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Climatic and Environmental Impacts of Dust over the Tibetan Plateau: An Overview

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Abstract

The Tibetan Plateau (TP), located at a height of nearly 4000 m above sea level, has a unique setting that effects the environment of the whole of northern hemisphere. It acts as the "water reservoir" of Asia as several important rivers originate from this region. Therefore, even slight alternations in the TP's hydrological cycle may have profound ecological and social impacts. However, it is experiencing a significant increase in accumulation of dust from local and global sources. The impact of dust on the region's climate has become an active area of research. Further, the study of sources of dust arriving at the TP is also critical. Accumulation of dust is impacting temperature, snow cover, glaciers, water resources, biodiversity and soil desertification. This manuscript tries to provide a comprehensive summary of the impact of dust on weather, climate, and environmental components of the TP. The impact of dust on clouds, radiative energy, precipitation, atmospheric circulation, snow and ice cover, soil, air quality, and river water quality of the TP are discussed. It further discusses the steps immediately needed to mitigate the devastating impact of dust on the fragile ecosystem of the TP.

Keywords

Tibetan Plateau, Dust, Clouds, Precipitation, Radiative Forcing, Snow

1. Introduction

The Tibetan Plateau (TP), which lies between 25˚ - 40˚N and 70˚ - 105˚E, is situated at a height of 4,000 m above sea level [1]. It has significant differences in elevation between its western and eastern parts [2] [3]. The annual precipitation in TP is more than 600 mm [4], which mostly occurs between May to September [5]; the western parts of the plateau also experience precipitation during December to May [4]. In the years of strong summer monsoon, eastern and central parts of the TP experience more precipitation and higher air temperature, while the western part receives less precipitation and has lower air temperature [6]. The TP uniquely controls the climate and environment of the whole of Northern Hemisphere [7]. TP causes thermal effects at the outbreak of the Asian summer monsoon [8] [9]. Similarly, due to the thermal forcing effect of the TP, it strives a huge influence on the regional as well as the global climate system [10] [11]. TP is also referred to as the water reservoir for Asia as several major rivers of China, India and Nepal originate here [12]. Therefore, even minor alterations in the hydrological circle of the TP would have a big impact on the environment as well as the economy of the TP and its surrounding areas [12].

However, TP has experienced a warming, which is leading to a glacier retreat [13]-[18]. The intrusion of dust over the TP could also play a major role by heating the atmosphere and lowering the snow albedo over the TP [16] [19] [20]. Besides, TP's warming also affects other parameters, such as precipitation, wind speed, and clouds [21] [22]. Therefore, studying dust's impact on weather, climate, and environment of the TP has become an important field of research.

Importantly, the TP itself is an important source of dust; a large amount of which enters into the atmosphere during the storms that mainly occur over the plateau during winter and spring [23]-[26]. Accumulation of dust also occurs in summer [27]-[30] and in autumn [31], which is observed at higher than the mid-tropospheric level of the windward side of the TP [32]. The dust advected from the Arabian Peninsula and the Indian subcontinent is deposited in the southern parts of the TP [33], while the dust deposited in the northern sides is sourced from the Taklimakan desert [27] [29] [34]. Additionally, dust from Gurbantunggut, Kumtag, and Qaidam deserts are also transported to the TP [34]. The dust from the Gobi and Taklimakan deserts can attain up to tropopause heights over the northern sides of the TP [35]. The dust from East Asia dominates the size of ≥1.25 to ≤10.0 μm diameter in spring and summer [35]. Further, during the pre-monsoon season, dust from the deserts of western China, Afghanistan, Pakistan, and Middle East are also piled up onto the TP [20].

Though there are several studies about the effects of dust on specific component of climate/environment over the TP [36]-[38], comprehensive studies on dust's impact on climate and environment, biogeochemical cycle, human health, and society are limited. They also lack specific recommendations on the outlook for further research for the control and mitigation of effects of dust over the TP. Here, we have attempted to bridge these gaps so that the effects of dust over the TP could be addressed in a comprehensive way and efforts to strengthen the monitoring of climate and environmental components over the TP could be encouraged. We also highlight the need of creating key scientific technology and infrastructure to conduct dust research on the ongoing climate change, biodiversity, water resources and management, snow/glaciers, soils, and prevention and control of desertification of the TP.

Below, we shall review the effects of the dust on weather and climate of the TP, evaluate the impact of dust on several environmental components, and finally conclude with perspective and recommendations.

2. Effects of Dust on Weather and Climate of the TP

2.1. Effects of Dust on Clouds

The atmospheric stability is enhanced by the accumulation of dust, which also affects the development of clouds over the TP by acting as cloud condensation nuclei or as ice nuclei [39]. The inclusion of dust in the clouds can decrease the ice particle dimension, and extend the longevity of the clouds [40]. Further, dust over the TP could enhance the development of convective clouds at higher levels and contribute to downstream precipitation [40]. These studies further suggest that the entry of dust into the atmosphere changes the characteristics of the clouds over the TP.

2.2. Effects of Dust on Radiative Energy

Dust substantially affects the radiative energy and thermodynamic profiles of the air over the TP by altering the shortwave radiation [37] [41]-[43]. The warming over the TP is amplified by an increase in the dust heating effect [44]. A deposited dust in the snow warms the TP surface and raises the thermal effects in the spring [45]. Consequently, this alteration of radiation may change the thermal structure between the TP and the surrounding areas that may lead to alterations in weather and climate of the TP [46] [47]. It has been pointed that the air of the southern sides of the TP could be heated by the dust, which is transferred from northern India in late spring and early summer [20].

In this regard, the direct radiative forcing, induced by the dust, would cause a cooling effect at the top of the atmosphere and the surface whereas warming in the TP's atmosphere [35]. On the other hand, it has been reported that the dust initiating from the TP cools its mid-atmospheric layer [47]. Similarly, it has been shown that due to dust, a shortwave irradiation was positive in magnitude, while the infrared radiative effect was negative over the TP [41]. They also indicated that the instant heating rate depends on the concentration of the dust. Further, it has been reported that the dust transported from the Taklimakan desert cools the atmosphere, which is close to the surface and heats above than the mid-tropospheric level over the TP [48]. Besides, this study indicated that dust amends the surface and top of the atmospheric energy, which may change the stability of the atmosphere as well as the surface sensible and underlying heating of the TP.

2.3. Effects of Dust on Precipitation

Dust particles affect ice nuclei in inhibiting the precipitation over the TP [12] [49]. Also, considerable negative correlations between dust and precipitation are noted in the dust source regions over the TP [12]. The clouds that head out towards the east, and are adulterated by Taklimakan dust, could slow down a substantial rainfall over the TP [50]. On the other hand, it has been discussed about a contrasting scenario where dust could assist in converting water vapor in the atmosphere into precipitation in clean and moist atmospheric conditions [12]. Some studies have further pointed that the air over the southern sides of the TP could be heated by the dust arriving from the deserts of northern India [51] [52]. This may act as a trigger for an earlier start and strengthening of the monsoon in the Indian subcontinent; a phenomenon called as the heat pump effect [51] [52]. Dust may also impact the quality of the rainfall. For example, the alkaline rain in northeast of the TP is caused by the dust of the local alkaline soils [53]. Thus, dust may play a dual role of suppressing the precipitation and promoting it too, an outcome that is based on the characteristics of the dust, locations, atmospheric condition, and the availability of moisture.

2.4. Effects of Dust on Atmospheric Circulation

Irrespective of the deflation of dust from the TP, simulations have shown a radiative cooling effect in the mid-atmospheric level that results in a clockwise circulation at the lower level of the TP's atmosphere [47]. This lessens the strength of the east Asian summer monsoon [47]. It has been found that the amplification of the warming of the surface and the upper level of the atmosphere was also caused by the accumulation of dust over the Himalayan-TP, leading to a diminished strength of the subtropical jet and an entry of the summer monsoon over southern China [44].

Depending on the frequency of its entry from the Taklimakan and the Thar deserts, dust also may have significant implications for the atmospheric circulation and monsoon of the TP [31]. Because of a strong ability of absorbing and scattering of solar radiation, dust can heat the air in the mid to upper levels of the TP [20] [54] [55], which results in its anticlockwise circulation in the lower level [32] [56]. While these studies give insights into the effects of dust on atmospheric circulation, especially at the lower level, there are still inconsistencies about the types of the circulations caused by the dust over the TP.

2.5. Effects of Dust on Environment of the TP

2.5.1. Effects of Dust on Snow and Ice Cover

Variations in the concentration of dust in the snow, with higher levels in the central to the northern parts of the TP, are reported [57]. Depending upon its concentration, dust may amplify the warming effect in the snow of the TP [58]. Consequently, the deposited dust on the snow/glaciers of the southeastern parts of the TP could warm the glaciers by lowering the albedo compared with that of the clean snow [59]. Further, atmospheric heating caused by the dust could also enhance the warming effect and accelerate the melting of the snow in the western TP [43] [60] [61]. Similarly, the deposition of dust can lead to a reduction of snow mass over the western parts of the TP [43]. Dust depositions on snow/ice can change the surface albedo [62] [63], which could result in a decrease of snow water equivalent in the western parts of the TP [62]. Furthermore, dust could significantly affect snow melting rate, amount of the snow, snow cover duration, and glacier receding timing in the TP due to alteration of surface albedo [57] [64].

An earlier report had estimated that dust deposition during snow melting season would result in a higher loss of mass from the glaciers of the TP [65]. This idea was supported in subsequent studies that found that area of the snow and glaciers are experiencing glacial lessening [14] [16] [66], permafrost declination [67], and reduction in the snow cover periods [68] [69]. These further affect the hydrological system of the TP [70] [71]. All of these have allured much attention of the concerned agencies/researchers since the region serves as a major water reservoir for several big Asian rivers [43] [72]-[75]. It has direct implications for the people of south/southeast Asia as they are supported by the water from the glaciers of the TP [76]. Furthermore, the biogeochemical cycle in snow/glacier regions are also significantly influenced by the dust over the TP [77].

Hence, dust has significant impact on the alteration of the snow and ice over the TP; these impacts need to be properly accounted for the regional climate projections since the existence of snow cover plays a major role for the ecological and social stability.

2.5.2. Effects of Dust on the Soil

The sources of aeolian matters, aeolian dust accumulation courses, and aeolian dust effects on the alpine soils are still obscure in spite of several studies [78] [79] [80]. It has been found that the primary substances in the alpine soils have an aeolian origin; and the aeolian dust accretion is a source of nutriment for alpine soils of the TP [81]. This is one of the positive effects of aeolian processes in alpine soils, a finding consistent with several other studies [82]-[87]. Similarly, deposited dust could provide nourishments to ecosystems and influence the carbon cycling of the TP [88]-[90]. For instance, calcium carbonate in the dust can ameliorate the softening capacity of the alpine soils of the TP [84] [85] [91] [92].

Aeolian clay and silt materials, with organic carbon, could develop composite forms and structures, which could prolong the carbon's presence in the soil [93] [94] [95]. Generally, aeolian dust accretion is fundamental to the formation of alpine soils, and the fusion of aeolian and organic substance create fertile alpine soils on the TP [81]. This emphasizes an important role of aeolian dust in supporting agriculture at the TP.

2.5.3. Effects of Dust on Air Quality

Though some studies have shown that the TP has been exposed to polluted air mixed with dust from its region and from other parts of the world [27] [96], background ambient air pollution levels in the TP are still very low [96]-[98]. However, the dust AOD (aerosol optical depth) peaks over the eastern parts of the TP in spring because of the transport of dust from the Taklimakan and Gobi deserts [36]. Compared to other atmospheric constituents, dust contributes to more than half of the total AOD. Even though there are several dust sources for the TP, a higher AOD in the year 2000 was noticed, which may have been caused by the dust advected from the Middle East [99]. Nevertheless, it can be accepted that the presence of dust over the TP has been affecting its air quality.

2.5.4. Effects of Dust on River Water Quality of the TP

Since ancient time, aeolian dust has been affecting the river water quality in the Xining Basin [100]. A large amount of eolian dust is deposited in different water bodies over the northeast side of the TP and may be affecting the water quality of that area [100] [101]. Similarly, the water basins in the northern sides of the TP are characterized by distinct river water ions in the spring due to the dissolution of dust carbonates and salts [99]. Hence, eolian dust may play a significant role in controlling the seasonal changes in river water quality of several bodies of the TP.

3. Conclusions and Recommendations

3.1. Conclusions

The existing trend of the deposition of dust over the TP may promote aridity in the region. This may be caused due to several reason, for example, the difficulty of formation of favorable clouds for precipitation and suppression of the precipitation processes, warming of the atmosphere, and the loss of the fresh water system. Processes such as rapid melting of snow, glacier retreat and degradation of wetlands may expedite the loss of fresh water system. TP is affected by dust from local sources and from across the world. Dust storms are getting enhanced by the ongoing climate change, drought, land degeneration, and feeble management of land and water resources. Notably, there are fewer studies about the effects of the dust on clouds, atmospheric circulation, air quality, soils, and river water quality of the TP.

3.2. Suggestions on Steps Needed Immediately

Clearly, dust has been accumulating from local and global sources, which is impacting the climate and environment of the plateau. In this context, following measures might be helpful in reducing its impact:

- A continuous program is needed to closely monitor the TP for the resilience and adaptability of its ecosystem to the impacts of dust in the future. Wherever needed, (bio-)engineering measures should be implemented so that soil erosion is deterred, dust deflation from the surface is reduced, and the disturbed areas are minimized. Bio-engineering measures may include management of natural vegetation so that top soils are preserved; soil stabilization by use of mulching, blankets, and plantation exercises; and setting up sediment traps or turbidity barriers for soil protection. It may act as a valuable tool for mitigating the impact of dust in the future.
- There is a need to address the sources of the accumulating dust and the dust storms. While global sources may be beyond the control, the dust emitted from the TP's surface could be minimized. This warrant executing the programs for protecting various water bodies (such as lakes/ponds) of the TP from drying

out, and of restoring dryland ecosystems. Further, dust emission over the TP may also be facilitated by human activities, such as cropping, livestock grazing, amusement, urbanization, and water deviation for irrigation; these activities need to be better managed to mitigate dust production.

- There is a need for extensive increment of data compilation, setting up early warning systems of dust storms, and extensive research work on climate change trends of the region to revive the TP's ecosystem and secure its sustainable development for the future.
- The wild fires caused by the human activities over the TP should be strictly minimized/controlled. Wild fires may destroy the vegetation cover and soil moisture, thus leaving the land as a potential source of dust emission [102].
- There is a pressing need for a mutual coordination/cooperation between the various agencies of the TP (China), North Africa, Middle East, and India, where sources of dust storms (like deserts) are located, and the management programs could be facilitated to minimize the emission of dust; this would also help to comprehensively address the issues related to climate change.

3.3. A Perspective on Future Directions

A long-term focus on innovation is needed in order to address the impact of dust over the TP and to support the betterment of its ecological environment. For this, the research activities should break the hurdles between basic and applied research on dust effects over the TP to revive its balanced ecosystem. In other words, efforts are needed for efficient prevention and control of the dust emission, which would warrant development of advanced technologies and tools. Also, technique for high-precision inspection and early warning system of dust storms/concentration are needed.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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