Poll Res. 41 (1) : 1-16 (2022)

ISSN 0257–8050
DOI No.: http://doi.org/10.53550/PR.2022.v41i01.001

CONVERGENCE ANALYSIS OF FINE PARTICULATE ($PM_{2.5}$) CONCENTRATIONS FOR 212 TO 108 COUNTRIES

YU SANG CHANG[1], DOHYUN PAK[2*] AND HYEONGSOP SHIM[3]

[1,3]*Department of Management, Gachon University, Korea*
[2]*Department of Financial Mathematics, C Seongnam-si, Gyeonggi-do 461-701, Korea*

(Received 12 July, 2021; Accepted 11 August, 2021)

ABSTRACT

Two measures of fine particulate matter, $PM_{2.5}$ exposure and exceedance are used to analyze convergence patterns of 212 and 108 countries during the period of 2000 to 2014. For exposure, sigma index diverges at the annual rate of +1.07%, while gamma index converges at -0.5% rate. For exceedance, sigma index also diverges at +1.24%, while gamma index converges at -1.22%. The results from income and regional subgroups also indicate that lagging countries are catching-up to leading countries throughout the period in each subgroup. Policy implications from these finding will be discussed.

KEY WORDS : Convergence analysis, Exposures, Exceedance, Sigma index, Gamma index, Catch-up effect

INTRODUCTION

According to a recent research (World Bank & Institute for Health Metrics and Evaluation, 2016 p.22), around 5.5 million people die prematurely every year due to air pollution, accounting for approximately one in every ten deaths annually. Nearly 90 % of air pollution related deaths occur in low and middle income countries with nearly two out of three occurring in South-East Asia and Western Pacific regions (WHO, 27 September, 2016). Ninety eight percent of cities in low and middle income countries with more than 100,000 inhabitants do not meet WHO air quality guideline. However, in high-income country, that percentage decreases to 56% (WHO, 12 May, 2016). The earlier report (World Bank & Institute for Health Metrics and Evaluation, 2016) estimates that air pollution cost the global economy approximately US $ 225 billion in 2013 alone due to lost labor, and about US $ 5 trillion per year as a result of productively losses and a degraded quality of life (World Bank and Institute for Health Method and Evaluation, 2016, pp50.52).

Therefore, air pollution is included in several Sustainable Development Goals and Targets established by the United Nations. For example, Goal 3, target 9 stated that by 2030 substantially reduce the number of deaths and illnesses from hazardous chemicals and air water and soil pollution and contamination. Also, Goal 11, target 6 stated that by 2030, reduce the adverse per capita environmental impact of cities including by paying special attention to air quality and municipal and other waste management.

While air pollution consists of a mix of different pollutions, particulate matter (PM) is among the deadliest (World Health Organization, 2016). It is estimated that exposure cause 3.1 million deaths a year worldwide, and any level above zero is deemed unsafe (WHO, 2014). Fine PM is defined as 2.5 microns or less in diameter (), which is small enough to lodge into human lung and has the potential to cause serious heart and lung disease (Goldberg, 2008). World Health Organization (2006) has provided air quality guideline for long-term exposure of at 103/3. In addition, they also provided 15 3/3, 253/3, and 35 3/3 as three interim targets.

For the analysis of fine PM, we use two measures for exposure and exceedance. exposure to be designated in this paper measures the average

Corresponding author's email: dhmpak@gachon.ac.kr

amount of fine PM in micrograms per cubic meter (3/3). measures the amount a person would be exposed to on a typical day in their country (Engel-Cox *et al*., 2013). exceedance to be designated as PME in this paper measures the weighted average of the percentage of the population exposed to elevated levelsof by measuring instances when concentration exceeded 10, 15, 25, and 35 3/3 which are the WHOs guidelines and interim targets. Annual data for these two PM measures during the period of 2000 to 2014 are used in this study.

The first academic research (Grossman and Krueger, 1991), which was followed by another report (Shafik, 1994) used the environmental Kuznets curve (EKC) model to estimate income turning points for local air pollutant concentrations. However, most subsequent applications of the EKC have focused on pollution emissions such as carbon dioxide (Selden and Son, 1994; Poon, *et al*., 2006; Song *et al.,* 2008; Cole *et al.,* 2011; Lee and Oh, 2015).

Among the few recent studies using the EKC to analyze pollution concentrations include an EKC analysis of concentrations for a cross section of US counties (Keene and Deller, 2015). In addition, there are several studies (Brajer *et al*., 2011; Hao and Liu, 2010; Stern and Zha, 2016) using the EKC approach to analyze concentrations for Chinese cities.

Alternatively, using convergence method to analyze the evolution of emissions has become popular, as indicated by a review of the extensive literature on convergence of carbon emissions (Pettersson *et al.,* 2013). Most recently Stern and Van Dijk (2017), have combined the EKC with convergence method to analyze changes in national level population-weighted concentrations in a global panel of 151 countries between 1990 and 2010. However, the application of traditional convergence methodology to analyze the changing trends of PM measures on a global scale has not been reported, to our best knowledge.

Therefore, this paper will use a simple convergence method to analyze the changing trends of PM measures for 212 to 108 countries in the world during the period of 2000 to 2014. The central question of this paper, then, is to examine whether country differences existing in 2004 of and PME have converged by 2014? More specially, the first question is whether countries with initially high and PME have improved faster to catch-up those countries with initially low and PME and if so, how fast? The second question is whether dispersions of PM measures have decreased during the period and if so, how fast? These two questions are analyzed in the contexts of income and regional subgroups of countries as well.

After this introduction, the paper is organized into four additional sections. In the second section, convergence methods to be used are explained followed by the description of data and data sources in the third section. Analyses of results are presented in the fourth section to be followed by conclusions in the fifth section.

Convergence Methodology

The convergence analysis attempts to examine two basis questions. First, do countries initially lagging in such performance measures as and PME tend to improve faster so that they catch up to the performance of leading countries over time? Second, does dispersion of performance measures among countries get reduced over time?

Traditionally, β convergence is used to examine the first question, while convergence is used to analyze the second question. β convergence implies that the performance measures improve faster in countries with poor initial performance values and improve slower in countries with superior initial performance values. The so-called Barro β convergence method (Barro, 1991) regress therate of improvement during a period on the initial value of the performance measure for respective countries. If the value of coefficient of slope is negative and statistically significant, then the catch-up process is demonstrated (Barro, 1991; Barro and Sala-i-Martin, 1992).

When the regression includes only the initial value as independent variable, it models unconditional or absolute β convergence in which all countries are assumed to move toward a common destination. Since such a restrictive assumption is rarely satisfied in practice, the resulting estimate may contain a significant bias. For that reason, the regression often includes multiple variables relating to the characteristics of countries such as productivity, quality of education, etc. Then, it represents a model of conditional convergence or club convergence.

The use of Barro regression for both unconditional and conditional β convergence was criticized to yield biased estimates (Friedman, 1992) due to Galtons Fallacy relating to the tendency of regression to mean. Instead, Friedman (1992) suggests that convergence can be more appropriately measured by tracking the inter-temporal change in the coefficient of variations of the distribution of performance measures for given countries. This method is known as convergence. If the trend is statistically significant and declining, α convergence is confirmed. In addition, α convergence method is simple to use.

Another criticism of convergence (Quah, 1996) is that the method does not provide us with the inter-temporal intra-distribution mobility of countries with respect to performance measures. Therefore, Quah (1993) suggests a method which is capable of capturing the full dynamics of evolving cross-country distribution using Markov Chain analysis. A simple approximation to Quahs methodology was proposed by Boyle and McCarthy (1997) where they use Kendalls index of rank concordance (Siegel, 1956) to measure changes in the ordinal ranking of countries over time. They label their method asconvergence. By using convergence with simple measure of convergence, they suggest that one can identify the nature of convergence and also a sense of the dynamics of the cross-country distribution of performance measures.

For our methodology, we use convergence (Boyle and McCarthy, 1997) and convergence (Friedman, 1992). Common measures of dispersion include the standard deviation and coefficient of variation (Heckelman, 2015). For convergence, we have selected to use coefficient of variation (CV). CV is measured by dividing standard deviation by the sample average. Using CV which is dimensionless ratio enables us to compare the degree of dispersion for performance measures with different units.We then measure the inter-temporal changes by normalizing CV in subsequent years to CV at the initial year of 1990. Therefore, CV in 1990 is always 1.0. If the values of normalized CVs in the subsequent years are less than the CV in the initial year, then, the normalized CV in subsequent years will be less than 1.0. If the values of normalized CVs in the subsequent years continue to decrease, and the differences between CVs are statistically significant, the result is viewed as evidence of convergence or reduction of dispersion. We use two sample t test for CV (http://www.real-statistics.com/students-t-distribution/coefficient-of-variation-testing/). Thistest works best when the sample sizes are at least 10. Sime our sample sizes are much larger than 10, this test should work well.

For γ convergence model

Boyle and McCarthy (1997) suggested the use of Kendalls index of rank concordance which measures mobility of the individual countries over time within the cross country distribution of a particular performance measure (Liddle, 2012; Chang *et al.*, 2019). In other words, convergence measures the degree of changing ranking order of countries between a given year and the initial year. The -convergence we use is Kendalls binary index version and isdefined as follows:

Where 545E (5L)= the actual rank of country is performance measure in year t

545E (0) = the actual rank of country is performance measure in year 0

= Binary Gamma Index in year t.

The index has the advantage of being of single number traced over time in two- dimension, analogous to the convergence index. The value of rank concordance ranges from zero to unity. If no change in rank order takes place, the rank concordance becomes unity. If a catch-up process is present, which result in change of rank order the index will be less than unity. The statistic is distributed as chi-square and we test the null hypothesis that convergence shows no difference between ranks of different years (Siegel, 1956).

Accordingto Real Statistics Using Excel (http://www.real-statistics.com/reliability/kendalls-w/), the proper use of X^2 test to test statistical difference between Kendalls coefficients of concordance (W) on yearly indexes requires that the number of countries involved should be equal to 5 or more. Or the number of years being compared should be more than 15 years. In our case, the number of countries involved will be much larger than 5 countries. Therefore, we can use this X^2 test to validate the null hypothesis that W=0 or that there is no agreement between the years being compared.

How do we use and index together to evaluate reduction of dispersion as well as catch-up process? There are four different cases that can occur. The simplest case is when both and index are increasing in values. Under the circumstance, neither reduction of dispersion nor catch-up may be taking place. The second case is that both and indexesare decreasing which indicates that both reduction of dispersion and catch-up process are taking place. The third case occurs where convergence measure is non-decreasing, while convergence value is in decline. Since convergence is a necessary but not sufficient condition for convergence, this indicates that catch-up process is taking place, while reduction of dispersion is not. The fourth case occurs where index is non-decreasing while a substantial decline occurred with index. This indicates that country differences in performance measures remain so that no rank change among countries takes place. However, performance differences among countries have reduced considerably, which indicates conditional convergence. Put it another way, catch-up process may be taking place within subgroups of countries.

Data and Data source

For this study, there are two basic measures of and which have been download from Environmental Performance Index web site at http://epi2016.yale.edu/downloads/Yearly were initially downloaded for 227 countries during the period between 2000 to 2014. Eliminating 15 countries with missing data, the total of 212 countries became the sample size for analysis.As for PME measures, only 126 countries had complete set of data during the same period from the same EPI web site.Eliminating 18 more countries for missing categorizes of income and region, the total of 108 countries became the final sample size for the analysis of measures.

For categorizing four subgroups of countries by income level,˙ World Banks GNI per capita data which converts the gross national income to US dollars using the World Bank Atlas method was used. According to the World Bank, four income groups are defined in 2014 as follows (https://blogs.worldbank.org/opendata/updated-income-classifications). The high income group contains those countries whose GNI per capita of $12,746 or more followed by the upper middle-income group with GNI per capita between $4,126 and $12,745. The lower middle-income group contains those countries with GNI per capita between $1,045 and $4,125, while the lower income group contains those countries $1,045 or less. GNI per capita using the Atlas method in current US dollars for countries in the world are available from the World Banks web site at https://data.worldbank.org/indicator/ny.gnp.pcap.cd. For measures, high income subgroup contained 46 countries, followed by upper middle income subgroup of 36 countries, lower middle income subgroup of 20 countries and low income subgroup of 12 countries. For PME, high income subgroup included 37 countries, followed by upper middle income subgroup of 30 countries, lower middle income subgroup of 28 countries and low income subgroup of 13 countries.

The World Bank uses 7 region of the world (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups) from East Asia and Pacific (EAP), Europe and Central Asia (ECA), Latin America and Caribbean (LAC), Europe and Central Asia (ECA), Middle East and North Africa (MENA), North America (NA), South Asia (SA), and Sub Saharan Africa (SSA). Due to the fact that NA contains only 3 countries, NA has been combined with ECA to become ECA & NA so that there are six regional subgroups in this study.

For measures, EAP contains 37 countries, ECA & NA with 59 countries, LAC with 40 countries, MENA with 20 countries, SA with 8 countries and SSA with 48 countries. For PME, EAP contains 14 countries, ECA & NA with 45 countries, LAC with 7 countries, MENA with 17 countries, SA with 6 countries and SSA with 17 countries.

Analysis of Results

Historical averaged and PME measures for total group of countries decreased during the period between 2000 to 2014. As Table 1 shows, the global averaged measure for whole 212 countries at 7.6 ug/m^2 in 2000 decreased only slightly to 7.38 ug/m^2 by 2014 at the negative compounded annual growth rate (CAGR) of 0.21%. On the other hand, the global averaged PME measure for whole 108 countries at 20.37% in 2000 decreased about 3 times faster to 15.5% by 2014 at the CAGR of -0.69%, as shown in Table 2.

As Figure 1 shows, both PM measures displayed three phase patterns of changes. During the first phase of 2000 to 2007, they showed a rapid increase, followed by a moderate decrease during the second phase of 2008 to 2012, and finally a very rapid reduction during the third phase of 2013 to 2014.

When the yearly and PME measures were analyzed by the four income subgroups, both PM measures decreased in the high and the upper middle income subgroups, whereas the lower middle and the low income subgroups showed generated increasing trends. The most rapid decrease took place in the high income subgroup. For, the 2000 measure of 8.54 ug/m^2 decreased to 7.16 by 2014 at the CAGR 1.25% which is about six times faster than the speed of reduction for the total group of 212 countries. For PME, the speed of reduction was even faster at the CAGR of 1.83%. For, the most rapid rate of reduction in the high income subgroup was followed by the upper middle group at 0.23%, by the low income group increasing at +0.63% and finally by the lower middle income group increasing at +0.98%, as shown in Table 1.

For PME, the fastest rate of reduction at -1.83% occurred again in the high income group which was followed by the order of income level - the upper middle income group decreasing at -1.36%, the lower middle income group increasing at +0.94%, and finally low income group increasing at +1.33%, as shown in Table 2. In short, both and PME measures decreased the in high and the upper middle income subgroups. In contrast, both PM measures increased in the lower middle and the low income subgroups.

These varying rates of increase and decrease resulted in a substantial ranking change among the four income subgroups. In the year of 2000, $PM_{2.5}$ level followed the level of income subgroup as follows. The high income subgroup displayed the highest $PM_{2.5}$ at 8.54 μg/m^3, followed by 7.25 μg/m^3 by the upper middle income subgroup, 7.21 μg/m^3 by the lower middle income subgroup and 6.57 μg/m^3 by the low income subgroup. By 2014, the lower middle income subgroup displayed the highest $PM_{2.5}$ at 8.27 μg/m^3, followed by 7.17 μg/m^3 by the low income, 7.16 μg/m^3 by the high income subgroup and finally 7.02 by the upper middle

Table 1. Averaged Measures for Total and Four Income Subgroups of 212 Countries (2000-2014)

Year	Total (212)	High Income (76)	Upper Middle Income (56)	Lower Middle Income (49)	Low Income (31)
2000	7.60	8.54	7.25	7.21	6.57
2001	7.75	8.54	7.59	7.47	6.55
2002	7.93	8.65	7.68	7.81	6.79
2003	8.17	8.98	7.79	8.07	7.04
2004	8.31	9.01	7.97	8.29	7.24
2005	8.45	9.05	8.16	8.50	7.43
2006	8.60	9.20	8.33	8.67	7.50
2007	8.65	9.14	8.39	8.89	7.52
2008	8.23	8.55	7.86	8.78	7.24
2009	8.05	8.21	7.70	8.75	7.22
2010	8.04	8.14	7.69	8.74	7.34
2011	8.20	8.34	7.95	8.80	7.35
2012	8.18	8.33	7.93	8.77	7.37
2013	7.55	7.49	7.32	8.27	6.95
2014	7.38	7.16	7.02	8.27	7.17
CAGR	-0.21%	-1.25%	-0.23%	0.98%	0.63%

Table 2. Averaged Exceedance Measures for Total and Four Income Subgroups of 108 Countries (2000-2014)

Year	Total(108)	High Income (37)	Upper Middle Income (30)	Lower Middle Income (28)	Low Income (13)
2000	20.37%	25.49%	18.92%	18.88%	14.08%
2001	20.29%	25.58%	18.94%	18.89%	13.21%
2002	20.94%	26.32%	19.48%	19.84%	13.31%
2003	21.96%	28.20%	19.88%	20.67%	13.58%
2004	22.41%	28.14%	20.39%	21.39%	14.83%
2005	22.85%	28.09%	20.77%	22.16%	16.10%
2006	23.50%	28.70%	21.73%	22.78%	16.27%
2007	23.63%	28.31%	21.83%	23.57%	16.40%
2008	21.15%	24.85%	19.03%	22.20%	15.21%
2009	20.70%	23.79%	18.49%	22.45%	15.21%
2010	20.34%	23.01%	18.23%	22.56%	14.77%
2011	21.76%	24.85%	20.33%	23.21%	15.04%
2012	21.63%	24.41%	20.20%	23.19%	15.77%
2013	19.95%	22.41%	18.02%	21.54%	15.75%
2014	18.50%	19.67%	15.63%	21.53%	16.94%
CAGR	-0.69%	-1.83%	-1.36%	0.94%	1.33%

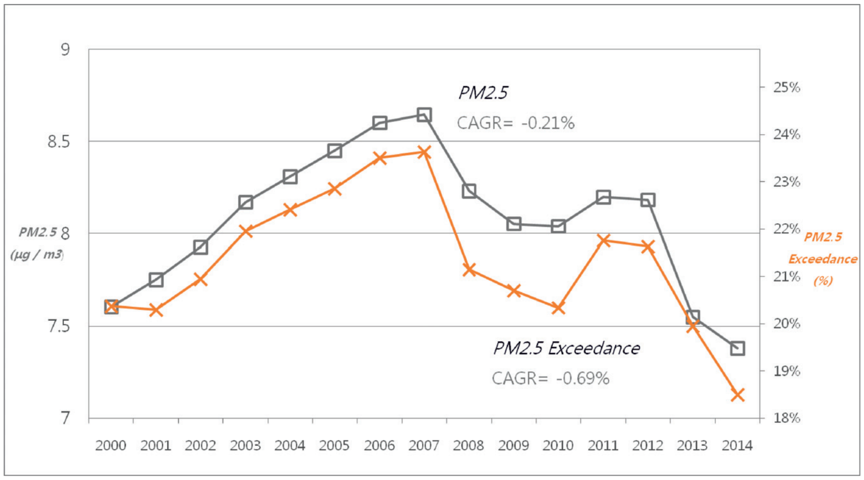

Fig. 1. Historical and Exceedance Measures for Total of 212 and 108 Countries (2000-2014)

income subgroup in that order, due to respective variable rates of change.

Similarly, the ranking of PME also underwent substantial change. In 2000, the PME level followed the ranking order from the high income to the low income subgroup. However, by 2014, the lower middle income subgroup displayed the highest PME if 21.53%, followed by the high income subgroup at 19.87%m the low income subgroup at 16.94% and finally by the upper middle income subgroup at 15.03%, once again due to variable CAGRs for individual income subgroups.

In short, the negative CAGR realized by the high and the upper middle income subgroups and the positive CAGR realized by the lower middle and the low income subgroups have reversed their ranking order so that the former subgroups now displayed lower averaged $PM_{2.5}$ and PME.

When the PM measures are analyzed by the six regional subgroups, both PM measures displayed a very wide variation by regions. The measures in 2000 showed the highest value of 12.91 μg/m^3 in SA region, 11.31 μg/m^3 in ECA+NA regionand 9.12 μg/m^3 in MENA region whereas LAC region showed the lowest value of 4.17 μg/m^3, followed by SSA region with 5.52 μg/m^3 and EAP region with 6.14 μg/m^3. The PME in 2000 showed the highest value of 35.96% in SA region, followed by 29.57% in EAP region, and 25.88% in ECA+NA region in 2000. LAC region showed the lowest value of 6.29% followed by SSA region with 8.01% in 2000, and 13.04% by MENA region, as shown in Table 4.

Similar to the variable rates of change shown by income subgroups, the same three regions of

Table 3. Averaged Measures for Six Regional Subgroups of 212 Countries (2000-2014)

Year	ECA+NA(59)	LAC(40)	SSA(48)	EAP(37)	MENA(20)	SA(8)
2000	11.31	04.17	05.52	06.14	09.12	12.91
2001	11.19	04.24	05.49	06.51	09.89	14.23
2002	11.38	04.21	05.61	06.74	10.14	15.05
2003	11.80	04.37	05.70	07.02	10.09	15.90
2004	11.70	04.63	05.87	07.33	10.22	16.19
2005	11.61	04.90	06.03	07.64	10.34	16.50
2006	11.81	04.83	06.13	07.86	10.64	17.05
2007	11.73	04.93	06.05	07.96	10.79	17.81
2008	10.49	04.62	05.68	07.96	11.02	18.91
2009	09.98	04.42	05.60	07.92	11.05	19.36
2010	09.91	04.47	05.74	07.68	10.97	19.84
2011	10.46	04.57	05.68	07.73	11.02	19.39
2012	10.21	04.66	05.56	07.74	11.52	19.73
2013	09.48	03.71	05.15	07.23	11.01	18.96
2014	08.82	03.69	05.33	07.32	10.45	19.55
CAGR	-1.76%	-0.88%	-0.25%	1.27%	0.97%	3.01%

ECA+NA, LAC, and SSA displayed the decreasing trends, whereas the remaining three regions of SA, EAP, and MENA showed the increasing trends for both PM measures, as shown in Table 3 and 4.

To explain, ECA+NA region decreased its $PM_{2.5}$ most rapidly at -1.70% per year because of its second highest 2000 $PM_{2.5}$ of 11.31 μg/ml^3. On the other hand, LAC and SSA in spite of their very low 2000 $PM_{2.5}$ decreased their $PM_{2.5}$ at the second and the third rapid declining CAGRs at -0.88% and -0.25% respectively. The same three regions also realized the most rapid declining CAGRs at -3.85% (ECA+NA), -1.83%(SSA), and -1.47%(LAC) in PME measures.

In contrast, SA, EAP, and MENA regions experienced varying positive CAGRs from +3.01% (SA), +1.27%(EAP), and +0.97%(MENA) in $PM_{2.5}$. In PME, the same three regions also realized varying positive CAGRs, from +3.45% (SA), +2.63% (MENA) and +1.41%(EAP). Interestingly, SA region have continued to maintain its highest $PM_{2.5}$ and PME throughout the period, yet sustained its highest annual growth rates for both measures. MENA and EAP regions also maintained their relatively high both measures throughout the period, yet continued their rapid growth rates of $PM_{2.5}$ and PME as well.

What about the micro convergence patterns within respective income and regional subgroups? Table 5 and 6 present presented normalized α and γ indexes of $PM_{2.5}$ and PME four income subgroups, while Table 7 and 8 presented normalized α and γ indexes of $PM_{2.5}$ and PME for regional subgroups.

Normalized, yearly m^3 indexes for $PM_{2.5}$ and PME displayed increasing trends for the total groups as well as respective four income subgroups without

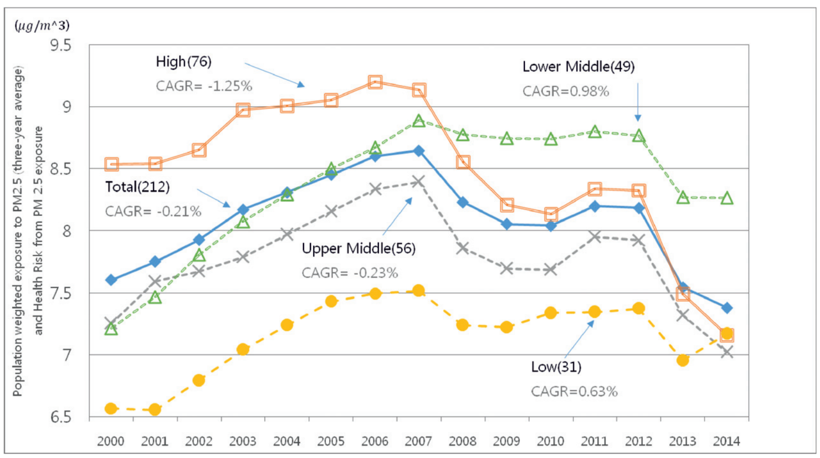

Fig. 2. Historical Distribution of Averaged Measures for Total and Four Income Subgroups (2000-2014)

Table 4. Averaged Exceedance Measures for Six Regional Subgroups of 108 Countries (2000-2014)

Year	ECA+NA(59)	LAC(40)	SSA(48)	EAP(37)	MENA(20)	SA(8)
2000	25.88%	6.29%	8.01%	29.57%	13.04%	35.96%
2001	25.47%	5.00%	6.24%	28.58%	15.03%	40.50%
2002	26.44%	5.21%	5.68%	28.97%	15.78%	43.08%
2003	27.98%	5.32%	5.50%	30.73%	15.62%	46.29%
2004	27.57%	5.75%	6.41%	33.20%	16.11%	47.33%
2005	27.16%	6.14%	7.28%	35.46%	16.63%	48.54%
2006	27.74%	5.29%	7.85%	36.39%	17.68%	49.79%
2007	27.55%	5.82%	7.29%	36.76%	18.37%	51.25%
2008	22.03%	4.61%	5.29%	35.53%	19.83%	53.63%
2009	20.61%	3.96%	5.00%	35.72%	20.54%	55.13%
2010	19.98%	3.57%	5.34%	34.00%	20.53%	56.88%
2011	23.27%	3.96%	5.43%	34.49%	20.71%	55.21%
2012	21.59%	4.54%	5.26%	35.51%	22.91%	56.33%
2013	18.56%	4.43%	5.10%	34.22%	21.32%	56.79%
2014	14.93%	5.11%	6.19%	35.96%	18.75%	57.83%
CAGR	-3.85%	-1.47%	-1.83%	1.41%	2.63%	3.45%

an exception. The CAGRs of α indexes clustered closely within +1.51% to +1.07% for $PM_{2.5}$. In contrast, The CAGRs of α indexes ranged more widely from +1.36% to 0.2%. However, none of α indexes met the statistical test of significance for both $PM_{2.5}$ and PME.

The γ convergence of both $PM_{2.5}$ and PME by income subgroups in Table 5 and 6 indicate that all four income subgroups displayed decreasing γ indexes, supporting the convergence pattern of γ indexes for while 212 countries. The annual speed of γ convergence was similar among the four income subgroup, ranging from -0.61% for the low income subgroup to -0.44% for both the upper and the lower middle income subgroups, as shown in Table 5.

As for PME, the annual speed of γ convergence was distributed much more widely. The most rapid annual speed of -2.27% for the high income subgroup was followed by -1.04% for the upper middle income subgroup. -0.82% by the lower middle income subgroup and finally -0.24% by the low income subgroup. The order of the annual speed of γ convergence matches exactly the order of the CAGRs for the averaged PME by the four income subgroup presented in Table 2. It should be noticed that yearly γ indexes met the statistical test of significance at the 1% level without and exception.

Finally, the same process of analysis by income subgroup is applied to six regions in order to gain further insights on and convergence. Table 6 and 8 show the distribution of normalized indexes of and PME respectively. Unlike the results of indexes by income subgroups, not all regional subgroups displayed divergence. For, only three regions of LAC (+1.22%), EAP (+0.52%) and SA (+0.11%) displayed divergence, whereas the remaining three regions of MENA (-1.03%), ECA+NA (-0.35%) and SSA (-0.01%) showed either convergence or stationary trend. Similarly, for PME, only three regions of ECA+NA (+0.64%), LAC (+0.32%), and SSA

Table 5. [Continued] Normalized Sigma and Gamma Indexes of Total and Four Income Subgroups (2000-2014)

	Lower Middle Income (49)		Low Income (31)	
	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00	1.00	1.00
2001	1.01	0.99***	1.07	0.98***
2002	1.02	0.98***	1.05	0.97***
2003	1.03	0.97***	1.05	0.96***
2004	1.01	0.98***	1.05	0.98***
2005	0.99	0.97***	1.06	0.98***
2006	1.01	0.97***	1.05	0.97***
2007	1.02	0.97***	1.06	0.97***
2008	1.08	0.97***	1.17	0.96***
2009	1.09	0.96***	1.19	0.92***
2010	1.11	0.96***	1.16	0.93***
2011	1.11	0.95***	1.13	0.93***
2012	1.13	0.95***	1.18	0.89***
2013	1.21	0.94***	1.24	0.89***
2014	1.22	0.94***	1.23	0.92***
Annual% Change	1.42%	-0.44%	1.51%	-0.61%

Table 5. Normalized Sigma and Gamma Indexes of Total and Four Income Subgroups (2000-2014)

Total (212)	High Income (76)			Upper Middle Income (56)		
	Sigma	Gamma	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00	1.00	1.00	1.00	1.00
2001	0.96	0.98***	0.94	0.97***	1.01	0.99***
2002	0.98	0.98***	0.99	0.97***	1.02	0.98***
2003	0.99	0.98***	1.03	0.97***	1.03	0.97***
2004	0.99	0.98***	1.04	0.97***	1.01	0.98***
2005	0.99	0.97***	1.04	0.96***	0.99	0.97***
2006	1.00	0.96***	1.07	0.95***	1.01	0.97***
2007	1.01	0.96***	1.09	0.95***	1.02	0.97***
2008	1.04	0.95***	1.13	0.97***	1.08	0.97***
2009	1.06	0.96***	1.15	0.97***	1.09	0.96***
2010	1.05	0.95***	1.12	0.97***	1.11	0.96***
2011	1.04	0.95***	1.12	0.96***	1.11	0.95***
2012	1.05	0.95***	1.10	0.96***	1.13	0.95***
2013	1.16	0.94***	1.21	0.94***	1.21	0.94***
2014	1.16	0.93***	1.21	0.94***	1.22	0.94***
Annual% Change	1.07%	-0.50%	1.34%	-0.48%	1.42%	-0.44%

(+0.22%) displayed divergence again, while the remaining three regions of MENA(-1.97%), SA (-1.63%) and EAP (-1.61%) showed rapid convergence. However, none of the yearly indexes met the statistical test of significance. Similar to the results of convergence by income subgroups, all regions generated convergence trends for both and PME. In case of convergence of the most rapid rate of reduction was displayed by the region of MENA at -2.61%, followed by LAC at -1.56%, SSA at -1.45%, SA at -0.9%, EAP at -0.54%, and finally by ECA+NA at -0.35%. For PME, the speed of convergencewas fastest by SA at -2.37%, SSA at -2.21%, MENA at -1.73%, ECA+NA at -1.55%, EAP at -0.13%, and finally by LAC at -0.04%. All the yearly indexes met the statistical test of significance at the 1% level.

CONCLUSION

The key finding from this research can be summarized as follows: First, the global averaged $PM_{2.5}$ and PME measures declined at the CAGR of -

Table 6. Normalized Sigma and Gamma Exceedance Indexes of Total and Four Income Subgroups (2000-2014)

	Total (108)		High Income (37)		Upper Middle Income (30)	
	Sigma	Gamma	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00***	1.00	1.00	1.00	1.00
2001	0.98	0.97***	0.86	0.96***	0.97	0.96***
2002	0.98	0.97***	0.82	0.94***	1.00	0.98***
2003	1.00	0.96***	0.81	0.94***	1.03	0.98***
2004	0.98	0.96***	0.82	0.94***	1.01	0.97***
2005	0.97	0.95***	0.85	0.95***	0.99	0.95***
2006	0.96	0.94***	0.82	0.92***	0.97	0.93***
2007	0.95	0.94***	0.81	0.91***	0.99	0.95***
2008	1.04	0.92***	0.83	0.86***	1.05	0.95***
2009	1.07	0.90***	0.86	0.83***	1.07	0.94***
2010	1.07	0.88***	0.87	0.78***	1.07	0.94***
2011	1.03	0.90***	0.87	0.85***	1.01	0.94***
2012	1.05	0.89***	0.89	0.82***	1.00	0.92***
2013	1.12	0.87***	0.96	0.80***	1.10	0.89***
2014	1.19	0.84***	1.03	0.73***	1.20	0.86***
Annual% Change	1.24%	-1.22%	0.20%	-2.27%	1.33%	-1.04%

Table 6. [Continued] Normalized Sigma and Gamma Exceedance Indexes of Total and Four Income Subgroups (2000-2014)

	Lower Middle Income (28)		Low Income (13)	
	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00	1.00	1.00
2001	1.03	0.96***	1.16	0.91***
2002	1.04	0.96***	1.21	0.90***
2003	1.06	0.97***	1.29	0.82***
2004	1.02	0.96***	1.20	0.89***
2005	0.99	0.95***	1.12	0.92***
2006	1.01	0.95***	1.09	0.90***
2007	0.99	0.95***	1.10	0.92***
2008	1.09	0.94***	1.27	0.87***
2009	1.10	0.90***	1.30	0.92***
2010	1.11	0.89***	1.30	0.88***
2011	1.09	0.91***	1.24	0.92***
2012	1.11	0.90***	1.24	0.93***
2013	1.19	0.89***	1.24	0.95***
2014	1.21	0.89***	1.15	0.97***
Annual% Change	1.36%	-0.82%	1.01%	-0.24%

0.21% and -0.69% respectively which indicated only moderate improvement from 2000 to 2014 for the total group of 212 countries for $PM_{2.5}$ and 108 countries for PME. Second, the CAGR of PM measures varied widely by the subgroups by income level and regions. The most rapid rate of decline was -1.25% (PM2.5) and -1.83% (PME) by the high income subgroup which was offset by the rapid rates of increase by the low middle and the low income subgroups. Also, the most rapid declining rates of -1.76% (PM2.5) and -3.85% (PME) by ECA+NA region were offset by +3.01% (PM2.5) and +3.45% (PME) by SA region. In fact, the two income and the three regional subgroups did reduce their PM measures which the remaining two income and three regional subgroups did increases their PM measures.

Third, the net result from the increasing subgroups versus the decreasing subgroups produced a substantial change in ranking order of PM measures among income and region subgroups and generated a very modest improvement of PM

Table 7. Normalized Sigma and Gamma Indexes of Six Regional Subgroups for 212 Countries (2000-2014)

	East Asia & Pacific (37)		Europe & Central Asia & North America (59)		Latin America & Caribbean (40)	
	Sigma	Gamma	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00	1.00	1.00	1.00	1.00
2001	0.94	0.96***	0.92	0.99***	0.78	0.90***
2002	0.94	0.96***	0.93	0.98***	0.84	0.87***
2003	0.97	0.96***	0.94	0.96***	0.83	0.90***
2004	0.98	0.96***	0.94	0.97***	0.80	0.90***
2005	0.99	0.94***	0.95	0.96***	0.78	0.89***
2006	0.98	0.94***	0.96	0.95***	0.76	0.86***
2007	1.01	0.94***	0.95	0.93***	0.77	0.87***
2008	1.01	0.95***	0.85	0.90***	0.77	0.87***
2009	1.02	0.94***	0.87	0.93***	0.76	0.89***
2010	1.01	0.96***	0.87	0.93***	0.72	0.87***
2011	1.00	0.95***	0.93	0.94***	0.73	0.83***
2012	0.99	0.95***	0.91	0.95***	0.75	0.80***
2013	1.09	0.93***	0.98	0.93***	1.18	0.81***
2014	1.07	0.93***	0.95	0.91***	1.19	0.80***
Annual%Change	0.52%	-0.54%	-0.35%	-0.66%	1.22%	-1.56%

Table 7. [Continued] Normalized Sigma and Gamma Indexes of Six Regional Subgroups for 212 Countries (2000-2014)

	Middle East & North Africa (20)		South Asia (8)		Sub-Saharan Africa (48)	
	Sigma	Gamma	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00	1.00	1.00	1.00	1.00
2001	0.83	0.91***	0.97	1.00***	1.00	0.98***
2002	0.71	0.90***	1.01	1.03***	0.96	0.97***
2003	0.67	0.88***	1.01	0.99***	0.90	0.97***
2004	0.67	0.90***	1.02	0.98***	0.88	0.96***
2005	0.68	0.89***	1.04	0.98***	0.88	0.95***
2006	0.75	0.81***	1.03	0.98***	0.87	0.94***
2007	0.75	0.77***	1.01	0.99***	0.86	0.94***
2008	0.81	0.74***	0.98	0.96***	0.85	0.92***
2009	0.76	0.71***	0.96	0.95***	0.87	0.89***
2010	0.79	0.70***	0.94	0.95***	0.86	0.89***
2011	0.81	0.71***	0.97	0.97***	0.86	0.88***
2012	0.92	0.70***	0.97	0.92***	0.88	0.86***
2013	0.98	0.71***	1.04	0.89***	1.01	0.82***
2014	0.87	0.69***	1.01	0.88***	1.00	0.81***
Annual % Change	-1.03%	-2.61%	0.10%	-0.90%	-0.01%	-1.45%

measures for the total group of countries. Fourth, the conventional convergence theory can only explain in part why different subgroups have experienced positive and negative rate of change in their PM measures. For example, relatively high PM measures in 2000 for the low middle income subgroup or SA region has generated high positive grow in rate during the entire study period. Instead of negative grow in rate, implied by convergence theory.

Fifth, the results of γ convergence analysis involving individual countries within respective income and regional subgroups did not meet the statistical test of significance the results in general showed divergence of γ convergence, indicating that dispersion of PM measures have not decreased within individual subgroups. In other words, country differences of PM measures have not narrowed within respective subgroups.

Sixth, the results of γ convergence analysis involving individual countries within all the respective income and regional subgroup did meet the statistical test of significance, indicating that substantial ranking change of PM measures among individual countries gave taken place. It is interesting to note that all the subgroups where their PM measures increasing such as the lower middle and the low income subgroups as well as SA, MENA and EAP regions also participated in γ convergence

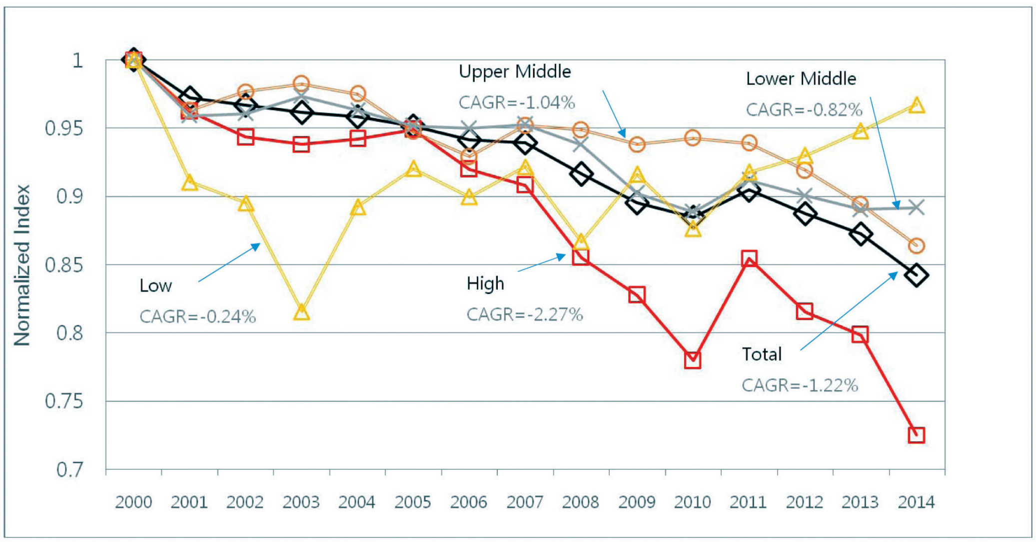

Fig. 3. Historical Averaged Exceedance Measures for Total and Four Income Subgroups of 108 countries (2000-2014)

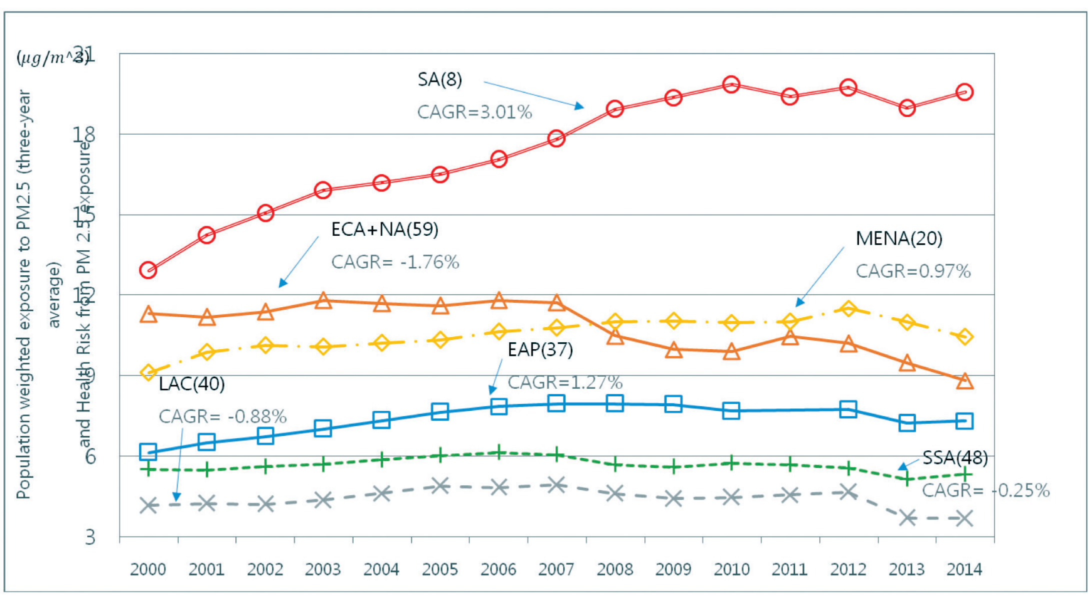

Fig. 4. Historical Averaged Measures for Six Region Subgroups of 212 Countries (2000-2014)

within respective subgroups. Seventh, income case of PME, there was a matching ranking between the CAGR of PME and the annual speed of γ convergence as a function of income subgroup. In other words, the high income subgroup experienced both the most rapid negative CAGR of averaged PME and the most rapid annual speed of γ convergence, followed by the upper middle the lower middle and the low income subgroup. In other words, the higher the reduction rate of PME the faster because the annual speed of ranking changes among individual countries within respective subgroups. However, such matching ranking was not observed in $PM_{2.5}$ measures for income subgroups on four regional subgroups.

In short, the most important conclusion from these findings is that multiple countries with initially poor PM measures have been catching up to countries with superior PM measures within thetotal group of countries as well as withineach and every income and regional subgroup. In other words, lagging countries in the initial year of 2000 are

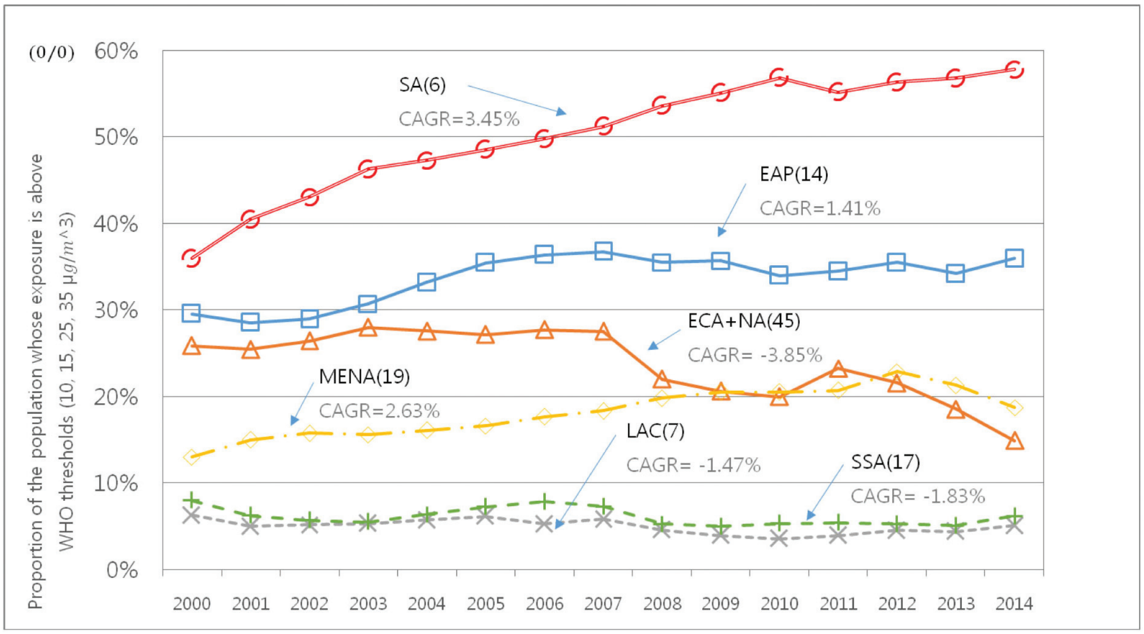

Fig. 5. Historical Averaged Exceedance Measures for Six Region Subgroups of 108 Countries (2000-2014)

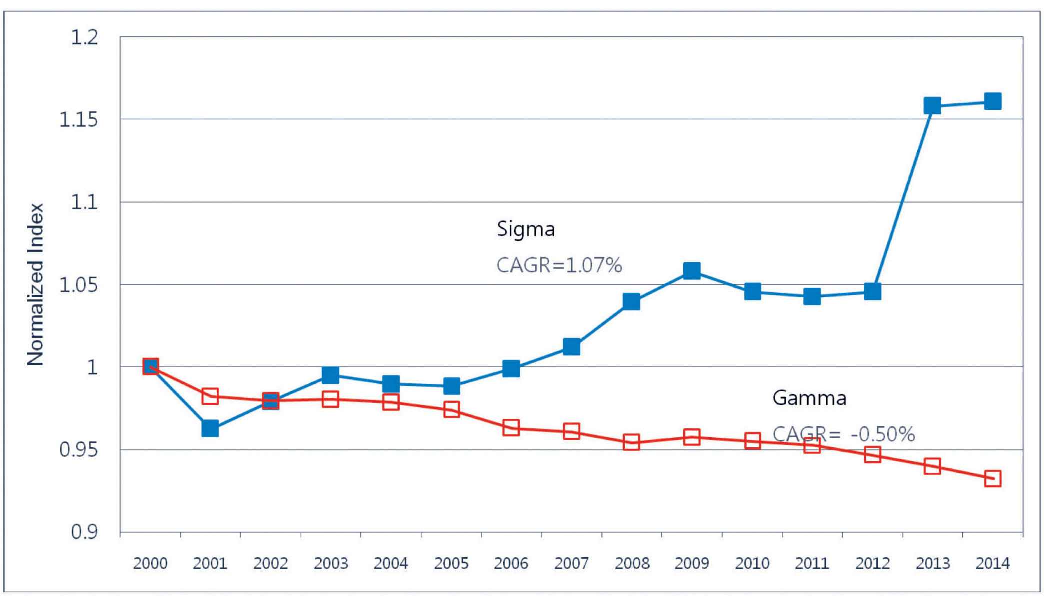

Fig. 6. Normalized Sigma and Gamma Indexes of for Total Group of 212 Countries (2000-2014)

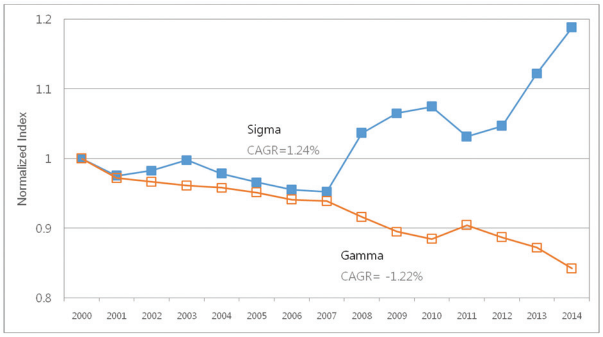

Fig. 7. Normalized Sigma and Gamma Indexes of Exceedance for Total Group of 108 Countries (2000-2014)

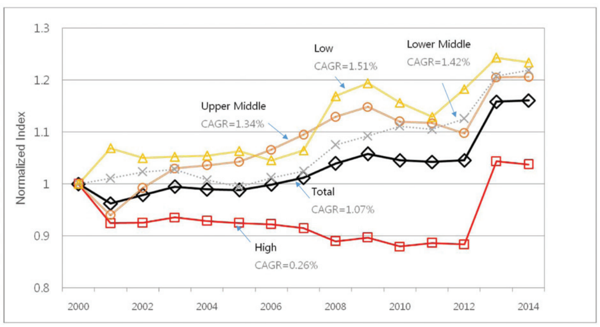

Fig. 8. Normalized Sigma Indexes of for Total Group and Four Income Subgroups (2000-2014)

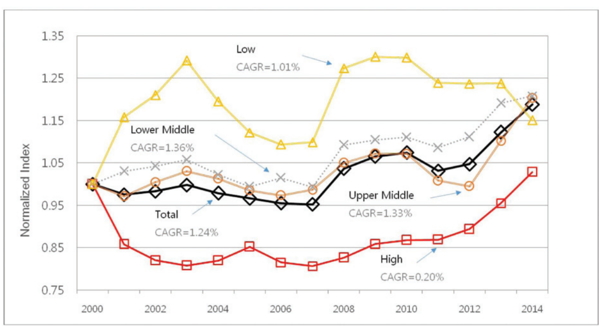

Fig. 9. Normalized Sigma Indexes of Exceedance for Total Group and Four Income Subgroups (2000-2014)

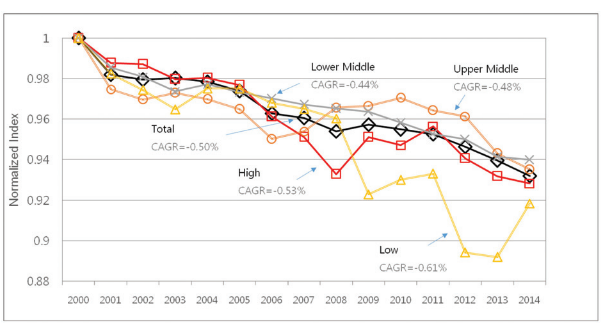

Fig. 10. Normalized Gamma Indexes of for Total Group and Four Income Subgroups (2000-2014)

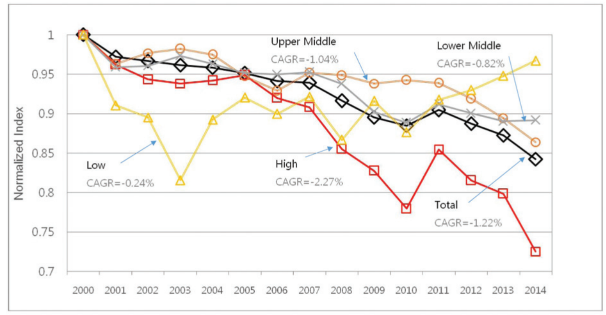

Fig. 11. Normalized Gamma Indexes of Exceedance for Total Group and Four Income Subgroups (2000-2014)

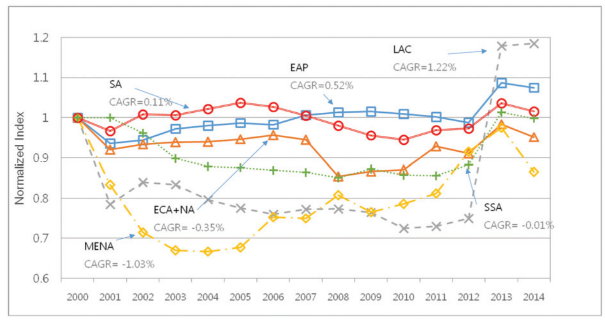

Fig. 12. Normalized Sigma Indexes of for Total Group and Six Regional Subgroups (2000-2014)

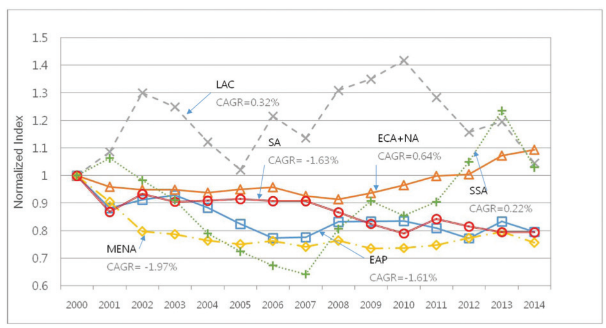

Fig. 13. Normalized Sigma Indexes of Exceedance for Total Group and Six Regional Subgroups (2000-2014)

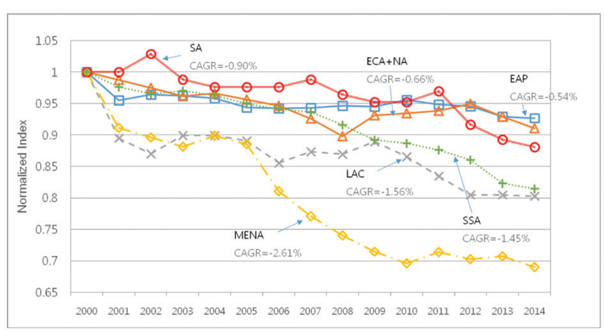

Fig. 14. Normalized Gamma Indexes of for Total Group and Six Regional Subgroups (2000-2014)

catching-up to leading countries throughout the period of 2000 to 2014 especially in the high income subgroup as well as insuch regional subgroups as MENA, SA, and SSA.

This pattern of catch-up occurs in spite of the fact that both PM measures in two income subgroups (The middle and The low income) and three regional subgroups (SA, EAP, and MENA) have increased during this period. Furthermore, the patterns of catch-up occur in spite of the fact that dispersions of PM measures have increased in both total group and in a majority of income and regional subgroups during the period.

What are some policy implications to individual countries interested in accelerating the speed of catch-up? First, a rapid increase of catch-up process which has taken place especially in PME for the total group of countries in the world should offer a

Table 8. Normalized Sigma and Gamma Exceedance Indexes of Six Regional Subgroups for 212 Countries (2000-2014)

	East Asia and Pacific (14)		Europe & Central Asia & North America (45)		Latin America & Caribbean (7)	
	Sigma	Gamma	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00	1.00	1.00	1.00	1.00
2001	0.88	0.97***	0.96	0.97***	1.09	0.82***
2002	0.91	0.96***	0.95	0.95***	1.3	0.88***
2003	0.93	0.95***	0.95	0.94***	1.25	0.70***
2004	0.88	0.96***	0.94	0.93***	1.12	0.92***
2005	0.82	0.96***	0.95	0.92***	1.02	0.99***
2006	0.77	0.97***	0.96	0.92***	1.22	0.76***
2007	0.78	0.98***	0.93	0.91***	1.14	0.74***
2008	0.83	0.97***	0.91	0.90***	1.31	0.70***
2009	0.83	0.99***	0.94	0.88***	1.35	0.72***
2010	0.84	0.99***	0.96	0.88***	1.42	0.62***
2011	0.81	1.00***	1.00	0.90***	1.28	0.66***
2012	0.77	0.99***	1.00	0.91***	1.16	0.86***
2013	0.83	0.97***	1.07	0.85***	1.20	0.86***
2014	0.80	0.98***	1.09	0.80***	1.05	0.99***
Annual % Change	-1.61%	-0.13%	0.64%	-1.55%	0.32%	-0.04%

Table 8. [Continued] Normalized Sigma and Gamma Exceedance Indexes of Six Regional Subgroups for 212 Countries (2000-2014)

	Middle East & North Africa (19)		South Asia (6)		Sub-Saharan Africa (17)	
	Sigma	Gamma	Sigma	Gamma	Sigma	Gamma
2000	1.00	1.00	1.00	1.00	1.00	1.00
2001	0.90	0.95***	0.87	1.00***	1.06	0.86***
2002	0.80	0.94***	0.93	1.00***	0.98	0.76***
2003	0.79	0.93***	0.91	1.00***	0.91	0.72***
2004	0.76	0.93***	0.91	1.00***	0.79	0.77***
2005	0.75	0.93***	0.92	1.00***	0.73	0.74***
2006	0.76	0.89***	0.91	1.00***	0.67	0.70***
2007	0.74	0.87***	0.91	0.97***	0.64	0.73***
2008	0.76	0.84***	0.87	1.00***	0.81	0.63***
2009	0.74	0.84***	0.83	0.95***	0.91	0.58***
2010	0.74	0.81***	0.79	0.80***	0.86	0.54***
2011	0.75	0.84***	0.84	0.74***	0.91	0.54***
2012	0.77	0.81***	0.82	0.74***	1.05	0.60***
2013	0.80	0.81***	0.80	0.71***	1.24	0.72***
2014	0.76	0.78***	0.79	0.71***	1.03	0.73***
Annual % Change	-1.97%	-1.73%	-1.63%	-2.37%	0.22%	-2.21%

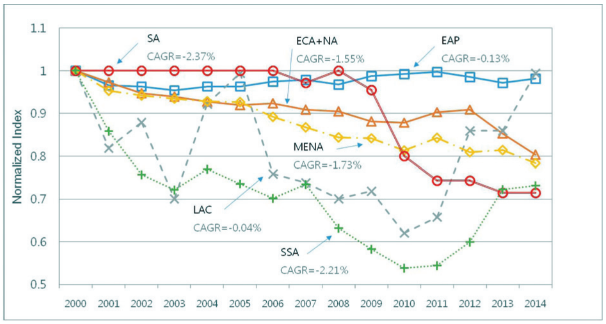

Fig. 15. Normalized Gamma Indexes of Exceedance for Total Group and Six Regional Subgroups (2000-2014)

challenge to many countries for improving their own policies toward faster catch-up process. Second, in setting specific target of speed for catch-up, our findings on varying speed from specific income and regional subgroups should become valuable sources for reference. For example, knowing the speed of catch-up at the negative CAGR of -2.61% by MENA region in contrast to -0.54% by EAP region should provide valuable inputs in formulating ones own target of speed for convergence for countries in these regions. Third, individual countries in certain region or income subgroups may be selected for in-depth benchmarking to identify catch-up policies and procedures that can be adopted.

There are several limitations to our research which can become fruitful topics for future research topics. In our methodology, we have relied on the use of simple and convergence methods only, leaving the room for more sophisticated stochastic and club convergence methods for future research. Another major implication of this research is not to adequately differentiate between those countries experiencing very high concentrations from those countries subjected to negligible concentrations.

On the other hand, the results of the convergence analyses presented here may represent a new contribution to the literature, as convergence analysis involving over 200 countries has not been reported in the literature of PM concentrations.

ACKNOWLEDGEMENTS

The authorsacknowledge competent help provided by MyungHoonJin, a research assistant at Gachon Center for Convergence Research.

REFERENCES

Barro, R.J. 1991. Economic growth in a cross section of countries. *The Quarterly Journal of Economics*. 106(2) : 407-443.

Barro, R. J. and Sala-i-Martin, X. 1992. Convergence. *Journal of Political Economy*. 100(2) : 223-251.

Boyle, G.E. and McCarthy, T.G. 1997. A simple Measure of â-convergence. *Oxford Bulletin of Economics and Statics*. 59 : 257-264.

Brajer, V., Mead, R.W. and Xiao, F. 2011. Searching for an Environmental Kuznets Curve in China's air pollution.*China Economic Review*. 22 : 383-397.

Chang, Y.S., Jeon, S. and Park, N.H. 2019. Do time phase and income influence the convergence in energy intensity? A cross-country analysis. *International Journal of Energy Technology and Policy*. 15(2/3) : 301-319.

Cole, M.A., Elliott, R.J.R. and Zhang, J. 2011. Growth, foreign direct investment, and the environment: evidence from Chinese cities.*Journal of Regional Science*. 51(1) : 121-138.

Engel-Cox, J., Kim Oanh, N.T., van Donkelaar, A., Martin, R.V. and Zell, E. 2013. Toward the next generation of air quality monitoring: Particulate Matter. *Atmospheric Environment*. 80 : 584-590.

Friedman, M. 1992. Do old fallacies ever die?.*Journal of Economic Literature*. 30(4) : 2129-2132.

Goldberg, M. 2008. A Systematic Review of the Relation Between Long-term Exposure to Ambient Air Pollution and Chronic Diseases. *Reviews on Environmental Health*. 23(4).

Grossman, G.M. and Krueger, A.B. 1991. Environmental impacts of a North American Free Trade Agreement. *National Bureau of Economic Research Working Papers*, pp. 3914.

Hao, Y. and Liu, Y.M. 2010. The influential factors of urban PM 2.5 concentrations in China: a spatial econometric analysis, *Journal of Cleaner Production*. 112 : 1443-1453.

Heckelman, J.C. 2015. Economic freedom convergence clubs.*Economic Behavior, Economic Freedom, and Entrepreneurship*, pp.102.

Keene, A. and Deller, S. C. 2015. Evidence of the environmental Kuznets' curve among US counties and the impact of social capital. *International Regional Science Review.* 38 (4) : 358-387.

Lee, H. and Oh, D. 2015. Economic growth and the environment in China: Empirical evidence using prefecture level data.*China Economic Review.* 36 : pp. 73-85.

Liddle, B. 2012. OECD energy intensity. *Energy Efficiency* 5 : 583-597.

Pettersson, F., Maddison, D., Acar, S. and Söderholm, P., 2013. Convergence of carbon dioxide emissions: A review of the literature. *International Review of Environmental and Resource Economics*. 7 : 141-178.

Poon, J. P. H., Casas, I. and He, C. 2006. The impact of energy, transport, and trade on air pollution in China.*Eurasian Geography and Economics.* 47(5):

568-584.

Quah, D. 1993. Galton's Fallacy and Tests of the convergence hypothesis.*Scandinavian Journal of Economics*. 95(4) : 427-43.

Quah, D. 1996. Empirics for economic growth and convergence. *European Economic Review*. 40(6): 1353-1375.

Selden, T. M. and Song, D. 1994. Environmental quality and development: Is there a Kuznets curve for air pollution? *Journal of Environmental Economics and Environmental Management*. 27 : 147-162.

Shafik, N. 1994. Economic development and environmental quality: an econometric analysis. *Oxford Economic Papers*. 46 : 757-773.

Siegel, S. 1956. *Nonparametric Statistics for the Behavioral Sciences,* McGraw-Hill, pp.229-239.

Song, T., Zheng, T. and Tong, L. 2008. An empirical test of the environmental Kuznets curve in China: A panel cointegration approach. *China Economic Review*. 19 : 381-392.

Stern, D.I. and van Dijk, J. 2017. Economic Growth and global particulate pollution concentrations. *Climatic Change.* 142 : 391-406.

Stern, D.I. and Zha, D. 2016. Economic growth and particulate pollution concentrations in China. *Environmental Economics and Policy Studies*. 18 : 327-338.

World Bank and Institute for Health Metrics and Evaluation. 2016. *The Cost of Air Pollution: Strengthening the Economic Case for Action*. Washington, D.C.: World Bank.

World Health Organization (Ed.). 2006. *Air quality guidelines: global update 2005: particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*. Copenhagen, Denmark: World Health Organization.

World Health Organization. 2014. Frequently Asked Questions: Ambient and Household Air Pollution and Health.

World Health Organization. 2016. *Ambient air pollution: A global assessment of exposure and burden of disease* (No. 978-92-4-151135-3). Geneva, Switzerland.

WHO News: "WHO releases country estimate on air pollution exposure and health impact" (27 SEP, 2016)

WHO News: "Air pollution levels rising in many of the world's poorest cities" (12 May, 2016)

Environmental Performance Index web site: http://epi2016.yale.edu/dpwmloads/

World Bank (2014 income group): http://blogs.worldbank.org/opendata/updated-income-classification

World Bank (GNI): http://data.worldbank.org/indicator/ny.gnp.pcap.cd.

World Bank (2015 income group): http://blogs.worldbank.org/opendata/new-country-classifications-2016