J.Natn.Sci.Foundation Sri Lanka 2015 43 (3):281-287
DOI: http://dx.doi.org/10.4038/jnsfsr.v43i3.7956

SHORT COMMUNICATION

Model assessment of acid deposition potential by SO_x in Sri Lanka

O.A. Ileperuma*
Department of Chemistry, Faculty of Science, University of Peradeniya, Peradeniya.

Revised: 16 March 2015; Accepted: 22 April 2015

Abstract: Asia is undergoing tremendous economic development and increased demand for energy, particularly from coal burning. As a result, acidic precursors move to neighbouring countries with the potential to cause serious environmental damage. Such transboundary pollution originating from countries in the Asian region such as India, China and Thailand contribute to acidic depositions in Sri Lanka. India in particular, because of its geographical proximity contributes significantly to sulphur depositions in Sri Lanka. The RAINS-ASIA model was used to calculate future acidic depositions in four major cities of Sri Lanka for the period 1990 – 2030 using baseline data from 1990. The total acid depositions due to Sri Lanka taken as a whole can be compared to those arising from transboundary pollution. It was found that the acidic depositions in all four cities will increase by 400 – 600 % during this period, with Kandy recording the highest increase at 600 %. It was also found that the share from transboundary pollution to acid depositions in Jaffna located close to the Indian peninsula is ~80 % of the total. On the other hand, the transboundary contributions in Colombo is predicted to decrease from 58.5 % in 1990 to 33 % in 2030. This can be attributed to increased local air pollution, resulting from the burning of fossil fuel such as coal and diesel in local power stations and also increased vehicular traffic. Ship movements around Sri Lanka significantly contribute to acid depositions and depending on the city it can vary from 10 – 15 %.

Keywords: Acidic deposition, RAINS-ASIA, transboundary pollution.

INTRODUCTION

Asian countries have undergone rapid economic growth during the last three decades and this trend is expected to continue. This has resulted in an ever increasing demand for energy, and Asia's energy demand is doubling every 12 years when compared to the World average of 28 years. Over 80 % of the energy is derived from the combustion of fossil fuels, particularly coal, which provides nearly 40 % of the energy in South Asia (World Bank, 1995).

With the increasing economic activity particularly in Asia, local pollution specifically from the transport sector has resulted in increased air pollution in major cities. Pollution arises from large point sources (LPS) and diffused sources such as cities, where increased vehicle population results in a high level of air pollution. The number of motor vehicles in Sri Lanka has more than doubled over the decade of 1992 – 2012 (Central Bank of Sri Lanka, 2013). Furthermore, for electricity generation hydropower contributed more than 90 % in 1996, while today it provides only 40 – 50 % of the total electricity requirement. The balance is provided by burning of fossil fuels such as coal and diesel in thermal power plants. Coal power plants such as the one at Norochcholai using coal with an average sulphur content of ca. 1.5 % releases large quantities of sulphur dioxide, but due to the operation of a scrubbing system, over 95 % of the sulphur dioxide is removed. However, other thermal power plants located close to the capital city of Colombo may generate significant levels of sulphur dioxide.

In the past, air pollution was perceived primarily as a local phenomenon. In mega cities, this is particularly true where air pollution tends to be dominated by emissions from local sources. However, in recent decades, scientific research has demonstrated that air pollution has increasingly become a regional or even a global problem (UNEP, 2008). Air pollutants can get transported over thousands of kilometres from their source of origin from high energy consuming countries such as India and China, and get deposited in other

* oliveri@pdn.ac.lk

countries in the region. This is the phenomenon of transboundary air pollution and is the major reason for acid rain incidences already well established in Europe and Canada (Menz & Seip, 2004). China, which accounts for 65 % of all sulphur emissions in Asia contributes heavily to sulphur depositions in neighbouring countries. For example, China is responsible for 39 % and 35 % of the total sulphur depositions in Thailand and North Korea, respectively (Robertson *et al*., 1995). Sri Lanka signed the Male Declaration, which is aimed at mitigating the effects of transboundary air pollution and consequent acid rain.

Over the years SO_x emissions in all parts of Asia have increased, and in China over the past two decades SO_x emissions have more than tripled (Streets *et al*., 2000a). Asia's total SO_x emissions may increase by a factor of three between 1990 and 2030 (World Bank, 1995). The transport and the fate of sulphur in Asia is an area of increasing interest and concern (Robertson *et al*., 1995).

The term acid rain is used to describe rainwater having a pH < 5.6, which is the result of the reactions of air pollutants such as SO_x and NO_x with atmospheric water and oxygen. Acid rain precursors are released into the atmosphere from burning of fossil fuel, particularly coal. The term acid deposition is used to encompass both wet deposition in the form of rain and other forms such as snow, frost, fog, and also dry deposition in the form of solid salts. Acidic precipitation is reported throughout the Asia (Hara, 1993) with many areas receiving levels exceeding the acid carrying capacity of soils. It is not only the mere pH of the rainwater that causes environmental damage but rather the response of the plants and soils to the chemical constituents of rainwater. Eventually, soil buffer capacity in the receiving bodies is critical in acid rain causing environmental damage. The reported mean buffer intensities computed for lowland Dry Zone rivers and highland reservoirs are $8.09 \pm 4.61 \times 10^{-4}$ and $55.05 \pm 21.18 \times 10^{-4}$ mol L^{-1} pH^{-1}, respectively (Silva & Manuweera, 2004). The presence of base cations such as calcium and magnesium from soil as well as sea water has a neutralising effect on the acidity of rainwater. In addition, ammonia in the atmosphere also has the ability to neutralise sulphuric and nitric acids in rainwater. However, sulphate ions still remain in the environment, which has the ability to replace HCO_3^- causing Mg^{2+} and Ca^{2+} to increase from the weathering of soil and reservoir sediments. As a result, the ratio of alkalinity to Mg^{2+} and Ca^{2+} will decrease affecting aquatic life (Schindler, 1988).

The impacts of acid depositions on ecosystems have been extensively studied. This has resulted in the disappearance of fish from the lakes in Scandinavia and Canada, destruction of pine forests in Europe and damage to monuments like Taj Mahal (Rodhe & Granat, 1984). The acidity in rain can affect agricultural crops and sensitive ecosystems where the soil buffering capacity is low. Already, China is facing serious problems owing to acid rain where several sensitive ecosystems are under threat (Kuribayashi *et al*., 2012).

There is very little research carried out in Asian countries on the effects of acid rain on ecosystems. However, there is evidence that the acidity of rainwater is on an increasing trend at locations where regular monitoring of the acidity of rainfall is implemented. A limited study on the acid rain occurrence in Sri Lanka during the 1996 – 2000 period showed that acid rain is prevalent in the hill country and also in the North-Central province, particularly during the North-East Monsoon (Ileperuma & Premakeerthi, 1998; Nissanka, 2005). Silva and Manuweera (2004) found that about 30 % of the rainwater samples collected from all over the island had a pH value in the range of 4.90 – 5.30, and 37.5 % of the samples had a pH value in the range of 5.40 – 5.80, again demonstrating the occurrence of acid rain in Sri Lanka. In an earlier study, rainwater acidity was not considered as a problem in Sri Lanka. Average rainwater pH values of 5.15 and 5.60 have been determined for the Wet and Dry Zones of Sri Lanka with 66 % of the samples having a pH < 5.60, and hence can be considered as acid rain (Dissanayake & Weerasooriya, 1985).

Regional Air Pollution Information and Simulation model (RAINS) was first developed as a tool for integrated assessment of strategies to reduce acid deposition in Europe. This model deals with the pathways of emissions and mechanisms of acidification in the environment for sulphur dioxide, which is the major acidifying component. The extension of the RAINS-EUROPE model to Asia resulted in the development of RAINS-ASIA model as an integrated acid rain and emissions policy analysis model for the development of national and regional energy policies in Asia.

The aim of the present study was to investigate how the projected acidic depositions will vary in the future in four major cities of Sri Lanka using the RAINS-ASIA model. This model was selected because it is the only model, which covers entire Asia providing data on large point sources such as coal power plants and also diffused sources in the form of entire states of different countries. This model also enables the allocation of such depositions due to transboundary pollution from the states of neighbouring India, and to large point sources such as power plants in India. Such data will be useful to assess the vulnerability of sensitive ecosystems as well as potential damage to agricultural crops in Sri Lanka.

METHODS AND MATERIALS

RAINS-ASIA model comprised four basic modules, and answers many questions such as energy generation policies, technical options to control emissions and their costs, endangered ecosystems and future acid deposition scenarios.

(a) The regional energy resource generator (RESGEN) module, which calculates energy consumption parameters based on socio-economic and technological assumptions
(b) The energy and emissions (ENEM) module, which uses these scenarios to calculate sulphur emissions and costs of control strategies
(c) The deposition and critical loads module (DEP), which consists of two sub-modules
(d) (i) The atmospheric transport (ATMOS) sub-module, which calculates the levels and patterns of sulphur depositions under a given emission scenario
(ii) The IMPACT module, which calculates ecosystem critical loads and their environmental effects

In this study DEP module was used to calculate future sulphur depositions in Sri Lanka.

RAINS-ASIA version 7.52 programme package was used for the study. The deposition module (DEP) was used to determine the sulphur depositions in the four cities; Colombo, Kandy, Anuradhapura and Jaffna for the period 1990 – 2030. From the DEP module, sulphur deposition option and the "no-control" scenario were selected. In this study, a "no-control" scenario was used where the existing technologies and fuel quality will remain as they are, while the other options such as the best available technology (BAT) and advanced emission control strategies (ACT) are also available to perform the calculations. Calculations were next run when a coloured map with different shadings depending on the level of sulphur deposition was obtained. These calculations were made for the period 1990 – 2030 at 5 year intervals and the results obtained in units of millgrammes of sulphur/m^2/year. The geographical locations of the four cities were identified with their longitudes and latitudes. From the map, sulphur deposition at any particular location can be determined.

In order to determine the contributions to sulphur depositions from local sources as well as transboundary sources, the data browser option in the deposition model was used. This gives the contributions from large point sources (LPS) in neighbouring countries and also from different states of India taken as a whole. This option also gives the contribution to acid depositions from Sri Lanka taken as a whole.

RESULTS

The projected annual variation of sulphur depositions during the period, 1990 – 2030 for the four cities, Colombo (6° 55′N, 79° 51′E), Kandy (7° 17′N, 80° 38′E), Anuradhapura (8° 20′N, 80°23′E) and Jaffna (9° 40′ N, 80° 0′ E) is given in Figure 1. This shows that sulphur depositions are projected to regularly increase during the period 1990 – 2030 with the City of Colombo having the lowest level of sulphur depositions. This Figure also reveals a clear increasing trend in acid depositions during the period of study from 1990 – 2030. RAINS-ASIA model uses the available data in 1990 as the baseline data and calculates sulphur depositions based on future energy requirements, combustion technologies in power plants, population increase and the socio-economic changes that will take place through this period. During the period under study, deposition is expected to increase from 51.86 kilotons in 1990 to 284.98 kilotons in 2030 for the city of Colombo, which represents a 550 % increase from the 1990 levels. The corresponding percentage increases for the other three cities are: Anuradhapura - 565 %,

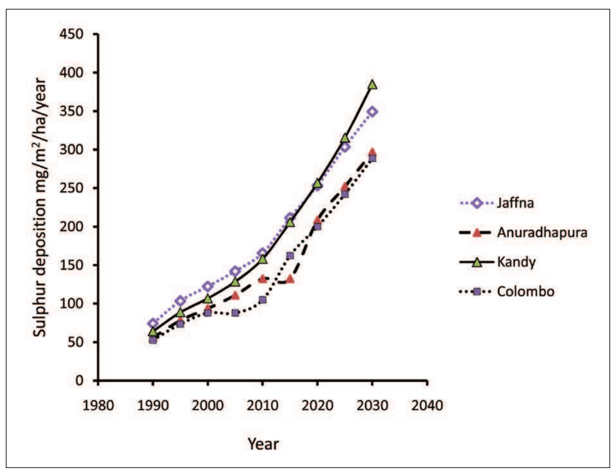

Figure 1: Projected variation of sulphur depositions in Jaffna, Anuradhapura, Kandy and Colombo under the no-control scenario

Kandy - 600 % and Jaffna - 471 %. A noteworthy feature is that depositions in Kandy exceed that of Jaffna from 2020 onwards.

Figure 2 gives the projections for acidic depositions when the ACT option is considered in the calculation. This option assumes that the following sulphur reductions are enforced:

(i) flue gas desulphurisation (ii) use of low sulphur heating oil for large boilers in industry, and (iii) use of low sulphur fuel for transport.

Figure 2 shows the reduction of emissions under the best possible ACT scenario. It is seen that the values are lower by a factor of ca. 5. Another feature is that Kandy records the highest sulphur depositions throughout this period followed by Jaffna. Depositions in Colombo and Anuradhapura under this scenario nearly overlap each other.

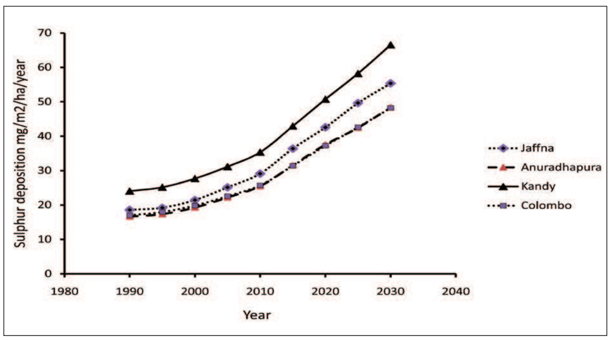

Figure 2: Projected variation of sulphur depositions in Jaffna, Anuradhapura, Kandy and Colombo under the advanced control technology scenario

An analysis of the various sources contributing to sulphur depositions can be obtained using the data browser option in the DEP module. It was found that the main contributors to transboundary air pollution are the Tamil Nadu and Kerala states as whole areas from India (Table 1). In addition, large point sources (LPS), which are the coal powered power plants in Southern India also contribute to sulphur deposition in Sri Lanka to an extent of ca. 5 %.

Table 1 gives the contributors share in kilotons/year of sulphur and how they are expected to vary during the period 1990 – 2030. Table 1 shows that the total sulphur deposition in Colombo and Kandy increases nearly six fold, while the levels in Jaffna and Anuradhapura increase by factors of 4.67 and 5.32, respectively for this period.

DISCUSSION

Colombo has the lowest level of sulphur deposition due to the city being located close to the sea and the flat terrain, which results in the effective dispersal of air pollutants. Jaffna has the highest level of sulphur depositions, which can be attributed to its proximity to India that contributes heavily to transboundary air pollution. These increases are due to both increased energy consumption in Sri Lanka and transboundary effects. Increased local air pollution arises from increased vehicle fleet and fossil fuel burning in power plants. The energy consumption in Sri Lanka in 1990 was 190 petajoules/year, while it is projected to increase to 632 petajoules/year by 2020 (World Bank, 1995). With the commissioning of the Norochcholai power plant and the proposed Sampur power plant, local air pollution and increased sulphur depositions are unavoidable. Socio-economic indicators such as the two - fold increase of per capita income every 10 years with concomitant increase in electricity demand are responsible for this trend.

The higher level of acid deposition in Kandy can be attributed to local air pollution from the Western Province getting transported to the hill country during the South-West Monsoon and the transboundary air pollution during the North-East Monsoon. This is in agreement with the air pollution levels reported in Kandy, which are often 4–5 times higher than those in Colombo (Abeyratne & Ileperuma, 2006). In the case of Jaffna, which receives rain predominantly from the North-East monsoon gets its major share of acid depositions due to transboundary pollution. While sulphur deposition will be drastically reduced (Figure 2) almost by a factor of about 5 under

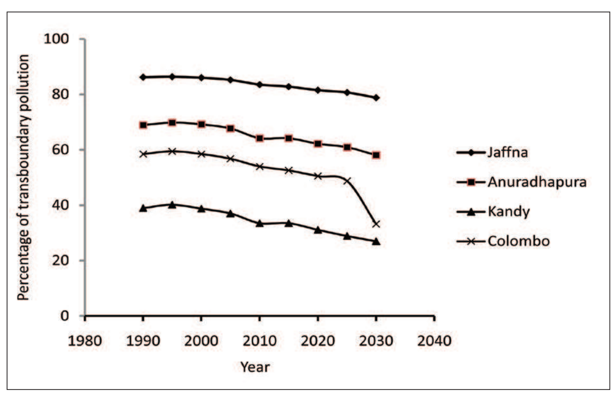

Figure 3: Projected share of transboundary air pollution for the period 1990 – 2030 in Jaffna, Anuradhapura, Kandy and Colombo

Table 1: Sulphur depositions from Sri Lankan sources and from major transboundary sources for each city in kilotons/year

		1990	1995	2000	2005	2010	2015	2020	2025	2030
Jaffna										
	Sri Lanka	9.96	13.57	16.64	20.35	26.43	35.11	44.97	56.58	71.61
	Tamil Nadu	45.83	63.57	72.90	82.85	95.62	119.06	137.04	166.16	189.57
	Kerala	6.13	10.09	15.75	20.35	24.94	34.15	43.35	50.72	56.61
	Karnataka	1.28	2.19	2.96	3.92	4.81	5.58	6.54	7.80	8.81
	Andra Pradesh	0.61	0.95	1.22	1.49	1.81	2.12	2.44	3.01	3.52
	LPS-Tuticorn	3.57	3.86	3.98	3.44	2.36	3.61	3.61	3.34	2.53
	LPS-Neyvelli	2.20	2.10	2.00	1.67	1.00	0.67	0.67	0.00	0.00
	LPS-Mettur	1.12	1.25	1.38	1.20	1.11	0.94	1.79	1.71	1.45
	Sea lanes	1.52	2.05	2.17	2.37	2.56	2.88	3.18	3.45	3.71
Total		72.22	99.63	119.00	137.64	160.64	204.12	243.59	292.77	337.81
Anuradhapura										
	Sri Lanka	16.95	23.09	28.32	35.07	44.97	59.75	76.52	96.28	121.86
	Tamil Nadu	25.14	34.83	40.00	45.43	52.43	65.28	75.13	91.11	103.94
	Kerala	5.43	9.73	13.96	18.04	22.11	30.28	38.44	44.97	50.19
	Karnataka	0.53	0.90	1.21	1.60	1.97	2.28	2.68	3.19	3.61
	Andra Pradesh	0.30	0.47	0.61	0.74	0.90	1.05	1.22	1.49	1.76
	LPS-Tuticorn	1.63	1.76	1.81	1.57	1.07	1.65	1.65	1.52	1.15
	LPS-Neyvelli	1.06	1.02	0.97	0.81	0.49	0.32	0.32	0.00	0.00
	LPS-Mettur	0.51	0.56	0.62	0.54	0.50	0.42	0.42	0.77	0.66
	Sea lanes	3.07	4.16	4.39	4.79	5.18	5.82	5.82	6.99	7.52
Total		54.62	76.52	91.89	108.59	129.62	166.85	202.20	246.32	290.69
Kandy										
	Sri Lanka	38.79	52.86	64.86	80.28	102.93	136.74	175.14	220.36	278.89
	Tamil Nadu	11.97	16.59	19.05	21.64	24.98	31.10	35.80	43.41	49.52
	Kerala	3.45	6.17	8.86	11.45	14.04	19.22	24.40	25.84	31.86
	Karnataka	0.24	0.40	0.55	0.73	0.89	1.04	1.22	1.45	1.63
	Andra Pradesh	0.15	0.23	0.29	0.36	0.44	0.51	0.59	0.73	0.85
	LPS-Tuticorn	0.80	1.05	0.89	0.77	0.53	0.81	0.81	0.74	0.56
	LPS-Neyvelli	0.46	0.60	0.42	0.35	0.21	0.14	0.14	0.00	0.00
	LPS-Mettur	0.28	0.38	0.34	0.30	0.28	0.45	0.45	0.43	0.36
	Sea lanes	7.40	10.03	10.60	11.55	12.51	15.56	15.56	16.86	18.15
Total		63.54	88.31	105.86	127.43	156.81	205.57	254.11	309.82	381.82
Colombo										
	Sri Lanka	21.54	29.35	35.99	44.58	57.16	75.93	97.26	122.37	154.88
	Tamil Nadu	16.07	22.27	25.58	29.04	33.53	41.74	48.04	58.25	66.46
	Kerala	4.50	8.06	11.56	14.95	18.32	25.08	31.84	37.25	41.58
	Karnataka	0.28	0.47	0.64	0.84	1.03	1.20	1.41	1.67	1.89
	Andra Pradesh	0.18	0.27	0.36	0.43	0.53	0.62	0.71	0.88	1.03
	LPS-Tuticorn	0.97	1.05	1.08	0.93	0.64	0.98	0.98	0.91	0.69
	LPS-Neyvelli	0.63	0.60	0.58	0.48	0.29	0.19	0.19	0.00	0.00
	LPS-Mettur	0.35	0.38	0.42	0.38	0.34	0.29	0.55	0.53	0.45
	Sea lanes	7.34	9.95	10.51	11.46	12.41	13.92	15.44	16.74	18.055
Total		51.86	72.40	86.72	103.09	124.25	159.95	196.42	238.60	284.98

the ACT scenario, the cost of such abatement of sulphur emissions is high and it is an unlikely proposition since many of the power plants in India have lower levels of desulphurisation, typically of the order of 30 %. ACT scenario demands a reduction of at least 80 % of its sulphur emissions using advanced control technology.

There is clear evidence of increased transboundary air pollution in all four cities during this period (Table 1). However, since local sulphur depositions also continue to increase at a slightly higher pace, the share of transboundary sulphur deposition shows a slight decrease as depicted in Figure 3. Kandy has the lowest share of transboundary pollution, because its major share of sulphur deposition is transported locally from the Western Province. The share of transboundary pollution for any given city remains approximately the same since local emissions are also concomitantly increasing. The three LPSs selected from Tamil Nadu had the maximum contributions to sulphur depositions and according to the databases of RAINS-ASIA, the one at Neyvilli is being decommissioned by 2025.

Another often ignored contribution comes from the ships, which traverse one of the busiest sea lanes in close proximity to the Southern tip of Sri Lanka. Fuel oil in ships have a high sulphur content typically between 3.5 – 2.5 % (Corbett & Winebrake, 2008) and hence their contribution to sulphur depositions is highly significant. Ship emissions represent 14 % of the nitrogen emissions and 16 % of the sulphur emissions globally from world petroleum use (Corbett & Fishneck, 1997). In Sri Lanka, coastal cities are vulnerable and in 1990, Colombo had 14 % of its sulphur deposition from ship movements while Jaffna had only 2 %. A sample calculation carried out for Galle, which is situated closer to the sea lanes reveal that ship movements accounted for nearly 40 % of all sulphur emissions in 1990. Estimates of sulphur depositions in Asia due to ship movements was predicted to increase from 545 gegagrams in 1988 to 817 gegagrams in 1995 (Streets *et al*., 2000b)

Acidic depositions in Sri Lanka will continue to increase owing mainly to transboundary pollution. Their environmental effects have not been fully assessed but it is likely to cause damage to sensitive ecosystems and also will affect crop yields. RAINS-ASIA has the capability to determine excess sulphur depositions and the ecosystems under threat owing to increased acidification. Kandy exhibits the highest increase owing to both transboundary pollution and also local air pollution from the Western Province getting deposited in the central hill country.

Acknowledgement

Author wishes to thank Dr Jitendra Shah, World Bank, Washington for providing the RAINS-ASIA software used for this study.

REFERENCES

1. Abeyratne V.D.K. & Ileperuma O.A. (2006). Air pollution monitoring in the city of Kandy: possible transboundary effects. *Journal of the National Science Foundation of Sri Lanka* **34**(3): 137 – 141.
2. Central Bank of Sri Lanka (2013). *Statistical Handbook.* Central Bank of Sri Lanka, Colombo.
3. Corbett J. & Fishbeck P. (1997). Emissions from ships. *Science* **278**: 823 – 824.
DOI: http://dx.doi.org/10.1126/science.278.5339.823
4. Corbett J.J. & Winebrake J. (2008). Emissions tradeoffs among alternative marine fuels: total fuel cycle analysis of residual oil, marine gas oil and marine diesel oil. *Journal of Air and Waste Management Association* **58**: 532 – 542.
5. Dissanayake C.B. & Weerasooriya R. (1985). Environmental chemistry of rainwater in Sri Lanka. *International Journal of Environmental Studies* **26**: 72 – 86.
DOI: http://dx.doi.org/10.1080/00207238508710245
6. Hara H. (1993). Acid deposition chemistry in Asia. *Bulletin of the Institute of Public Health* **42**: 426 – 437.
7. Ileperuma O.A. & Premakeerthi R.M. (1998). Country report for acid rain monitoring in Sri Lanka, *Proceedings of the Workshop on Acid Rain monitoring and Atmospheric Modeling* (ed. O.A. Ileperuma), Kandy, Sri Lanka, 20 – 23 April, pp. 85 – 89.
8. Kuribayashi M., Oharab T., Morinob Y., Unoc I., Kurokawad J. & Harae H. (2012). Long-term trends of sulphur deposition in East Asia during 1981 – 2005. *Atmospheric Environment* **59**: 461 – 475.
DOI: http://dx.doi.org/10.1016/j.atmosenv.2012.04.060
9. Menz F.C. & Seip H.M. (2004). Acid rain in Europe and the United States: an update. *Environmental Science and Policy* **7**(4): 253 – 265.
DOI: http://dx.doi.org/10.1016/j.envsci.2004.05.005
10. Nissanka N.M.J. (2005). Investigation of the extent of acid precipitation in Sri Lanka. *M.Phil. thesis*. University of Peradeniya, Peradeniya.
11. Robertson L., Rodhe H. & Granat L. (1995). Modelling of sulphur deposition in the southern Asian region. *Water, Air and Soil Pollution* **85**: 2337 – 2334.
DOI: http://dx.doi.org/10.1007/BF01186183
12. Rodhe H. & Granat L. (1984). An evaluation of sulphate

in European precipitation 1955 – 1982. *Atmospheric Environment* **18**: 2627 – 2639.

13. Schidler D.W. (1988). Effects of acid rain on freshwater ecosystems. *Science* **239**: 149 – 157. DOI: http://dx.doi.org/10.1126/science.239.4836.149
14. Silva E.I.L. & Manuweera L. (2004). Surface and rainwater chemistry in Sri Lanka- a risk of acidification. *Asian Journal of Water, Environment and Pollution* **1**: 79 – 86.
15. Streets D., Guttikunda S. & Carmichael G.R. (2000). The growing contribution of sulphur emissions from ships in Asian waters, 1988 – 1995. *Atmospheric Environment* **34** (26): 4426 – 443.
16. Streets D.G., Tsai N.Y., Akimoto H. & Oka K. (2000). Sulphur dioxide emissions in Asia for the period 1985 – 1997. *Atmospheric Environment* **34**(26): 4413 – 4424.
17. United Nations Environment Programme (UNEP) (2008). Male declaration on control and prevention of air pollution and its likely transboundary effects for South Asia. Bangkok, Thailand.
18. World Bank (1995). RAINS-ASIA: Report on "An assessment model for air pollution in Asia" (eds. Wes Fowell *et al*.) Report to the World Bank, Washington DC, USA.