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Significance of Transboundary Air Pollution in South Asia

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The Earth's atmosphere is a shared global space without geographical borders. As a result, both natural and anthropogenic emissions released in a region can travel long distances and influence air quality, ecosystems, and human health. A number of studies have highlighted the role of long range transport and transboundary air pollution worldwide.[1-6] Studies reveal intercontinental impacts, such as Asian emissions contributing to ozone levels in North America. European emissions have been shown to influence PM_{10} concentrations in Turkey.[7-8] Himalayan ecosystem is also under threat due to long range transport of air pollution.[9-10] Increasing concentrations of carbon particulates have been observed even in remote polar regions due to long-range transport.[11] Importatntly, a well-known International framework called Convention on Long-Range Transboundary Air Pollution (LRTAP) and its protocols were established under United Nations Economic Commission for Europe (UNECE) to create a coordinated regional approach in Europe to understand, monitor, and reduce air pollution that crosses borders and causes widespread environmental damage.[12-13]

Effect on Environment and Health

Long-range transport also affects marine environments. Aerosols deposited into oceans supply nutrients like nitrogen, phosphorus, and iron, influencing marine biogeochemistry and enhancing phytoplankton growth.[14] Studies using models such as HYSPLIT and WRF-Chem demonstrate that pollutants can travel thousands of kilometers, affecting air quality, weather, and climate.[15-16] Global modeling studies indicate that transboundary $PM_{2.5}$ contributes significantly to premature mortality worldwide. While emission reductions in one region can reduce local deaths, a substantial portion of health benefits occurs in downwind regions, emphasizing the global nature of the problem.[17] Air pollution driven climate change has altered crop yield by increasing the frequency of extreme events such as cloud bursts, storms and smog etc.[18-19]

South Asia is geographically and climatically diverse, bounded by the Himalayas in the north, the Thar Desert in the west, and the Indian Ocean in the south. This region is among the most polluted regions globally due

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to rapid industrialization, urbanization, and extensive biomass burning. High concentrations of aerosols and gaseous pollutants pose serious risks to ecosystems and human health. Seasonal variations in temperature, wind patterns, and precipitation significantly influence atmospheric chemistry.[20-22]

Air Pollution and Male Declaration

Particulate matter (PM), especially fine particles ($PM_{2.5}$and PM_{10}), plays a central role in transboundary pollution. A notable example is crop residue burning in northwestern India, which generates large amounts of aerosols that spread across the Indo-Gangetic Plain and even affect neighbouring countries.[23] Severity of air pollution is seen during winters when air masses blow from Europe and Middle-east through Pakistan and IGP to Bangladesh and Bay of Bengal. South Asian countries initiated regional cooperation through the Malé Declaration (1998), involving nations such as India, Pakistan, Bangladesh, Sri Lanka, Nepal, Bhutan, Maldives, and Iran. This initiative aimed to assess and mitigate the impacts of transboundary air pollution.

NCR-Delhi and Indo-Gangetic Plain (IGP)

The Indo-Gangetic Plain (IGP), one of the most densely populated regions in the world is highly vulnerable to air pollution.[24] IGP is also an active role player in LRT of air pollution, backwardly to Middle-east and Europe, and forwardly to Bay of Bengal and Indian Ocean. National Capital Region of Delhi which is located in the IGP, is often in news for poor air quality. According to Aggarwal and Kulshrestha, around 50% fraction of carbonaceous aerosols in Delhi is contributed by transboundary sources and windblown resuspension.[25] As mentioned above, the city is affected by transboundary pollution. Air masses moving across Punjab, Haryana, Uttar Pradesh, and even neighboring countries carry particulate matter ($PM_{2.5,}$ PM_{10}), sulphates, nitrates, and carbonaceous aerosols to Delhi. Crop residue burning in northwestern India is a major episodic contributor, especially during post-monsoon months. Meteorological conditions such as low wind speeds and temperature inversions trap pollutants near the surface, leading to severe haze and health hazards during winters. However, same meteorological and topographical conditions are helpful in pushing the air pollution of Indo-Gangetic plains and further to over Bay of Bengal through the Camel-ride push.[26]

Himalayan Ecosystem Under Threat

Air pollutants transported over long distances eventually deposit on Earth's surface through wet deposition (rain, snow) and dry deposition. These processes significantly influence the chemistry of precipitation and sensitive ecosystems. In the Himalayan region, studies show that sulphate and nitrate concentrations in snow are strongly linked to long-range transport, affecting snow chemistry and pH levels.[21] Even remote and pristine areas are not safe, as pollutants originating from Europe and the Middle East have been detected in Himalayan snow.[27] Rainwater chemistry in South Asia is influenced by both marine sources (via monsoon winds) and continental emissions. The chemical composition of precipitation varies depending on factors such as land use, meteorology, altitude, and air mass trajectories. Monitoring precipitation chemistry helps assess ecosystem stress and critical loads of pollutants.[28]

Mineral Dust Transport

Dust storms can transport particles over thousands of kilometers, influencing air quality, climate, and biogeochemical cycles. Mineral dust is one of the most abundant components of atmospheric aerosols, originating primarily from arid and semi-arid regions such as the Sahara and the Thar Desert.[3,29] In South Asia, dust from the Thar Desert significantly contributes to particulate pollution. Dust particles interact with anthropogenic pollutants, enhancing their radiative effects. These interactions can lead to surface dimming and atmospheric heating, affecting regional climate and monsoon dynamics.[30-31] Dust also plays a crucial role in precipitation chemistry in the region. Calcium and magnesium content of atmospheric dust buffers the acidity of sulphate resulting in relatively higher pH of Indian rainwater compared to Western temperate regions.[32]

In a nutshell, transboundary and long range transport of air pollution is a complex environmental challenge that demands coordinated scientific research and policy action. Addressing it requires long-term, high-quality data on pollutant transport, deposition, and ecosystem impacts, with focused monitoring in sensitive

regions such as the Himalayas. Strengthening regional cooperation among South Asian countries through data sharing and joint initiatives is essential, along with the implementation of international environmental laws and principles like “polluter pays.” Establishing monitoring systems along national borders under a defined framework can improve accountability by tracking pollutant flows including the emission impact of ongoing Iran-Israel and Russia-Ukraine conflicts. Long-term satellite observations of long-range transport and transboundary pollution are crucial for accurately quantifying net import and export of pollutants of a country with improved spatial resolution.

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