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Space Remote Sensing Needs for Monitoring Chlorine and Other Air Pollutants for Improved Decision Making in Human Health and Climate Change Policies

UMESH CHANDRA KULSHRESTHA

School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India.

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Space remote sensing plays a crucial role in monitoring air quality by bridging the gaps left by ground-based monitoring systems. Recently, space remote sensing has become an essential tool for air pollution and human health studies.[1] NASA has a dedicated program called Applied Remote Sensing Training Program (ARSET) which covers health monitoring too.[2] In fact, ground based air pollution monitoring stations have their limited spatial coverage which makes it difficult to assess air quality in all the regions. Satellite data help fill these gaps, offering insights into air pollution levels where ground monitors are absent. Various satellite systems can detect criteria pollutants like (indirectly) in between $PM_{2.5}$ and NO_2, as well as greenhouse gases such as CH_4 and CO_2. The choice of satellite data for specific air quality analysis depends on factors such as accuracy, spatial coverage, and temporal resolution. Large-scale data collection through remote sensing can be more cost-efficient than deploying extensive ground-based monitoring networks, particularly in remote or underserved areas.

Remote sensing improves the accuracy of exposure assessments by providing detailed spatial distribution maps of pollutants. Air pollution is linked to a wide range of health conditions, including respiratory diseases, cardiovascular issues, and premature mortality.[3-4] Remote sensing enables researchers to study correlations between pollutant levels and health outcomes at large scales. For example, satellite data on $PM_{2.5}$ can be integrated with epidemiological studies to estimate mortality rates attributed to particulate pollution.[5-6] Remote sensing helps track pollutants, aerosols, and particulate matter in the atmosphere, identifying regions with poor air quality that can lead to respiratory diseases.[7-12] Satellite data can monitor environmental conditions conducive to disease outbreaks, such as mosquito-breeding habitats linked to malaria or dengue. By

CONTACT Umesh Chandra Kulshrestha umeshkulshrestha@gmail.com School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India.

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analyzing land temperature, humidity, and extreme weather events, remote sensing aids in assessing the health risks posed by climate change, including heat stress and vector-borne diseases.[13-15]

Remote sensing can identify pollution hotspots near schools, hospitals, and residential areas, allowing authorities to prioritize mitigation efforts in locations where public health is most at risk. Accordingly, a plan of school admission period, peak time traffic management and even permission for opening of a new school in a particular area can be planned. With the rise of wildfires, industrial accidents, and other pollution events, remote sensing provides rapid data for emergency response.[16-18] It helps track the dispersion of pollutants such as smoke from wildfires or chemical emissions from industrial disasters.

The Indian Space Research Organisation (ISRO) has started initiatives related to air pollution monitoring. One notable program involves the Ocean Colour Monitor (OCM-3) onboard the EOS-6 satellite.[19] This advanced sensor provides high-resolution data on Aerosol Optical Depth (AOD), which is crucial for understanding particulate matter ($PM_{2.5}$/PM_{10}) distribution and transport. OCM-3 AOD product is rigorously validated against ground measurements.[19]

As air pollution originating from one country can affect neighboring regions, understanding of transboundary pollution is a major challenge. Remote sensing helps in the study of transboundary and long-range transport of air pollutants through Remote Transportation Pollution Events (RTPEs) and the effect of meteorological factors.[20-22] This feature enables use of remote sensing data for international cooperation and policy coordination. Long-term satellite observations associated with LRT and transboundary pollution are essential for identifying net import and export of pollution of a country as well as linking it to climate-related changes such as increases in ground-level ozone due to global warming in the Indo-Pacific region.

Remote sensing has undergone remarkable advancements in recent years, transforming how we observe, analyze, and manage Earth's systems. Presently, remote sensing technologies are advanced enough to capture high-resolution imagery data that can identify localized pollution sources. This data is especially valuable in urban areas where pollution hotspots are frequent.[23-26] Instruments such as the Tropospheric Monitoring Instrument (TROPOMI) on the Sentinel-5P satellite are revolutionizing air quality monitoring with fine-scale spatial and temporal data.[27-28] These innovations have expanded the scope of applications across fields such as environmental monitoring, disaster management, agriculture, urban planning, and climate science.[29-34] Hyperspectral sensors, capable of capturing hundreds of spectral bands, have revolutionized the ability to detect subtle variations in surface materials. Synthetic Aperture Radar (SAR) technology has advanced significantly, enabling high-resolution imaging regardless of weather conditions or time of day. Recent developments include polarimetric SAR, which provides detailed information about surface structures, and interferometric SAR (InSAR), which is used for monitoring land subsidence, glacier movements, and seismic activity.[35] Now the near-real-time monitoring of dynamic phenomena such as deforestation, urban expansion, and disaster impacts is possible through Cubesats constellations. LiDAR technology is now widely used for creating detailed 3D maps of forests, urban areas, and coastal zones. Advances in airborne and terrestrial LiDAR systems have enhanced applications in archaeology, flood modeling, and infrastructure planning.

AI and machine learning are transforming remote sensing by automating data analysis and improving predictive modeling.[36] These technologies are particularly effective in processing large datasets from hyperspectral and multispectral sensors, identifying patterns, and detecting anomalies. The integration of IoT with remote sensing has enabled the development of smart monitoring systems.[37] For example, IoT-connected sensors on the ground can complement satellite data to provide a more comprehensive understanding of environmental conditions. Cloud platforms such as Google Earth Engine and Amazon Web Services have made it easier to process and analyze vast amounts of remote sensing data. These platforms support global-scale studies on deforestation, climate change, and biodiversity loss.

Remote sensing helps track pollutant emission trends over time, providing critical information for policy formulation. Despite the above advancements, remote sensing faces challenges such as data accessibility, high costs of advanced sensors, and the need for skilled personnel to interpret complex datasets. The growing importance of remote sensing calls for further investments in satellite technology and data analytics. Efforts must also be made to enhance accessibility to remote sensing data for policymakers, researchers, and the general public. Partnerships between space agencies, governments, and environmental organizations will play a key role in leveraging remote sensing for better air pollution management and improved public health outcomes. Ultimately, remote sensing represents a powerful tool in the quest for cleaner air and healthier communities. It holds immense potential to transform how we monitor, understand, and address air pollution and its health and climate impacts in South Asia and Indo-Pacific region.

In the case of India, as highlighted in my earlier Editorial of August 2020, it is essential to incorporate additional air pollutants such as Cl_2 and HCl into the list of criteria pollutants.[38] This inclusion would help assess the impact of plastic and coal burning on human health and climate change. Our recent studies have revealed connections between particulate chlorine and ozone levels in urban ambient air.[39-41] While numerous satellites provide O_3 data, only a few are equipped to detect Cl_2 or HCl. For example, NASA's Aura satellite, utilizing the Microwave Limb Sounder (MLS) instrument, can measure chlorine, HCl, and ozone. Additionally, the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) aboard SCISAT monitors HCl levels in the stratosphere.[42] To enhance air quality monitoring, satellite-derived data should be validated and evaluated as a reliable alternative to extensive online analyzer networks, which are costly and pose various challenges. These networks often suffer from inconsistencies related to uniform inlet heights, site distances from roads, data discrepancies, calibration irregularities, and overall quality control. Transitioning to satellite-based monitoring of criteria pollutants would improve data accuracy, reduce spatial uncertainties across larger regions, and potentially offer a more cost-effective solution too. However, few selected sites for selected pollutants would be needed for ground validation of remote sensing data.

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