0.64 | 0.52 |
| **Control** | | | | | | |
| **TP** | $\mathbf{SO_2}$ ($\mu$gm$^3$) | Abrupt | 1.6 | 1.3 | 1.3 | 0.21 |
| | | Gradual | 0.12 | 0.092 | 1.3 | 0.20 |
| **YL** | $\mathbf{SO_2}$ ($\mu$gm$^3$) | Abrupt | 0.62 | 1.5 | 0.43 | 0.67 |
| | | Gradual | 0.16 | 0.099 | 1.6 | 0.11 |
| **TPM** | $\mathbf{SO_2}$ ($\mu$gm$^3$) | Abrupt | 0.37 | 1.4 | 0.27 | 0.79 |
| | | Gradual | 0.28 | 0.092 | 3.1 | 0.003 |

statistic test which gave a value of <2. Autocorrelation was then corrected by using the Cochrane-Orcutt estimator. The results were similar. In the sensitivity analysis, the 3 false policy periods we evaluated before the policy showed no significant changes in mean monthly $SO_2$ concentration compared to the actual policy periods (see Supplementary Table 4).

Fig. 3, using CUSUM analysis, confirmed a reduction in ambient $SO_2$ concentration at the shipping port (KC) at the time the shipping emission policy was implemented. In contrast, at one of the control station (TP) $SO_2$ appears to have been declining before the policy was implemented. For Hong Kong as a whole the CUSUM analysis does not confirm a reduction in ambient $SO_2$ concentration when the shipping emission policy was implemented (Fig. 4). Similarly, for the other stations in Hong Kong CUSUM showed $SO_2$ concentration to be declining before implementation of the policy (Appendix D).

### 3.2. Health impact associated with the policy

Based on the changes in these air pollutants for all of Hong Kong during the period 2010–2014 compared to 2015–2016 the total number of avoidable deaths per year for all natural causes (deaths not caused by external forces), cardiovascular disease and respiratory disease were 379, 72 and 30 respectively for all ambient pollutants combined. The corresponding avoidable deaths per year for all natural causes, cardiovascular disease and respiratory disease attributable to ambient $SO_2$ were 118, 18 and 10. In comparison to the above time period evaluated, avoidable deaths were higher when comparing 2010 with 2016. Combining the ambient concentrations of all 4 pollutants, avoidable deaths per year for natural causes, cardiovascular disease and respiratory disease were 437, 92 and 36 respectively, with cardiovascular disease having more avoidable deaths than respiratory diseases. The corresponding avoidable deaths associated with $SO_2$ during this period were also slightly higher for natural cause of death (123), cardiovascular diseases (20) and respiratory diseases (11) (Table 3.).

## 4. Discussion

Consistent with the implementation of policies to reduce the sulfur content of shipping fuel in Europe and the United States (Schembari et al. 2012) (Velders et al., 2011), this first study of the implementation of a shipping emission policy on the sulfur content of fuel in Hong Kong shows it was very effective in reducing $SO_2$ levels near the major shipping port in Hong Kong, which previously had the highest levels of $SO_2$ in Hong Kong. However, the effects for Hong Kong overall and for Hong Kong excluding the major shipping port were less marked but not at all negligible (e.g., 20% reduction for $PM_{10}$).

Our study had sufficient observations over time to use ITS to draw conclusions about the magnitude of the impact of the intervention on pollution concentrations independent of any secular trend (Penfold and Zhang, 2013; Pharmd et al., 2002; Lopez Bernal et al. 2016), which is more reliable than a before and after comparison (Penfold and Zhang, 2013). We also used CUSUM to confirm that the timing of the change matched the timing of the intervention (Barratt et al., 2007), because the concentration change was large in comparison to seasonal fluctuations and the long term trend (Barratt et al., 2007).

From a public health perspective, this study shows the benefits of reducing the sulfur content of shipping fuel, although this need to be contextualized within the overall environmental and health costs of any other consequences of this policy. More broadly, this study also raises specific issues about air pollution in Hong Kong. The declining trend of $SO_2$ concentration at the control station (TP) and for all of Hong Kong, is probably a reflection of tighter power plant regulations (Ng et al., 2013) and introduction of the Second West-East Natural Gas Pipeline in 2013— supplying cleaner fuel to generate electricity (Environmental Protection Department 2016). However, $SO_2$ concentration at non port areas in Hong Kong, such as Tsuen Wan (TW), Sham Shui Po (SS), Central Western (CW), Tung Chung (TC), TPM and YL were also high, possibly because of close proximity to the major shipping lanes in Hong Kong and for the latter two, close location to shipping ports based in mainland China (TPM and YL) (Ng et al., 2013) —which does not have strict marine vessels emission regulations. Although the measures such as tighter power plant regulations, mentioned, might have resulted in synergistic declines of $SO_2$ in Hong Kong, these interventions were implemented over a long time period for gradual $SO_2$ reduction in Hong Kong. The shipping emission policy, however, was implemented punctually on July 1st' 2015, which is a more likely the explanation for the abrupt decline in $SO_2$ concentration.

$SO_2$, unlike all other pollutants, has a peak season both in the summer (July and August) and winter months (October and January) (Lau et al., 2005). In the winter months, the pollutant ranges for moderate to high at all stations due to the northwesterly winds which bring in pollution from the Pearl River Delta (Lau et al., 2005). However, during the summer month peak period, the wind direction is from weak south westerlies and stations such as Tsuen Wan (TW), Sham Shui Po (SS), Central Western (CW) and KC in particular, has the highest levels of $SO_2$ with the south westerlies, while other stations the levels are low (Lau et al., 2005). This highlights the significance of $SO_2$ from local shipping emission sources —such as the large container port located to the south-south west of KC (Lau et al., 2005).

The policy undoubtedly reduced air pollution related deaths in Hong Kong, as seen in other similar intervention studies focusing on sulfur and coal bans, which revealed a substantial reduction in $SO_2$ concentration accompanied by a drop in cardiovascular and respiratory diseases (Clancy et al., 2002) (Hedley et al., 2002). An intervention study carried out by Hedley and company, showed that the 1990 intervention in Hong Kong to reduce sulfur in fuels

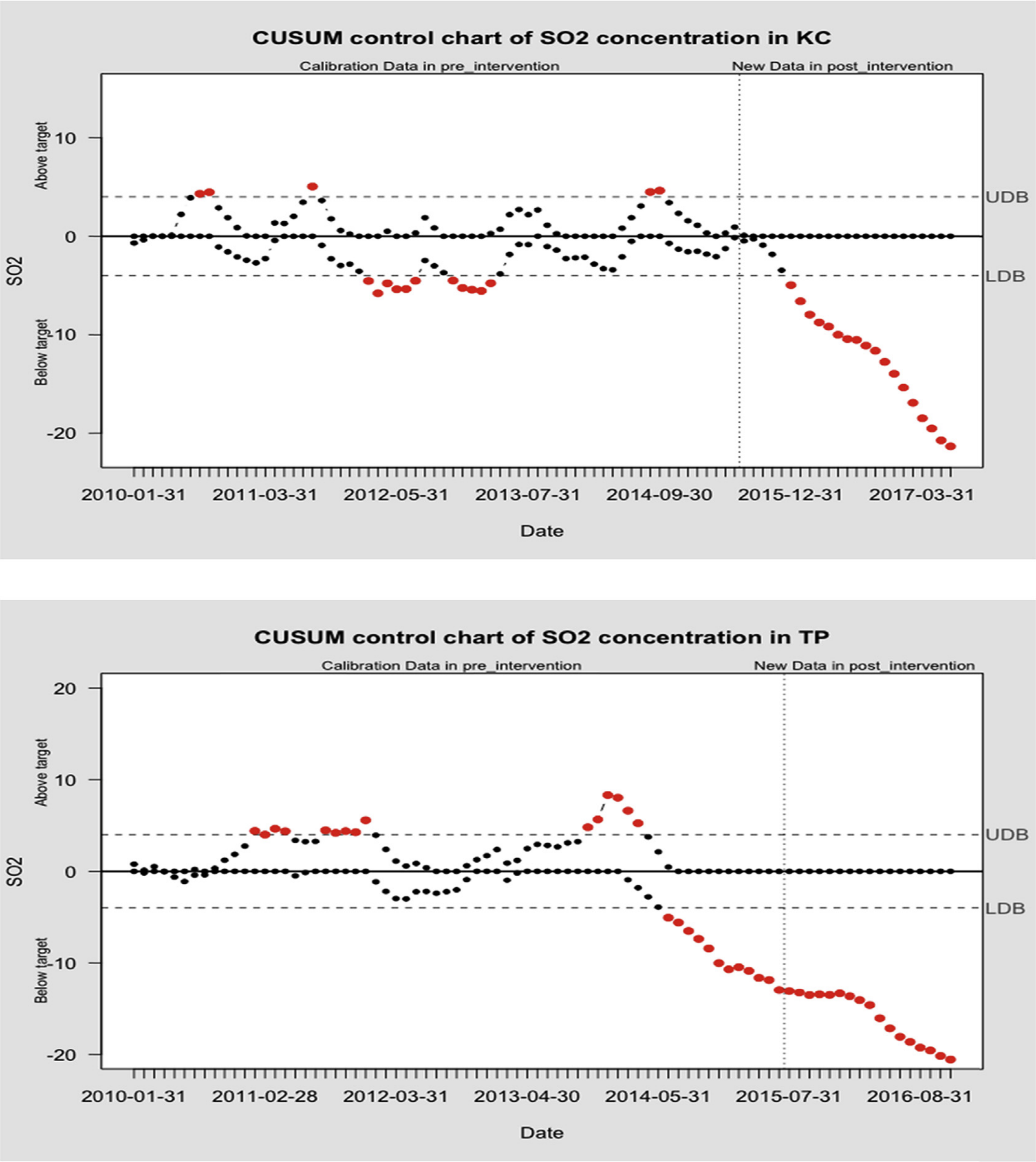

**Fig. 3.** CUSUM chart comparing KC and TP $SO_2$ concentrations before and after the shipping emission policy.

had resulted in an reduction in seasonal deaths for cardiovascular and respiratory diseases, 12 months after the implementation of the policy (Hedley et al., 2002). Albeit, some research have shown respirable particles to be the main component in air pollution that causes death, some time series studies have reported strong associations between $SO_2$ and daily cardiorespiratory deaths even after adjusting for other gaseous pollutants and suspended particles (Kan et al., 2010; Katsouyanni et al., 1997a; Venners et al., 2003; Wong et al., 2001).

Our study has some limitations. First, the health impact assessment should be interpreted with caution because it was based on ambient air pollution concentrations and not on concentrations solely due to shipping emissions. For the health evaluation, we also adopted a method which is a simple, robust and conservative (Hedley et al., 2008). Nevertheless, the total estimate of avoidable deaths is close to what was predicted for a 0.5% reduction in sulfur content of marine vessel fuel in Hong Kong (Kilburn et al., 2012). Moreover, many studies have also indicated an association of $SO_2$ with hospital admissions and deaths (Chen et al., 2012; Derriennic et al., 1989; Geravandi et al., 2016; Kan et al., 2010; Kermani et al., 2016; Wong et al., 2002).

Second, we estimated health effects across Hong Kong from levels at the monitoring stations rather than on individual exposures. However, Hong Kong is very compact and most people live within close proximity to the monitoring stations (Huang et al., 2017). Third, due to the lack of data we were unable to evaluate $PM_{10}$ components that are specific to shipping emissions. However, in Hong Kong, $PM_{10}$ comes from 4 major sources: traffic, local power plants, regional air pollution from China and ships. Out of these 4 sources, shipping emission only accounts for a small fraction (1/3). Lastly, the CUSUM technique was used in the most basic form, which means any subtle changes in pollution levels were not detected because underlying temporal variation was not adjusted for in the mean and standard deviation used for the CUSUM plots.

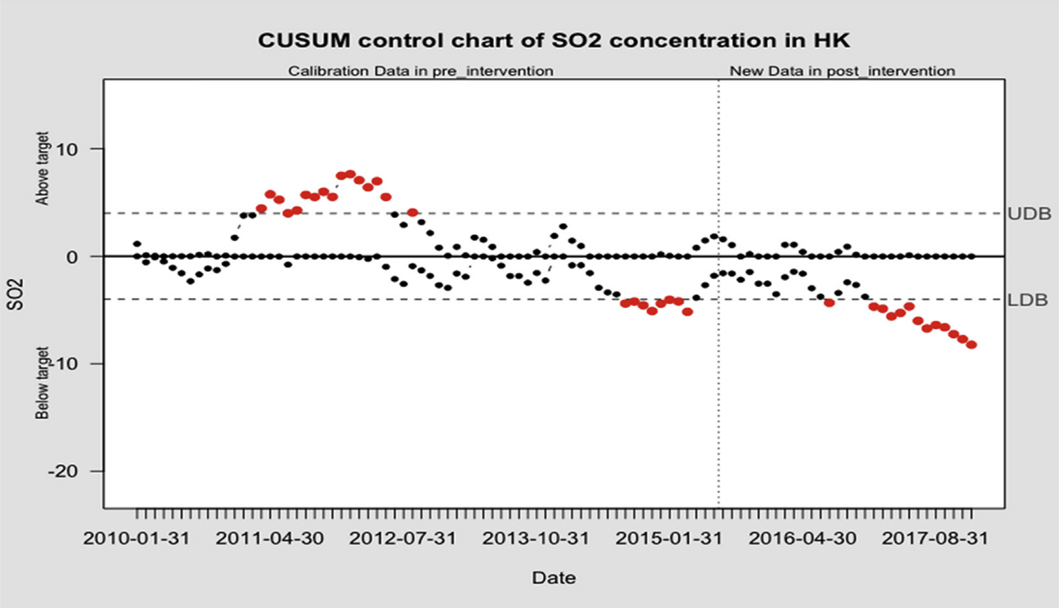

**Fig. 4.** CUSUM chart comparing $SO_2$ concentrations before and after the shipping emission for all of Hong Kong.

**Table 3**
Estimates of avoided deaths due to the decline of four ambient pollutants ($\mu g/m^3$) after the shipping emission policy, comparing two time periods: 1) 2010–2014 vs. 2015–2016 & 2) 2010 vs.2016.

| Excess deaths | Air pollutant ($\mu gm^3$) | $N_1$ | | ERp | Lp | | Avoidable deaths | |
|---|---|---|---|---|---|---|---|---|
| | | 2010–2014 vs. 2015–2016 | 2010 vs. 2016 | 2010 – 2016 | 2010–2014 vs. 2015–2016 | 2010 vs. 2016 | 2010–2014 vs. 2015–2016 | 2010 vs. 2016 |
| All natural causes (T) | | | | | | | | |
| | $SO_2$ | 41777 | 40835 | 0.71 | 4.0 | 4.2 | 118 | 123 |
| | $NO_2$ | 41777 | 40835 | 1.4 | 7.4 | 8.8 | 431 | 501 |
| | $PM_{10}$ | 41777 | 40835 | 0.31 | 11.0 | 14.0 | 145 | 181 |
| | $O_3$ | 41777 | 40835 | 0.42 | −0.95 | −1.2 | −17 | −20 |
| total | | | | | | | 379 | 437 |
| Cardiovascular disease | | | | | | | | |
| | $SO_2$ | 6298 | 6636 | 0.72 | 4.0 | 4.2 | 18 | 20 |
| | $NO_2$ | 6298 | 6636 | 1.6 | 7.4 | 8.8 | 75 | 94 |
| | $PM_{10}$ | 6298 | 6636 | 0.49 | 11.0 | 14.0 | 35 | 46 |
| | $O_3$ | 6298 | 6636 | 0.51 | −0.95 | −1.2 | −3 | 2 |
| Total | | | | | | | 72 | 92 |
| Respiratory disease | | | | | | | | |
| | $SO_2$ | 1904 | 2093 | 1.3 | 4.0 | 4.2 | 10 | 11 |
| | $NO_2$ | 1904 | 2093 | 2.2 | 7.4 | 8.8 | 31 | 40 |
| | $PM_{10}$ | 1904 | 2093 | 0.57 | 11.0 | 14.0 | 12 | 17 |
| | $O_3$ | 1904 | 2093 | 0.48 | −0.95 | −1.2 | −1 | −1 |
| Total | | | | | | | 30 | 36 |

$N_1$ is the annual number of the event I in the population.
ERp is the pooled excess risk (%) for 10 $\mu g/m^3$ change in pollutant.
Lp the change in the level of pollutant P for the reduction from one defined year to the other.
P is each of the criteria pollutant.
$T = SO_2 + 0.88PM_{10} + 0.31NO_2 + O_3$.

## 5. Conclusion

Implementation of a policy to reduce the sulfur content of shipping fuel substantially reduced ambient $SO_2$ with likely corresponding effects on deaths. However, future research on the effect source specific shipping emission pollutants have on mortality is needed, to estimate more accurate mortality rates associated with shipping emissions. For coastal cities like Hong Kong to gain full benefits, the policy needs to be implemented regionally.

## Acknowledgements

We thank the Center for Health Protection (CHP) report for supplying the health data and the Environmental Protection

Department of the Hong Kong Special Administrative Region for providing the air monitoring data for this study.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2019.03.173.

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