A Review on Long Range Transport of Air Pollution in South Asia

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ABSTRACT

Long Range Transport (LRT) of air pollutants is an important process of pollution transport to very distant sites. In order to estimate sources of pollution and the possible impacts, it is necessary to understand local as well as long range transport of pollution. Such long distance and inter-continental transport of both natural as well as anthropogenic pollutants adversely affects different atmospheric processes. The South Asian region is severely affected by long range transport and transboundary pollution originated from Europe, Middle-east, Africa, Southeast Asia etc. which very much depends on the seasons. The transported mineral dust in west and south Asia contributes to high particulate loadings in the region. On the other hand, the forest fires in Southeast Asia lead to long-term climate implications. The transport of polluted continental air masses up to the Indian Ocean has implications for Indian Summer Monsoons (ISM). The LRT of acidifying substances has been found damaging for receptor site soils and sensitive ecosystems. The LRT is also a great threat to the sensitive ecosystems such as the Himalayan region and Western Ghats in the Indian subcontinent or South Asia. Furthermore, the continental outflow has been found to be rich in anthropogenic pollutants which get mixed with marine atmosphere and their deposition alters the C/N ratio of oceanic waters. The backward trajectories have shown that the downwind locations mostly suffer from bad air quality. The present study reviews the effect of LRT on rain, snow, and dust and aerosol chemistry and reiterates the need to calculate the fraction of transported pollutants from other regions while formulating the strategies to improve the air quality. There is a need of constituting a task force and regional cooperation which can look into the modalities of the calculations and policy framing between the stakeholders.

Keywords: *South Asia, Long Range Transport, Atmospheric depositions, Acidifying substance and Air quality.*

1. Introduction

The Earth's atmosphere does not have geographical boundaries. Therefore, the natural or anthropogenic emissions from one region have impacts on another region. Pollutants with longer residence time get transported to remote environments with the air flow and impact adversely. Such impacts on ecologically sensitive locations is one of the major concerns of atmospheric scientists. The Antarctic region has shown an increasing concentrations of CO_2 and deposition of Carbon particulates primarily owing to the long-range transport through number of observations made over various monitoring sites (Subcommittee., 2001). Similarly, ice cores of the mid-latitude glaciers of the world have shown a clear evidence of the beginning of industrial revolution. Eskimos found that arctic haze is primarily associated with the industrial emission of pollutants from Europe even much before their contacts with explorers. Furthermore, the increasing interdependence of environment as well as global economic development has significant implications on human health, global climate, and regional environmental quality.

Globally, the international community has sought to address the problem of transboundary air pollution through a number of protocols. In this context, 1979 Convention on Long Range Transboundary Air Pollution (LRTAP) and its eight associated protocols stand out. The convention was administered by United Nations Economic Commission for Europe (UNECE) and encompasses the U.S., Canada and all of the Europe. It addresses the transboundary fluxes of ammonia, ozone, nitrogen oxides (NOx), sulfur, volatile organic compounds (VOCs), persistent organic pollutants (POPs) and heavy metals (http://www.unece.org/env/lrtap). Furthermore, the Multi-Effect Protocol in 1999 has addressed the concept of critical load linked with transportation of ammonia, sulfur, NOx and VOCs and their impacts as eutrophication, acidification and ground-level. The importance of a clear need for continuous support for approximate scientific analysis in the context of LRT of chemicals has been also emphasized in the Stockholm Convention and the Aarhus Protocol on POPs. The study of LRTAP has been conducted in Europe within the framework of European Monitoring and Evaluation Program (EMEP). The results of such studies have demonstrated that LRTAP is majorly responsible for particulate matter pollution in urbanized as well as rural areas of Europe (Lazaridis et al., 2002; EMEP Report 4/2003). The estimate of Asian contribution to the buildup of ambient ozone over central California in 1990 and projected NOx emission levels for 2020 has been arrived at by Yienger et al., (2000) through chemistry transport model. This model was significant because it anticipated a surge in Asian contribution to surface ozone from 5–6 ppb in 1990 to 10–20 ppb by 2020. Similar long range aerosol transport simulation has been shown to work between Europe and Turkey as well. In fact, it has been shown that the impact on PM_{10} levels in Istanbul was affected by emission of individual European countries in the range of 0.5 to 13%. A study by Kindap et al. (2006) has even suggested that anthropogenic emissions from Europe may account for almost half of the background concentration of PM_{10} in Istanbul. This strong correlation is also visible in the context of Seoul, where the high PM_{10} episodes in the city have been linked to the vast amount of air pollutants drifting into its atmosphere from the direction of China (OECD, 2013). Studies have demonstrated through various international experiments such as ABC-EAREX, ACE-ASIA and remote sensing that this pattern of pollutants generated in China, carried over long distances and affect the atmosphere of its neighboring countries which is an increasing concern (Nakajima et al., 2007; Lee et al., 2013; Wang et al., 2014 and Tang et al., 2020).

To monitor the LRTAP, the global community has developed the International Cooperative Programme on Integrated Monitoring (ICP IM) of Air Pollution Effects on Ecosystems (ICP IM). This network has covered forty-eight sites from fifteen countries of the world and most of them are located in undisturbed areas. Its full implementation will allow scientists to assess ecological effects of persistent organic substances, tropospheric ozone and heavy metals (Kleemola and Forsius, 2020). The high levels of nss-SO_4^{2-} at Oki located in the Sea of Japan have been contributed by the air pollutants linked with continental outflow under synoptic weather conditions. The numerical model calculations and the trajectory analyses have shown that origin of polluted air in remote islands occurs due to LRTAP (Murano et al., 2000). The applications of trajectory analysis have been reviewed by Prez et al. (2015). The trajectory analysis became popular when Rodhe (1972) calculated trajectories and established that the phenomenon of acid rain in northern Europe was mainly due to industrial sources of southern and western Europe.

As a major concern, the increasing air pollution in South Asia has led to bad air quality and shown adverse impacts on ecosystem and human health within the region. South Asian countries suffer from severe air pollution problems and among the most polluted nations due to high concentrations of aerosols as well as gaseous pollutants (Shi et al., 2018 and Kulshrestha, 2019). This study reviews the scenario of LRT and trans-boundary air pollution in Asia. These reports have been analyzed for the correctness of data, interpretation and future scope of research estimating the shared burden of non-local pollution load across Asia. The study also presents recommendations for future course of action by the researchers and policy makers.

2. Climate of South Asia

South Asia is mainly dominated by Indian plate and it is surrounded by mountains of the Himalayan and Hindu-Kush region in the north and northeastern side, arid lands of Thar Desert from the west and Indian Ocean from the south. The Indo-Gangetic Plain, which accounts for 40% of Asian population is located in the north India, making it among the world’s most populous region. Landforms and climate of this region varies widely from north to south owing to the variation in altitude, monsoon patterns and proximity to the sea coast. The intense heat experienced over northern India and Pakistan causes the formation of hot and dry continental air in the lower tropospheric region over the area which is even hotter than the air moving northwards from the southern part of Indian Ocean due to advancing Inter Tropical Convergence Zone. As this air laden with monsoon rainfall comes into this area, it settles itself under the over line hotter continental air mass. Thereby endangering a low-angle thermodynamic discontinuity, or intertropical front where it leads to the development of cloud and causes precipitation (Gunnell, 1997). Being an agriculturally rich region, monsoon phenomenon plays an important role in the economy. However, changing climate in the last few years is highly impacting the rainfall patterns. Occurrence of extreme weather events have also been increased such as drought, storms, cloud bursts, smog, haze, etc.

3. Trade Winds and Trans-Boundary Pollution in South Asia

The trade winds are counted among the primary air circulations of the world. Due to their global impact, the trade winds and associated ocean currents have played a major role in facilitating the movement of people across areas separated by the expensiveness of the oceans. The trade winds have been observed to have also contributed to the movement of airborne pollutants over vast distances (Mayol-Bracero et al., 2001). Therefore it becomes important to factor in the role exerted by them in impacting the atmospheric chemistry of a given area. It could be inferred that the atmosphere of an area is not a product of local emissions alone and that external influences also play an increasingly vital role. This connection has attracted the focus of scientists and policy makers across the world. In this context, the UNEP and Stockholm Environment Institute (SEI) in 1998 started an initiative to study the possible impacts of transboundary air pollution in South Asian region. This initiative culminated in the adoption of the Malé Declaration (Declaration, 2002). The declaration addressed the need of regional cooperation to avoid possible threats caused by long range transport of pollutants. It has included India, Iran, Maldives, Pakistan, Bhutan, Bangladesh and Sri Lanka. Discovered in the Indian Ocean Experiment (INDOEX) campaign, it has been found that pollutants emission from some hotspots in south Asian countries leads to the formation of the Atmospheric Brown Haze which adversely affect the regional climate (Ramanathan and Carmichael, 2008; Ramanathan et al., 2008 and Khwaja et al., 2012). This haze consists of organics, nitrates, black carbon, sulphates, fly ash and other pollutants emitted from vehicular emission, biomass burning, industrial activities and urbanization.

4. LRT Impact on Rain and Snow Chemistry

Air pollutants emitted locally or transported through winds finally settle down on the surface. Atmospheric deposition is broadly divided into two type i.e. wet and dry deposition. Nitrogen and Sulphur oxides are two of the very important airborne pollutants which are used to observe fuel use pattern in a region through long term wet deposition studies (Kumar et al., 2016; Pillai et al., 2001). Precipitation chemistry and deposition fluxes of various air pollutants gives significant information regarding the critical load of elements and their subsequent impact on sensitive ecosystems (Sharma et al., 2018). Hence, understanding the sources of pollution through snow and rain chemistry becomes essential to monitor and mitigate possible impacts on the environment (Kulshrestha et al., 2005).

The sulphate and nitrate contents in the Himalayan snow has been found to be linked with LRT which significantly affects pH and snow chemistry of sensitive areas, despite relatively low levels of pollutants in deposited fresh snow (Kulshrestha and Kumar, 2014; Marinoni et al., 2001 and Kang et al., 2004). Generally, snow composition varied from site to site depending upon local sources, land-use pattern of the site, sampling protocols, prevailing meteorology, mean sea level, pollutants transport on regional and global scale in relation to air masses etc. (Marinoni et al., 2001). A study of fresh snow chemistry and sources from central Himalayas revealed that both seasonality and geographical locations have crucial roles in the determination of chemical composition of snow (Kang et al., 2004). In another study from Central

Himalayan region, the dominance of dissolved organic matter was noticed in snow samples (Xu et al., 2013).

Air mass trajectories observation have revealed that remote Himalayan ranges receive significant amount of acidic pollutants from Middle East and European regions via long range transport. The meteorological conditions play an important role in diffusing the pollution. Such diffusion is much more effective in the plains e.g. the Camel-ride push of winds and topography have been reported responsible for flushing out the air pollution from the NCR Delhi and Indo-Gangetic Plains (Kulshrestha, 2019a). Trajectory calculations provided very vital information about the continental transported emissions which were responsible for the elevated level of acidity of rain water at an Eco sensitive site in Western Ghats in Southwest India (Satyanarayana et al., 2010). Rain chemistry in major parts of South Asia gets mainly affected by the marine sources where air masses originate from either Bay of Bengal or Arabian Sea owing to the Southwest monsoon (Budhavant et al., 2009, 2014; Kulshrestha et al., 2009 and Rajeev et al., 2016).

5. Transport of Atmospheric Particulates

Air pollution over the South Asia is catching serious attention due to industrialization and rapid urbanization. The air pollutants not only influence the continents but also perturb into the composition and characteristics of air within the marine atmospheric boundary layer (Ramanathan et al., 2001; Gustafsson et al., 2009 and references therein). Furthermore, the LRT of aerosols from continental sources have been found as a major source of nutrients to oceans and thereby influencing the marine biogeochemistry (Srinivas and Sarin, 2013; Jickells et al., 2005 and Arimoto et al., 2003). Real example of this is usually seen during the winter monsoon period when the continental outflow of nutrients via atmospheric pathways is critically linked with enhanced the primary production of phytoplankton biomass (Rastogi et al., 2020).

Widely studied crop residue burning incidents in northwestern part of India not only envelops Indo-Gangetic plain (IGP) but also affects the air quality of adjoining countries and marine atmosphere (Kaskaoutis et al., 2014). Higher ambient levels of pollutants in post monsoon have been found to be associated with large scale burning of biomass in north India and prevailing meteorology (Mishra and Kulshrestha, 2020; Rajput et al., 2011). Real time monitoring of sixteen air pollutants by Ravindra et al. (2019) have reported that PM levels during post monsoon season becomes much higher as compared to National Ambient Air Quality Standards (NAAQS). Though the ambient concentration of gases and VOCs were observed to be less than 24 h average limits but they are of major concern due to their potential role in formation of secondary aerosols which has longer residence time based on meteorological conditions. The spatial maps have shown that the fire-emitted $PM_{2.5}$ plumes gradually move to south-eastward direction from Punjab to other parts of the north India. But due to lower mixing height and weak wind speed these $PM_{2.5}$ plumes effectively adds up with the already existing pollutants and get accumulated in the lower atmosphere. This phenomenon leads to a sustained haze like condition for several days and severely impact the human health. This also explains how, apart from fire activity, weak ventilation and stable atmospheric conditions aggravate the $PM_{2.5}$ levels in IGP region and nearby areas during October and November months. (Kulkarni et al., 2020 and Kulshrestha, 2017). Such kind of trans-boundary pollution issue needs to be tackled through constituting an interstate body considering all stakeholders (Kulshrestha, 2019).

Observations made over the eastern Himalayan region at Lake Pangang Teng Tso using the HYSPLIT back-trajectory model, have shown that the wet or dry deposition fluxes of various components are dominated with the atmospherically derived pollutants (Deka et al., 2016). However, the transportation of theses pollutants and their subsequent deposition mainly depend on the nature of aerosols, residence time, source region and population density of the region from where the air mass originated/traveled. Tyagi et al. (2020) have demonstrated that Northeast Indian cities experience poor air quality problem during winters owing to the pollutants laden air-masses transported from industrial areas of eastern states of Odisha, West Bengal and Jharkhand and air mass clusters from Bangladesh during post monsoon (Begum and Hopke, 2018). However, the air pollution issues also aggravate due to already existing emissions from biomass based fuel uses for cooking purpose in northeast India (Pandey et al., 2017). It can travel up to long distances and alters the atmospheric composition on intercontinental scales. Anenberg et al. (2014) have simulated the global chemical transport model in coordination with the Task Force on Hemispheric Transport of Air Pollution and studies the epidemiologically response functions. The estimates have shown that the mortality is resulted from $PM_{2.5}$ and its precursor emission from four major industrial regions of northern hemisphere located in Europe, North America, South Asia and East Asia. These authors reported that while large fraction of avoided deaths occurred by reducing emissions in aforementioned regions, a significant percentage associated with outside the source region influenced by long-range transport of pollutants. Nearly 17 and 13 % of global deaths can be avoided by reducing emissions over North America and Europe, due to the large downwind populations, as compared to 4 and 2 % for South and East Asian region (Anenberg et al., 2014). Fine particulate matter over south Asia has been found to be linked with premature mortality (Lelieveld et al., 2015).

Singh et al. (2020) examined the impact of open biomass burning led carbonaceous aerosols by coupling the chemistry with Weather Forecasting model (WRF-Chem). They conducted a simulation for the post-monsoon and pre-monsoon periods when active fires are usually reported. Their results indicate that the carbonaceous aerosols are vertically lofted as high as 5 km and then affects many parts of South Asian region by advection. A study from Gazipur station near Dhaka city, has reported that when air-masses are aroused from the Middle East and routed through the Himalayan valley the PM_{10} concentrations are higher than 150 $\mu g/m^3$ (Rana et al., 2016). Thus, based on concentration weighted trajectory (CWT) method in conjunction with the monthly average aerosol optical depths (AOD) the long-range transport of air pollutants was identified as one of the major causes of hazy episodes, besides local pollution, over Bangladesh during drier season. High levels of BC and OC in atmosphere adversely affect the radiation budget of Indian subcontinent and thus causes melting of Himalayan glaciers and weakening of the Indian monsoon, as has been reported by IPCC, 2007 (Kripalani et al., 2007). Parashar et al. (2005) estimated the budget of carbonaceous aerosols (BC and OC) through the emission factors of various fuels to understand their effect on regional climate and found that about 80% of carbonaceous aerosols in India originate from burning of biomass.

6. Dust Transportation and Regional Climate

Dust cycle plays a crucial role in various processes that goes around on Earth and thus proper investigation about the origin of dust aerosols, its transportation, deposition and effects are needed to understand its contributions. Andreae et al. (1986) in their study of the contributions of various sources to atmospheric aerosols found that soil derived mineral dust is the most abundant component of the atmosphere and contribute more than half of the aerosol burden from both natural and anthropogenic sources. Tegen and Schepanski (2009) have reported the estimates of the global dust emission as 1000-3000 Mt/year and reported that the arid and semi-arid regions of the world are the largest dust source which was also supported by other studies (Prospero et al., 2002).

Goudie (2009) has presented a review on the recent developments in the field of dust storms and explained the importance of dust storms in transporting the atmospheric particles over thousands of kilometers. He not only identified Sahara and western China as the vital progenitors of global dust storms, but also documented the impact of these storms on the environment, such as radiative forcing and biogeochemical cycles. Tegen and Lacis (1996) studied the particle size of dust aerosols and used eight sizes of mineral aerosols between 0.1µ and 10µ in a transport model to calculate their radiative parameters at wavelength from 0.3µ to 30µ. They showed that the regional changes in annual mean of radiative flux are as large as $+15 W/m^2$ at solar wavelength and $+5 W/m^2$

at thermal wavelengths suggesting a very important role of dust aerosols in regional radiation budget.

Atmospheric dust with significant quantities of carbonaceous aerosols have been reported to be the leading cause of lower tropospheric heating and dimming effect on Earth's surface (Mishra and Kulshrestha, 2017 and Dey et al., 2004). Windblown dust is considered as the predominant source of air pollution in African and Asian regions (Tegen and Fung, 1995). Dust originating from the Northwestern India (Thar Desert) is primarily responsible for high loading of particulate matter in the Indian region which along with anthropogenic emissions often results in increased levels of $PM_{2.5}$ and PM_{10} in urban atmosphere (Kulshrestha et al., 2003). Various studies in Indian region have highlighted the significant interference of mineral dust in wet and dry depositions of atmospheric aerosols at urban sites, rural sites, and over the ocean (Kulshrestha et al., 2003; Prakasa Rao et al., 1992; Khemani et al., 1989 and Jain et al., 2000). It is interesting to note that, unlike western countries, even at high ambient sulfate levels in Indian region pH of rain water has been observed to be very high. It may be due to neutralizing capacity of alkaline crustal components (Ca and Mg) from dust in the atmosphere (Kulshrestha et al., 2003).

Dust storms have considerable impact on monsoon patterns over Indian region due to their optical properties. Badarinath et al. (2007) studied the impact of dust storms transport pathway and the pollutants from the local and distant sources. They have found the impact of dust storms originated from the Thar Desert to the air quality of the Hyderabad city, situated in south India. Badarinath et al., (2010) presented a case study of long range transport of dust aerosol that pass over the Arabian Sea using satellite data and ground based measurements. They studied the dust storms originating in the Persian Gulf region and passing over the Arabian Sea using the retrievals from Very High Resolution Radiometer (VHRR). Dey et al. (2004) studied the effect of dust storms along with local aerosol loading and reported high Aerosol Optical Depth (AOD) over the Indo-Gangetic Plain (IGP) in pre-monsoon period. Deepshikha et al. (2005) studied the characteristics of dust aerosols over India through satellite remote sensing. The study was significant in that it drew attention to the discrepancy in the intensity of radiative absorption of the dust between the stretches where the dust originates, such as sandy settings, and urban clusters. Contrary to what one may expect, it was observed that the effectiveness was lower in the context of source areas and greater in urban settings on account of the interaction at the latter of dust with urban pollutants. Tare et al. (2006) presented the chemical properties of aerosols (PM_{10}) during ISRO- Geosphere Biosphere Program Land Campaign II over Ganga basin and observed higher levels of nitrate, ammonium and BC during foggy days as compared to clear days. This may be due to increased biomass burning in winters, which, in turn, may be responsible for prolonged hazy conditions.

7. Conclusions and Recommendations

In order to quantify the amount of exported and imported pollution load, there is a need to fill the gaps of information. The primary requirement is to identify the hot spots in terms of high deposition areas and highly sensitive areas. Then we need to generate long term data of the concerned parameters. For example, the long-term data of trajectories, snowfall, acidifying substances in snowmelt and soil chemistry information are essential parameters to assess the extent of damage of Himalayan ecosystem. Also, the trans-boundary pollution from the garbage burning emissions could have substantial impact on regional particulates loading and pose serious threat to human health impacts which needs to be monitored systematically across south Asia. Secondly, there is a need for regular air pollution monitoring along borders to quantify the amount of pollutants and their directions of flows so that it can be compensated with each other under polluter pays principle. Monitoring and regulating these emissions should be one of the top priorities for environmental regulating agencies. Emissions from coal-fired power plants generate large amount of greenhouse gases and other pollutants which flow to nearby countries through trade winds which needs to be taken care by the researchers and policy makers. Thirdly, there should be collective formulation of the international environmental law, since air cannot be differentiated like geographical boundaries. Similar application of Environmental laws for air and water pollution control can effectively tackle the issue of trans-boundary pollution in South Asia. Also, a mechanism should be established between countries to support the execution of such assessments and to communicate the results to the interested stakeholders.

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