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A global review of cloud seeding techniques for rainfall enhancement

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ABSTRACT

In a climate change scenario, water scarcity is a big problem for the sustainable development of the society. For this reason, searching for unconventional water resources are of utmost importance in water management. In this context, cloud seeding offers a potential option for alternative water resources, particularly in arid and drought-prone regions, such as the rain shadow zones of Western Ghat mountains in India. Cloud Seeding is a weather modification process (i.e., weather is changed or modified by the artificial mechanism), aimed to enhance precipitation by introducing artificial aerosol particles, which serve as ice nuclei or cloud condensation nuclei, into the naturally formed clouds. This report explores the existing cloud seeding techniques across the globe, inclusive of both glaciogenic and hygroscopic seeding methods. It highlights the specific approaches, target clouds, and cloud seeding experiments employed in different countries, including India, China, United States, UAE, Australia, Thailand, Canada, and others. Our study will be useful to the scientific community in planning of any future cloud seeding projects apart from social awareness related to cloud seeding approaches.

Key Words: Cloud seeding, Weather modification, Rain enhancement, Water resources, Cloud physics

INTRODUCTION

In the last few decades, many countries have been exploring cloud seeding technology to overcome the water security problem. However, the main concern is the efficacy of the cloud seeding, which is strongly dependent on the types of clouds formed over the region and the local weather conditions (Kulkarni et al., 2012). Several studies have shown the effective use of hygroscopic cloud seeding over the rain shadow regions (where natural rainfall is very limited) for the rain enhancement purpose (Gayatri et al., 2023; Prabhakaran et al., 2023). For the seeding application, the flares used are of hygroscopic nature that means the aerosol particles released from these flares can be easily activated to cloud droplets and may induce early rainfall by forming larger cloud drops at a lower height (Al Hosari et al., 2021).

Atmospheric aerosols are the tiny particles in solid and liquid phases suspended in the air and have a significant impact on weather, climate, ecology and human health (Kommalapati and Valsaraj, 2009). A fraction of atmospheric aerosols serves as a substrate upon which water vapour can condense to form cloud droplets under supersaturation (SS) conditions (RH >100%) of clouds. These aerosol particles which act as nuclei of water vapour condensation, are called Cloud Condensation Nuclei (CCN) (Mikhailov et al., 2017).

The size and chemical composition of the aerosol particles determine its wetting properties by water vapour; the more soluble a particle is, the lower the value of supersaturation required for it to serve as a CCN (Petters and Kreidenweis, 2008; Pöschl et al., 2009). The ability of an aerosol particle to attract and absorb water vapour from its surrounding environment is known as hygroscopicity. Generally, water soluble particles have higher hygroscopicity and are easier to activate as a droplet. For example, to serve as a CCN at a supersaturation of 1%, particles that are maximally wetted but water-insoluble must have a minimum radius of 0.1 μm, while a soluble particle may serve as CCN at this supersaturation even if their radius at the point of wetting is as low as 0.01 μm (10 times smaller). Most CCNs are a combination of both soluble and insoluble material, known as mixed nuclei (Hudson and Clarke, 1992; Dalirian et al., 2014). The number concentrations of CCN at various levels of supersaturation (0.1 – 1.2%), can be measured using a thermal diffusion chamber known as CCN Counter (Roberts and Nenes, 2005). Small water droplets form over the tiny particles (CCN) at various supersaturation levels in the clouds. Larger size aerosols can be easily activated to droplets, compared to smaller size aerosols with the same material composition. Larger size hygroscopic aerosols such as sea-salt (NaCl) particles with size > 1 μm, are referred to as Giant CCN (or GCCN) and they have high potential to be activated as droplets at a lower supersaturation.

In general, continental origin aerosols lack such giant cloud condensation nuclei (GCCN) due to high contribution from anthropogenic sources that produce mostly sub-micron particles. Continental aerosols, especially in urban city regions, have very high particle number concentration and impact clouds with high droplet number concentration and reduce droplet size, which lead to suppression of warm rain. Under such polluted conditions, where warm rain is suppressed by elevated CCN loading, the introduction of a small concentration of GCCN can modify the cloud microphysics by broadening the droplet size distribution and accelerating the coalescence growth, ultimately enhancing warm precipitation (Jung et al., 2015). This mechanism poses the possibility of weather modification (i.e., rain