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Review article

Aerosol-orography-precipitation – A critical assessment

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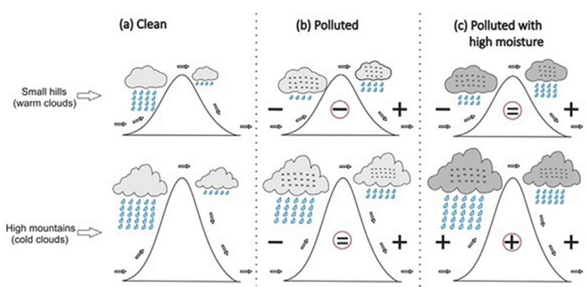
GRAPHICAL ABSTRACT



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ABSTRACT

The increasing anthropogenic pollution and its interaction with precipitation received much attention from the research community and have been explored extensively for understanding the aerosol-cloud interactions. The impacts of orography and aerosols on the precipitation processes have unveiled the Aerosol-Orography-Precipitation (AOP) interaction as an essential research area. The understanding of AOP interaction is critical for improving the extreme rainfall events prediction over mountainous regions. The phase of clouds (warm or mixed) along with orography has emerged as a significant factor for influencing the AOP relations. The present work reviews the modelling and observational based studies dealing with the relationship between orography and aerosols on the precipitation. The study reveals the principal role of aerosols in shifting the precipitation pattern for orographic regions. The environmental factors, especially ambient temperature, humidity and flow patterns are also identified to affect the orographic precipitation. The review also discovers that AOP studies exist only to limited areas of the world due to limited observations, and mostly with idealised cases in the modelling framework.

1. Introduction

Most of the freshwater available to humankind is coming from the orographic precipitation (Schär and Frei, 2005). The precipitation over mountains and hills occurs when cloud systems developed with different mechanisms (e.g., frontal, convective, topographical lift) help to condensate the moisture in the form of solid or liquid precipitation. The precipitating snow accumulates in the high mountains and serves as a necessary freshwater reservoir in many regions of the world. The orographic precipitation however, depends on many parameters e.g. the terrain features (mountain height and cross-mountain width) (Colle, 2004; Roe, 2005; Jiang, 2003 & 2007; Watson and Lane, 2012),

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atmospheric stability (Schneidereit, 2000; Colle, 2004; Kirshbaum, 2008; Kunz, 2011), upslope velocity and low-level water content (Schneidereit, 2000; Neiman, 2002; Jiang, 2003, 2009; Colle, 2004; Kunz, 2011; Watson, 2012), surface temperature (Kirshbaum, 2008; Zängl, 2008; Kunz, 2011), the concentration, size spectrum and chemical composition of the aerosols on which the water vapour condenses (Borys, 2000, 2003; Griffith, 2005; Rosenfeld and Givati, 2006 and many more).

The impact of orography forcing on the amount and distribution of precipitation depends on the value of Bulk Damköhler number which is the ratio of the advective time scale (the time it takes for an air parcel to move across the mountain) and microphysical time scales (to convert cloud hydrometeors to precipitation) of the cloud system (Jiang, 2003; Miltenberger, 2015). Cloud droplets take time to grow and fall out as precipitation, and the elevation and slope of the terrain limit the locations of precipitation occurrence. For example, if the time scale of microphysical processes is less than the time scale of advection across the orography, then under ideal conditions, the cloud may precipitate over the windward side. Otherwise the cloud may cross the barrier and may increase the leeward precipitation (spillover effect). Since aerosols, by acting either as cloud condensation nuclei (CCN) or ice-nuclei (IN), affect the time scales of cloud microphysical processes, they play a vital role in modifying the orography forcing.

In the present scenario of understanding the climate change and its association with various processes, the aerosol-cloud-climate interactions are vital to understand the extreme rainfall/drought events globally (Intergovernmental Panel on Climate Change (IPCC), 2013; Stocker, 2014 Koren et al., 2014; Fan et al., 2015; Sarangi et al., 2015; Fan et al., 2016). With evident increase in aerosols, especially over developing countries (e.g. Gogikar and Tyagi, 2016; Gogikar et al., 2018; Singh et al., 2019; Gogikar et al., 2019; Sahu et al., 2019), the investigation of extreme precipitation patterns association with aerosols are more crucial. As explored by many researchers, the aerosol-cloud interactions are having direct impacts on the associated rainfall over any region of interest and follow feedback mechanism (e.g. Baker and Charlson, 1990; Xue and Feingold, 2006; Morrison et al., 2012; Bollasina et al., 2013; Altaratz et al., 2014; Saleeby et al., 2015; Fan et al., 2016). The mechanism is further complicated when we are trying to understand aerosol-cloud interactions modulated by topographical features. However, understanding how topographical features interact with aerosols, clouds and associated rainfall is becoming more and more crucial with the increasing extreme rainfall events (cloud-burst) in the vicinity of orographic structures (Chaudhuri et al., 2014; Fan et al., 2015; Dimri et al., 2017). Various researchers are exploring the aerosol-orography-precipitation (AOP) interactions over different regions of the world with both observational and modelling analysis (e.g. Rosenfeld and Givati, 2006; Lynn et al., 2007; Fan et al., 2014; Fan et al., 2017).

The aerosol-cloud interactions are well explored (e.g., Khain, 2009; Tao et al., 2012; Fan et al., 2016; Kant et al., 2017). The AOP understanding is still under progress. The present paper is an attempt to review the findings of the AOP interaction, with a focus on the indirect effects of aerosols on orographic precipitation (hereafter termed as OP). The paper has been organised in different sections as follows: Section 1 presents a brief introduction of the impact of aerosol indirect effects on the OP. In Section 2, we will discuss the simulations performed with various mesoscale models and various proposed theories for understanding the AOP interactions. Section 3 will summarise the findings established by the observational data analysis. The final segment (number 4) summarises overall conclusions based on the review of articles (both modelling and observations), with the identification of the gap areas in current knowledge on AOP interactions.

2. Model simulations based understanding of aerosol-cloud-orography interactions

Aerosols serve as CCN and IN forming liquid droplets and ice crystals in the atmosphere. Precipitation over orography is a result of complex interactions between the microphysical timescales and the advection time scale of the orographic cloud. Thus changing aerosol concentration in such a scenario will modify the cloud droplet number and size distribution, thereby altering the cloud microphysical processes, amount, lifetime, distribution and amount of precipitation. The numerical simulations allow the sensitivity studies of various microphysical processes, topographical features, the concentrations change in CCN/IN/Aerosols over different regions of the world using different initial and boundary conditions for a better understanding of the AOP interactions. Depending on the height of the topographical region, orographic clouds either can be a warm phase or mixed phase. In general, for warm clouds when everything else remains constant, increase in aerosols results in more small cloud droplets (Twomey, 1977) and an increase in cloud lifetime (Albrecht, 1989). This increase may result in the suppression of precipitation due to the decrease in coalescence efficiencies because of the reduced drop size (Rosenfeld, 2005). However, for mixed-phase clouds, the understanding of aerosol impact is still in progress because of complex microphysics involvement in ice nucleation. We can summarise the warm and mixed phase cloud studies related to orography and aerosol as follows.

2.1. Warm phase clouds

The growth processes for warm phase clouds are condensation and collision – coalescence (C–C). Condensation, the change of water vapour into liquid water, usually occurs in the atmosphere when warm air rises, cools and lose its capacity to hold water vapour. The excessive water vapour results in cloud droplet formation via condensation. Initial growth of droplet by condensation is high, but it reduces with time, and is not sufficient to produce the large raindrops alone. The dominant growth process in warm phase clouds is C–C, which has three categories:

(i) Autoconversion – The initial phase with formation of small cloud droplets which results in drizzle drops after coalescence
(ii) Self-collection – The large drizzle drop formation from the smaller ones, i.e. small raindrop (drizzle drop) collects other small raindrop (drizzle drop) to form larger ones and
(iii) Accretion – The cloud drops collection by the large drizzle drops formed in the previous step.

Out of the three processes, the efficiency of accretion is higher than self-collection (Ochs III et al., 1984), with the well-established relationship between the warm phase cloud and precipitation efficiency (e.g., Testik and Barros, 2007; Villermaux and Bossa, 2009; Wilson and Barros, 2014). However, the understanding related to warm phase clouds and orography is under progress with fewer attempts of aerosols interacting with these complex processes. The microphysical, geometry and flow pattern impacts on the precipitation for the warm phase clouds can be summaries as follows:

2.1.1. Impact of aerosols on microphysics and precipitation

The orography initiated precipitation that interacts with varying physical (e.g. size) and chemical (e.g. solubility) properties of aerosols is complex in nature and reported by various researchers with a focus on microphysics, evaporation, aerosol regeneration and destruction process, and diverse timescales of hydrometeor advection (e.g. Mühlbauer and Lohmann, 2006, 2008; Xue et al., 2010; Glassmeier and Lohmann, 2018). The studies investigating these relationships used various models from micro to regional scale over different areas. By using the local short-range model developed by German Weather services, Mühlbauer and Lohmann (2006) observed that the increase in aerosol (potentially serving as CCN) concentration for the warm phase orographic clouds result in overall less precipitation. This reduction in overall precipitation is accompanied by the raindrop size distribution towards a narrow spectrum with a change in the maxima precipitation to upslope. The ratio of precipitation over the leeward and windward side (also known as spillover factor) was higher in polluted case indicating the increase in the leeward precipitation. The possible explanation for such outcome may be due to the increasing aerosol concentration, which leads to the formation of smaller size cloud droplets with reduced auto-conversion rate, thus reducing the mean raindrop size (Mühlbauer and Lohmann, 2006). Using the regional scale 2D **Co**nsortium for **S**mall-scale **Mo**deling (COSMO) model with two-moment bin microphysics scheme, Mühlbauer and Lohmann (2008) studied the effects of aerosols on warm phase orographic clouds with varying mountain geometry. The results are similar to that of the local short-range model of Mühlbauer and Lohmann (2006), indicating an escalation in spillover effect and overall precipitation suppression with increasing aerosol concentration. The results indicate that increased microphysical time scale enhances the cloud lifetime. This increased lifetime allows the clouds to move past the mountain ridge and to experience greater evaporation due to the subsiding wind/flow, resulting in an overall decrease of precipitation. Glassmeier and Lohmann (2018) also used 2D COSMO model with two-moment cloud microphysics scheme to study the interaction between different microphysical pathways in a fully adjusted steady state and externally constrained condition as a response to aerosol perturbations. The study is accomplished over an idealised bell-shaped mountain with height 800 m and cross mountain half-width 20 km using the concept of precipitation susceptibility (defined by the ratio of differential change of natural logarithm of the precipitation-mixing ratio and the cloud droplet number). The study observed a low precipitation susceptibility to the aerosol perturbations, and the net effect of aerosols to the autoconversion and accretion hydrometeor growth process tends to compensate each other. Increase in aerosol concentration may reduce the autoconversion efficiency because of the formation of smaller size droplets but may also favour growth by accretion. Thus, the effect of aerosol on the warm phase orographic precipitation may be less significant because of the compensation effect between different microphysical growth processes.

The solubility of aerosols is another important property affecting the AOP interaction due to aerosol enhancement. The impact of solubility depends highly on the available moisture content in the atmosphere. Under highly humid conditions with high solubility, the surplus number of activated GCCN results in more efficient C–C process, and produce high precipitation when compared to low solubility case. However, in the dry conditions, the high solubility reduces the precipitation amount compare to the low solubility case. Xue et al. (2010) incorporated 2D idealised mountains with 3D Weather Research and Forecasting (WRF) model with elaborated bin microphysics scheme for understanding the effect of solubility and regeneration of aerosols for the warm phase orographic clouds over two bell-shaped mountains. They found that for a given background concentration, aerosol solubility influence the CCN and giant CCN (GCCN) concentrations such that high solubility leads to the activation of high concentration of CCN and GCCN. Xue et al. (2010) found that the clouds sensitivities with aerosol solubility reach to an agreement with cloud parcel model simulation, as discussed by Reutter et al. (2009). The study concludes that the second mountain experience a decrease in precipitation (2%–80%) due to increased cloud droplet number concentration (CDNC) by aerosol regeneration due to evaporation on the leeward side of the first mountain. The precipitation suppressing effect of regenerated aerosol particles is significant only for polluted clouds with high aerosol solubility. The second mountain precipitation may increase by the regenerated aerosol solubility modification, with decreasing solubility and increasing sizes of primary aerosol particles.

By statistical analysis of station rainfall and visibility data (a proxy for aerosols), Guo et al. (2014) found an inverse relationship between light rainfall (< 2 mm/h) and visibility (discussed in section 3.1) over the Taihang Mountain range, north China. To validate this observational result, they performed cloud resolving real case simulation of a precipitation event that occurred on 13 July 2008 over the Taihang Mountain by using 3D WRF model incorporating spectral bin microphysics. The simulation was performed for 78 h for the clean and polluted case with CCN concentration 280 cm^{-3} and 1680 cm^{-3} respectively and no ice-phase processes were considered. The output was composed of both orographic-forced shallow clouds and mesoscale stratiform clouds. Compared to the clean case, the results for the polluted case showed a decreasing frequency of light rainfall for both the clouds in accordance with the observation. They also found that when no terrain was considered in the simulation, the light rain intensity increased as a response to the increase in CCN concentration indicating the prominent role of orography in modulating the AOP interaction.

Pousse-Nottelmann et al. (2015) studied the influence of aerosol processing by using different aerosol generation and deposition parametrizations on the aerosol number and size distribution and the development of non-precipitating warm phase orographic clouds by using 2D COSMO model. They considered two identical 2D bell-shaped mountains with a peak height of 800 m and half width of 20 km, such that their peaks were separated by a distance of 200 km. The aerosol data collected from the field campaign at the Alpine research station in the year 1999 was used for the initialisation of aerosols in the model. For warm and cold phase clouds, a total of 8 simulations (4 each) by varying the representation of aerosol generation and scavenging processes in the model were performed with

(i) standard (without any scavenging) (Muhlbauer and Lohmann, 2008, 2009),
(ii) consisting of below-cloud scavenging and aerosol activation scavenging (Zubler et al., 2011a),
(iii) processes in (ii) but with modified below cloud scavenging (where all the inactivated aerosol particles colliding with precipitating rain or snow are removed) and cloud scavenging within the cloud or in-cloud scavenging and
(iv) new aerosol handling scheme with thorough aerosol activation and processing including all scavenging process. In the first case where the aerosol regeneration and scavenging processes are neglected, the number concentration of aerosols that can act as potential CCN (radius > 35 nm considered in the model, hereafter termed as N35), can change only by the change in dynamics due to flow over the orography and hence show minute variations.

In the second case, because of the inclusion of activation and below cloud scavenging processes, the air masses encounter a reduced N35 concentration when passing through the cloud across the first mountain. However, for the third case, the N35 concentration showed very minute variations when compared to the former case may be because the in-cloud scavenging due to collisions primarily involves Aitken mode particles which are a small subset of N35 particles. The fourth case which includes all the scavenging, activation, regeneration processes along with the aerosol processing within the cloud, the aerosol regeneration by evaporation in the leeward side of the mountain compensates some of the scavenged. These regenerated aerosols move towards the second mountain because of the unidirectional 2D wind influencing the cloud development process. The aerosols before being regenerated by evaporation are subjected to aerosol mass transfer within cloud hydrometeor. The processes that can contribute to the mass transfer are microphysical growth processes (collisions and autoconversion), below cloud scavenging and compaction scavenging within the cloud. This regeneration of aerosols results in comparatively high number concentration and mass of aerosol particles (both Aitken and accumulation mode) compared to the third case. They found that the Aitken mode particles formed by this process have an increased size and mass shifting the size distribution towards a larger size. The sensitivity tests confirm that the effect of aerosol particles regenerated by evaporation on the net aerosol mass, size and number concentration depends on the cloud system considered and the initial aerosol properties. The simulations performed in this study considered non-precipitating warm phase clouds and thus could not explain the impact of the regenerated aerosols on the OP.

2.1.2. Impact of geometry and flow pattern

The OP distribution significantly depends on the geometry of the mountain. The geometry can modulate the relative contribution of microphysical processes, and hence the total precipitation pattern (Mühlbauer and Lohmann, 2008). The flexibility of choosing the desired geometry of mountain during simulations (e.g. linear hydrostatic mountain wave, small mountains, and blocked orographic flows) allows many possibilities of geometry impact on AOP interactions. For the warm phase clouds, the studies by Mühlbauer and Lohmann (2006, 2008) discovered that increase in the mountain height increases the total precipitation, whereas the spillover factor decreases for both polluted and pristine cases. However, the difference in the spillover factor for the polluted and pristine case was maximum for a mountain height of 500 m (Mühlbauer and Lohmann, 2006) implying that the aerosol effects on warm phase clouds are more pronounced for small mountains. The hydrometeors advection on the leeward side for the linear hydrostatic mountain waves favours evaporation processes in the warm and dry downdraft region. Thus, when considered along with increasing aerosol effects, it can result in high loss of OP in both upslopes by aerosols and downslope by evaporation. According to the sensitivity studies, the precipitation suppression by aerosols in the upslope region (in case of linear mountain waves) is most notable for small mountains. For narrow mountains (half-width = 10 km), the advection timescale of air parcels in the cloud is shorter than that for wide mountains (half-width = 30 km) limiting the time available for precipitation development by microphysical processes. In the case of blocked orographic flow, the contribution of the accretion process to the OP becomes more dominant than the unblocked flow, which may lead to a net compensation of the slow auto-conversion process (Mühlbauer and Lohmann, 2008). The formation of more number of smaller droplets results in a reduced auto-conversion efficiency. Because of high advection time scale associated with the blocked flow along with the large number of droplets there is more time for these droplets to grow, increasing the accretion growth process. This compensation effect may result in comparable or more precipitation in the polluted condition, although the upslope precipitation is reduced. Even with the overall precipitation loss by aerosols and OP interactions, the simulations in both large (half-width = 30 km) and narrow (half-width = 10 km) topographic barrier case shows enhanced precipitation in the leeward side of the mountain (Mühlbauer and Lohmann, 2008). The leeward precipitation enhancement may occur due to the increase in time availability for the growth of cloud hydrometeors, large enough to sustain the evaporation due to subsidence on the leeward side.

2.2. Mixed-phase clouds

The precipitation of mixed-phase clouds is a result of the growth of hydrometeors by the concurrence of warm and cold processes. The vapour deposition is the crucial process for the initial growth of the cloud drops. During vapour deposition, the atmospheric water vapour diffuses to the cloud drop, sticks, and thus makes it grow. Initial growth of cloud drop by deposition is fast at the beginning. However, it takes more time to develop a cloud drop 10–20 μm than the cloud lifetime itself. Hence vapour deposition alone is not the mechanism for cloud drops to grow into rain drops. Including the warm phase growth processes, the major ice-phase growth processes in mixed-phase clouds are:

(i) Riming – The growth of ice crystals with the collision of liquid water droplets between -5 and -25 ^{O}C, freeze the droplet instantly preserving an almost spherical shape (Harimaya, 1975; Pitter, 1977; Lowenthal et al., 2011)
(ii) Aggregation – The collision and sticking of ice crystals within the cloud between -5 and -40 ^{O}C with high sticking probability when coated with supercooled water on crystal surfaces (Hosler et al., 1957)
(iii) Wegener–Bergeron–Findeisen (WBF) process – The growth of ice crystals in the liquid sub-saturated region at the expense of supercooled water droplets (Wegener, 1911; Bergeron, 1935; Findeisen, 1938; Storelvmo and Tan, 2015)

All the three processes can co-exist in mixed-phase clouds. However, the relative contribution to the growth of precipitation depends on the number and size of cloud droplets, environmental dynamics and thermodynamics, particularly mixed-phase cloud temperature. Sometimes vapour deposition may be more crucial than riming for cold mixed phase orographic clouds (Fan et al., 2017). The mixed phase clouds over orography are more explored comparative to warm phase clouds for understanding the impacts of microphysics or the associated precipitation, mainly because all the major mountains contributing to the world OP are high enough to promote the growth of mixed-phase clouds with surface temperatures well below freezing levels. The next sections discuss the understanding developed for the orographic mixed-phase clouds interaction with the aerosols and OP.

2.2.1. Impact of aerosols concerning microphysical and precipitation effects

Lynn et al. (2007) by implementing spectral (bin) microphysics using in 2D WRF model showed the effect of aerosol on the amount and spatial distribution of precipitation of mixed-phase orographic clouds over Sierra Nevada mountains by comparing the simulations of maritime (clean-air) aerosol (MA) and continental (dirty-air) aerosols (CA). They found that after 3 h of simulation, the MA produced 30% more precipitation over the windward slope than CA. The MA also produced more graupel on the upslope of the mountain than the CA. The precipitation suppression was enhanced by including the ice phase microphysics. However, the simulation for CA produced more cloud ice and snow hydrometeors with clouds being more vigorous and reaching higher heights than the case of MA. The ice particles did not grow sufficiently large to fall as precipitation and advected with the wind towards the leeward side of the mountain where they evaporate because of adiabatic warming caused by descending air. They suggested that this may be due to the simple ice microphysics considered in the simulated case, by assuming that graupel particles do not collect any ice particles. Thus including ice processes further suppressed the overall OP. Besides, the combined effect of MA and CA size distribution indicate that the existence of a relatively small amount of large maritime aerosols does not change the impact of anthropogenic aerosols. The results are matching with the observed precipitation decrease over the mountain regions located downwind from coastal urban areas during past several decades by about 30% (Givati and Rosenfeld, 2004; Jirak and Cotton, 2006). Simulations show that the effects of anthropogenic aerosols can be the reason for such a decrease.

Mühlbauer and Lohmann (2009) investigated the impacts of anthropogenic (black carbon) and natural aerosols (mineral dust) on mixed-phase OP at different temperatures over Alpine and central Switzerland by using 3D COSMO model (two-moment microphysics scheme). They considered the heterogeneous freezing nucleation in the immersion and the contact mode but neglected the deposition nucleation (≤-20 °C) and homogeneous ice nucleation (≤-38 °C) (Pruppacher and Klett, 1997; Schaller and Fukuta, 1979). Their results show that mineral dust serves as efficient IN and can initiate the ice-phase processes effectively resulting in enhanced rimming and increased the ice water content of the cloud in the windward side. Hazra et al. (2016) also reached to a similar conclusion for their study near the foothills of the Himalaya, using aircraft measurements, Mesoscale Meteorological

Model version 5 (MM5) model and Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis data sets. The precipitation efficiency increased due to formation of more snow and graupel. The entrainment of aerosols/CCN/IN during the AOP interactions for a mixed phase cloud also affects the overall precipitation trends. The results show the internally-mixed aerosol spectrum assumption has to be satisfied for the reproducibility of decreased riming rates with increasing aerosol load, as the contact nuclei availability for initiating the ice phase in orographic clouds will reduce. Thus, the CCN effects will be dominant and lead to the suppression in riming and C–C, which leads to a decrease of the OP. By considering the externally mixed black carbon aerosols, activation of more efficient contact IN (even at comparatively warmer temperatures) leads to enhance OP and thus increasing the rimming process. However, the internally mixed BC resulted in the formation of ice crystals in less efficient immersion mode (at relatively colder temperature) and resulted in decreased rimming and ultimately to a reduced OP.

Muhlbauer et al. (2010) explored the AOP interaction for different temperature profiles and idealised flow regimes by comparing the 2D simulations of three models namely the COSMO with bulk microphysics, WRF model with bin microphysics and The University of Wisconsin Non-Hydrostatic Model (UWNMS) with spectral habit prediction microphysics scheme. The study analysed eight cases with different initial conditions for each model (total twenty-four case studies). The initial conditions for the model over the Alpine region were remote–continental aerosol size distribution. The simulations for all the cases suggest that aerosol loading may not lead to a decrease in riming. As a response to an increase in aerosol concentration, a reduction in riming or C–C process may not lead to reduced precipitation due to compensation by other microphysical pathways, reported by most of the simulations. The results show that for some cases, a buffering effect of aerosol perturbation to the OP decreases the precipitation susceptibility to aerosol loading, and results in a net redistribution of the contribution of different microphysical hydrometeor growth processes without changing the total precipitation significantly. Some simulations also reported a small increase in OP with aerosol loading. The study did not propose any particular model or method as superior for the understanding of aerosol effects on precipitation, and the results vary for different cases used in different models. Muhlbauer et al. (2010) also explored the impact of geometry and flow regimes on AOP interaction, described in section (3.2.3) of the present manuscript.

The effects of CCN on precipitation associated with mixed phase orographic clouds particularly on the collection growth of ice-phase particles (generated aloft) falling through the feeder part was discussed by Saleeby and Cotton (2009), using Colorado State University – Regional Atmospheric Modeling System (CSU-RAMS) model coupled with two-moment, bin-modulating bulk microphysics scheme. They found that with an increase in the CCN concentration, (resulting from the pollution) CDNC increases in the feeder part and shifts the droplet spectrum towards narrow side resulting in a decreased rimming efficiency of ice crystals falling through it. Thus with less efficient collection process, the lighter snow is formed and further advected downstream because of their small settling velocity, thereby reducing/enhancing the precipitation over windward/leeward slopes. They also found that the precipitation modification is not linear with increasing aerosols. The addition of aerosols leads to a decrease (increase) in the graupel (snow) mixing ratio above the ridge and an increase in the snow mixing ratio farther down the lee slope. However, the domain-summed precipitation over the mountain was not significantly affected by the aerosol perturbations.

By extending the works of Saleeby et al. (2009), and using the same model setup, Saleeby et al. (2011) explored the orographic impacts on aerosol-precipitation interactions with multifold objectives. The study investigated the role of Colorado mountain range geometry for the vulnerability of higher aerosols concentrations to snowfall and the nature of spillover effect dependence on infrequent events during the winter season. The study also discusses the interseasonal variability of AOP, and the cumulative precipitation response of aerosols impact. The results revealed that as a response to aerosol loading, the spillover effect is higher in the mountains like San Juan Range (the highest mountain range of the study domain) where high cloud water path (CWP) and ice water path (IWP) co-exists. The increased spillover effect is relatively lower in central high mountains because of less super-cooled liquid water content availability. The increased spillover effect may be attributed to cloud drop riming growth (significant enough to sustain the evaporation loss due to leeward subsidence). In this case, the overall precipitation loss over the entire domain is found to be negligible, similar to the findings of Saleeby and Cotton (2009). They also found that the interseasonal synoptic variability has the dominant impact on the orographic snowfall as compared to aerosols. The synoptic scale flow and environmental factors like humidity largely control aerosol effects on the OP. Thus for a given season, when the dominant flow pattern and atmospheric conditions do not differ much, the aerosols may impact on the distribution and magnitude of precipitation over orography.

In subsequent work, Saleeby et al. (2013) simulated four winter orographic snowfall events, mainly focused on the aerosol impacts to the microphysical growth processes and restructuring of snowfall over the mountain due to these variations. Spillover effect was prominent with a net reduction of precipitation over the windward slope and an increase over the leeward slope. The addition of aerosols leads to a decrease (increase) in the graupel (snow) mixing ratio above the ridge and an increase in the snow mixing ratio farther down the leeward slope. With an increase in aerosol concentration, Saleeby et al. (2013) found an increasing trend in the cloud water content and total snow precipitation, and a decrease in the total graupel precipitation. However, the magnitude increase in total snow mass concentration was comparable with the loss of total graupel mass concentration. The increase in the snow with an increase in aerosol loading was due to the enhancement of the WBF growth process thus reducing the loss of precipitation by suppression of rimming growth. One can explain the WBF growth process enhancement with an increase in aerosol loading for two reasons:

(1) Availability of more super-cooled water, and
(2) Evaporation of more cloud water by numerous small cloud droplets (Tao et al., 2012)

The study of Saleeby and Cotton (2013) discovered that WBF ice growth process was enhanced with the aerosol loading along the spillover zones (leeward slope) thus compensating the loss of precipitation because of reduction in rimming growth, resulting in a spillover effect without a significant decrease in total snowfall. The reason may be the re-saturation of atmosphere and slowing down the sublimation of ice crystals by rapid evaporation of liquid cloud droplets under polluted conditions.

Letcher and Cotton (2014) used WRF-Chem and RAMS coupled model with two-moment bin emulating (binned riming scheme) bulk predictive parametrization scheme to study the effect of aerosols on mixed-phase orographic clouds considering a particular case (FEB, 2007) of snow falling cloud over NW Colorado. Their results were similar to the findings of Saleeby et al. (2009), with a downwind shift in the precipitation (spillover effect). The whole domain precipitation did not change significantly because of the involvement of effective ice growth processes (WBF process), as discussed by Saleeby et al. (2013). However, the results show that change in precipitation because of increase in CCN is highly sensitive to the spatial and temporal homogeneities in CCN concentration.

The effect of aerosols on the mixed phase orographic clouds using a 2D COSMO model and a two-moment bulk scheme by incorporating 270 simulations for both clean and polluted air cases was analysed over Alps (Zubler et al., 2011). The results indicate that the contribution of ice phase determines the magnitude and sign of aerosol effect on precipitation. The polluted case shows more precipitation shift towards leeward side of the mountains (2.4%–14.6%) with total domain precipitation decrease for the contaminated scenario by an average of 36%, supporting the findings of Lynn et al. (2007). The only ice-nucleating process considered in Zubler et al. (2011) was immersion/condensation freezing.

By using coupled WRF model with spectral bin microphysics scheme, Fan et al. (2014) examined the relative and combined effects of CCN and IN on orographic clouds by considering two snowfall cases from CalWater campaign (Ralph et al., 2016): 16 February 2011 (significant snow precipitation and deeper clouds) and 2 March 2011 (light snow precipitation and shallow clouds) over the Sierra Nevada mountains. For the case of low CCN, as the concentration of IN increased the snow formation is also enhanced (∼40%) because of stronger WBF and rimming process. The total rimming growth increased by three times and the total growth of ice crystals by WBF process (20 times larger than riming) increased by five times (similar to the findings of Saleeby et al., 2013). Thus, the total precipitation increased over the Sierra Nevada Mountains by 10–20% in both the cases (16 February 2011 and 2 March 2011). For the instance of high CCN, the precipitation again increased by ∼5% mainly on the windward slope of the Sierra Nevada when dust aerosols were present, as the increase in the CCN concentration suppress the warm rain processes, so that more amount of supercooled liquid droplets are available for ice-phase growth. However, in the absence of dust or IN, the net precipitation decreases by 5–8%, as microphysical growth processes become less efficient. Thus for both the conditions (high or low CCN concentration), the increase in IN leads to an increase in precipitation and hence IN effects are more dominant in the precipitation forming process in the mixed-phase orographic cloud with CCN concentration being less significant. CCN effects are insignificant in case of thin-layered low-level clouds. The impact of local pollution on warm rain processes strongly depends on meteorological conditions and dynamics (the strength of Sierra Barrier Jet in this case).

Fan et al. (2017) extended the work of Fan et al. (2014), and studied the impact of CCN and IN on the microphysics and precipitation associated with mixed phase orographic clouds, over the Sierra Nevada mountain range. For this study, they subdivided mixed phase orographic clouds to warm mixed phase orographic clouds with cloud top temperature (CTT) $> -20\,^{\circ}C$ (denoted as WMPO) and cold mixed phase orographic clouds with CTT $< -20\,^{\circ}C$ (denoted by CMPO). The CCN and IN concentrations were varied from 30 to 3000 cm^{-3} and 0.1 to 100 cm^{-3} respectively. The model framework and initial conditions used are similar to that of Fan et al. (2014), but have reduced domain size and increased resolution. They found that, for the growth of ice phase hydrometeors (snow particles), the depositional growth plays an important role in CMPO while riming is the dominant process in WMPO. Increasing the CCN concentration (under low CCN concentration $< 1000\,cm^{-3}$) in the WMPO with low IN concentration suppresses total precipitation. However, when this CCN concentration is increased above $1000\,cm^{-3}$, widespread shallow clouds are formed with relatively higher cloud water in the windward side of the mountain range, resulting in the release of high latent heat. This latent heat strengthens the zonal transport of moisture by changing the local circulation. The availability of more moisture enhances the deposition and riming growth leading to an increase in the snow precipitation and hence the total precipitation. The suppression of warm rain process by the increase in the CCN concentration also allows the transport of more droplets to higher elevations contributing to more efficient immersion freezing. This invigoration was observed for both WMPO and CMPO cases. As a response to increase in IN concentration, the precipitation increased in both the WMPO (due to increase in deposition and riming) and CMPO (due to enhanced deposition growth). For WMPO with comparatively higher liquid water content, the increase in IN formed more ice particles and thus enhanced the riming growth. This also decreased the WBF growth because of reduction in the LWC of the cloud (used up by IN). However, for CMPO, the increase in IN resulted in the formation of more number of ice particles leading to an increase in deposition growth. However, due to comparatively less liquid water content, the riming growth is suppressed. The results indicate that the impact of increase in CCN concentration on the supercooled water and cloud phases is smaller when compared to the impact IN concentration. The spillover effect for this study is found to be less for both the cases and most of the precipitation formed on the windward side of the mountain.

Xiao et al. (2014), by using a 2D WRF model with a detailed bin microphysics scheme found that the total OP as a response of increasing aerosol concentration in mixed-phase orographic clouds can result in a decrease by ∼23.4%. The study considers an idealised bell shape mountain of the maximum height of 1000 m, and discusses urban pollution affecting the aerosol precipitation interaction with orography without the inclusion of urban heat island effects. The results show that increasing aerosol concentration leads to an increase in CDNC and liquid water mixing ratio with relatively smaller size cloud droplets. Here the precipitation formed mainly through warm phase processes, and ice particles were too less to affect cloud development. However, a decrease in the graupel-mixing ratio caused by the decreasing riming efficiency in high CCN conditions was evident for the polluted case when compared to the clean case. Thus with CCN dominated effect on precipitation, the C–C process reduced with increasing pollution, resulting in a decreased precipitation. A downwind shift of OP was observed mainly because the higher CCN concentration increased the time required for the development of precipitation, leading to the spillover effect.

In continuation to the previous works, Xiao et al. (2015) examined the effects of aerosols on mixed-phase orographic clouds by using the same model set up and idealised bell shape mountain of maximum height 1500 m but by considering ice-phase processes. Xiao et al. (2015) found that with an increase in CCN concentration, the CDNC increased leading to a delay in precipitation, but the precipitation amount increases by ∼10%. Aerosol loading increased the contribution of rimming and WBF process to the growth of ice phase particles mainly due to the presence of more droplets with diameter 10–30 μm. They also showed that by increasing the concentration of ice crystals ten times, the precipitation might enhance by 7%. With an increase in the ice crystals concentration, the effect of CCN concentration on the orographic clouds and precipitation becomes less significant implying that the ice-phase processes have a substantial contribution to the total precipitation. The form of precipitation was predominantly liquid because of the high freezing level considered in this case; resulting in the melting of ice hydrometeors falling below freezing level and enhancing the C–C process and enhanced liquid phase precipitation. It is to be noted that the findings of Xiao et al. (2015) are consistent with Fan et al. (2014) where the increased CCN enhanced the riming and inconsistent with Saleeby et al. (2013) where the riming suppressed as a result of decreased mean cloud diameter (from 16 to < 10 μm). Saleeby et al. (2013) conducted the simulation with limited availability of vapour for the growth of cloud droplets, by considering low freezing levels. Another reason for the inconsistency may be the use of different models, as the riming sensitivity to aerosols concentration differs in each case and model (Muhlbauer et al., 2010). The difference in results of different models may be because of grid accuracy, parametrization schemes chosen, domain size, local effects, topographical variations etc., which we cannot comment on as different models are not used at a site comparatively. They further continued the research on AOP interaction with varying freezing levels (Xiao et al., 2016), which is in a different section (3.2.2) of the present article.

Chu et al. (2014) validated the simulations by WRF model in large eddy simulation (LES) and non-LES modes of varying resolutions with the airborne radar observations collected on February 18, 2009 for studying the impact of glaciogenic seeding of Silver Iodide (AgI) on shallow orographic clouds over Wyoming as a part of Wyoming Weather Modification Pilot Project (WWMPP)Breed et al., 2014. The main advantage of using numerical simulations to model the cloud seeding is that the seeding can be considered as a sensitivity experiment. This would not only allow isolating the magnitude of seeding effect from the natural precipitation, but also address the question that whether the non-seeded regions do actually resemble the natural precipitation. By validating different model configurations, they found that WRF run in LES mode with a spatial resolution of 100 m performs the best in capturing the observed essential environmental features and cloud properties (in agreement with Xue et al., 2014). The model results indicated that the variations in natural precipitation always overwhelmed the seeding impact for the case considered, such that it is difficult to capture the seeding signal. Further, the upper and lower level changes in radar reflectivity showed that the changes in the unseeded area may not be a true representative of natural variability of in the seeded region.

Extending the work of Chu et al. (2014), Xue et al. (2016) studied the distribution of AgI after cloud seeding and its impact on the properties of orographic clouds using the same model in LES and non-LES mode with resolutions 2700 m, 900 m and 300 m, 100 m respectively. The results indicate that the terrain-induced turbulence is the dominant process responsible for the vertical AgI dispersion (in accordance with Xue et al., 2014). As a response to cloud seeding, for cloud regions below the boundary layer, extra ice particles formed and grow more efficiently by WBF, deposition and riming process as compared to the non-seeded case. This increases the ground precipitation by 5–20% depending on the spatial resolution considered. However, the impact of seeding on cloud dynamics was negligible. Effect of cloud seeding on the shallow orographic cold cloud was studied by Chu et al. (2017) using observations from airborne radars and WRF large eddy simulation at 100 m resolution. Both the observations and simulations showed a higher radar reflectivity in the seeding area when compared to the neighbouring control region. Results from simulations show that the seeding activates more ice crystals which grow efficiently by vapour deposition and WBF process, leading to increased snowfall.

Shrestha et al. (2017), by using the WRF model with bulk microphysics scheme studied the sensitivity of cloud properties and precipitation to aerosol and temperature perturbations over the foothills of the Himalayas, Nepal. The results indicate that the effect of an increase in aerosols on precipitation is non-linear but not significant (− 3 to 4%). The ice crystal number concentration was particularly not sensitive to the aerosol perturbation, maybe because of simple parameterisations of ice nucleation processes. They found that even if the cloud liquid droplet size decreased with increasing aerosol concentration; the volume of cloud ice increased, attributing to the ice hydrometeor growth by WBF process (previously observed by Saleeby and Cotton, 2013; Letcher and Cotton, 2014). This process may have resulted in a buffering effect in ice phase clouds where the suppression of warm rain compensates the increase in ice phase process and ultimately leads to no significant change in total precipitation.

Glassmeier and Lohmann (2018) (described in previous section 3.1.1) also extended their study for the mixed-phase clouds. The results show that the effect of aerosols on the liquid and ice phase processes tend to compensate for each other resulting in low precipitation susceptibility. In polluted conditions, the increased riming may recompense for the suppression of C–C process (warm phase growth) due to an increase in the CDNC and vapour deposition by WBF process (increased ice phase growth). This process may result as a non-significant change in precipitation for mixed-phase clouds, as a response to an increase in aerosols.

For the mixed-phase clouds, the impact of aerosol solubility on precipitation during AOP interaction was studied by Xue et al. (2012). The study domain is the same as that of Xue et al. (2010), considering two bell-shaped idealised mountains. The result shows that the impact of aerosol loading and solubility on cloud drops and rain rate are more significant in polluted clouds than clean clouds. Cloud ice crystals are not sensitive to aerosol loading and solubility, may be because ice initialisation in the scheme is independent of the aerosol properties. The ice nucleation and diffusion growth controls the ice crystal number concentration and mass and is not sensitive to aerosol properties. However, graupel was found to be very sensitive to the aerosol loading mainly because its growth is dependent on collisions with ice particles (aggregation) and large water drops (rimming) with its sensitivity increasing for polluted clouds. The lower aerosol solubility with the same aerosol background resulted in a broader cloud drop spectrum. This lead to increased riming rates, because aerosol solubility determines the concentration of CCN and GCCN in mixed-phase clouds (similar to the findings of Xue et al., 2010; for warm phase clouds).

Pousse-Nottelmann et al. (2015) studied the microphysical processing of aerosols in mixed phase orographic clouds by the 2D COSMO model considering the clouds formed by forced orographic lifting over two identical bell shaped mountains. The mountain dimensions, aerosol initiation in the model and the simulations performed are similar to that of warm clouds and are discussed in section 2.1.1. They identified two main aerosol processing cycles. The first cycle involves two processes:

(i) The input of aerosols into the hydrometeor by activation scavenging, a portion of which is converted to ice crystals via contact and immersion freezing, when transferred to higher altitudes, and
(ii) The transfer of mass from liquid droplets to ice crystals in the liquid water sub-saturated region by WBF process.

The second cycle includes the growth of snow particles and is connected to the first cycle by riming. The ice crystals grow by deposition and accretion in the higher altitude to form snow particles which collects the aerosol mass by colliding and collecting liquid droplets (by riming) and in the lower altitude by cloud scavenging process. The four simulations (discussed in section 2.1.1) yielded similar vertical aerosol mass in the upslope of the first mountain. However, in the down slope of the mountain the aerosol mass profile varied for all the simulations. The first simulation case showed no change in vertical profile because the aerosol regeneration and scavenging processes are neglected. The second case resulted in a loss of aerosol mass in the lower altitude (below 3.7 km) due to the inclusion of activation and below cloud scavenging process. However, the third case showed significant low aerosol mass especially below 2 km, because of the implementation of modified below cloud scavenging process (where all the aerosol particles colliding with the precipitating rain and snow particles are removed). This scavenging is more efficient compared to that of warm phase orographic cloud due to more efficient scavenging by snow particles. The fourth simulation generated additional aerosol particles due to evaporation in the down slope region and compensated the reduced aerosols by scavenging processes. Similar to that of warm phase clouds, the regenerated aerosols have increased mass and size in both the Aitken and accumulated modes. These regenerated aerosols modified the available CCN and IN concentration over the second mountain such that the ice crystal number concentration increased. However, the cloud ice and liquid water content changes were negligible.

2.2.2. Impact of aerosols radiation interaction on OP

Aerosols also influence the cloud development and precipitation process by virtue of aerosol-radiation-interaction (ARI) effect by changing the vertical thermodynamic structure and stability of the atmosphere (Chung et al., 2005; Yu et al., 2006; Li et al., 2011; Yang and Li, 2013; Fan et al., 2016). For the case of orography, recent studies have identified a key role of absorbing aerosols in modifying the atmospheric circulation and moisture transport especially for those which are close to polluted urban areas (Fan et al., 2015; Yang et al., 2016). By using the WRF-Chem model, Fan et al. (2015) simulated an extreme flood event over mountains downwind of the Sichuan basin, China. The results indicate an enhancement of the intensity of OP by the trapped polluting aerosols in the basin. The absorbing aerosols present in the basin suppress convection during the day time by stabilising the lower atmosphere and decreasing the boundary layer height such that the clouds consume less moisture. During the night, this accumulated moisture gets transported by the wind towards the orography, increasing OP. As discussed in the previous section, for mixed-phase clouds, Fan et al. (2017) found that increase in CCN results in higher latent heat release, changing the local circulation and strengthens the transport of moisture, which increases OP.

On the other hand, Yang et al. (2016) by using improved WRF-Chem model, found a decrease in ~40% of OP because of polluting aerosols over Mt. Hua, central China. They found that the ARI effect by the absorbing aerosols stabilises the lower atmosphere resulting in the weakening of valley breeze. This results in a decrease in moisture transport towards the mountains and a decrease in OP.

2.2.3. Impact of atmospheric conditions

For the mixed-phase clouds, the AOP interactions dependency on atmospheric conditions is salient, especially on surface temperature, freezing level, humidity and wind speed. However, the exploration of atmospheric conditions assessment to AOP interactions is relatively less. The present section discusses the results from various research works, where the sensitivity of AOP to different atmospheric conditions was significant.

The variation of humidity is a significant factor for the AOP interaction, as higher values of humidity in presence of higher aerosol concentration are supporting more cloud water content. Lynn et al. (2007) performed the sensitivity experiments to discover the effect of aerosols on the amount and distribution of OP under different atmospheric conditions (e.g. humidity and wind speed). The results show that higher humidity lowered the cloud base level and the clouds formed further downslope on the windward side, where the vertical velocity is smaller than upslope. As a result, the droplet concentration turned out to be relatively small, and droplet spectra distributions were favourable for raindrops development. The efficient, warm rain formation occurred even under a high aerosol concentration with some lag in time and space in the downwind direction. Besides, the high humidity reduces the precipitation loss caused by raindrop and ice evaporation. Thus, the increase in atmospheric moisture decrease the difference in precipitation amounts between the pristine and polluted aerosol cases, and can even lead to an increase in precipitation in the polluted case.

Carrio and Cotton (2014) by using the RAMS model with two-moment bin-emulating microphysics scheme studied the impact of CCN on the mixed phase OP over the Sierra Nevada under varying moisture conditions. As expected for relatively lower moisture content (close to actual soundings), with an increase in the CCN concentration the CDNC showed an increasing trend but with a reduction in the cloud droplet size and hence reduced rimming leading to less precipitation. However, with an increase in the humidity, increasing CCN values lead to a monotonic enhancement of snow precipitation (up to 4%) with a reduced drizzle (warm rain) formation when compared with low CCN case. They suggested that the enhancement in riming is due to the availability of more supercooled liquid water and henceforth utilised by the ice-phase processes leading to a suppression of warm rain. Their results also indicated the spillover effect. Thus, the traditional concept of decreasing precipitation for increasing CCN concentration cannot be generalised for higher low-level moisture content (orographic clouds with warmer base).

The decrease in the initial horizontal wind may result in a reduction of the vertical velocity on the mountain upslope, and thus may delay the cloud and precipitation formation. For this case, the precipitation for MA formed earlier and in higher amounts than the CA. Low vertical velocities lead to the creation of small clouds, which precipitate by cloud "sedimentation" (drizzling) on the upwind mountain slope (Lynn et al., 2007).

The surface temperature (ST) or freezing level may modulate the precipitation form (which is evident because lower ST, i.e., the lower freezing level would facilitate more ice-phase precipitation than higher ones) and the amount by influencing the relative contribution of microphysical processes (ice phase and warm phase). As mentioned in section 3.2.1, Mühlbauer and Lohmann (2009) investigated the impacts of aerosols on mixed-phase OP at different freezing levels over Alpine and central Switzerland. They observed that an increase in ST from 273 K to 280 K resulted in a change in relative contributions of the growth processes where the collection growth contribution by warm phase processes increased. Due to availability of more liquid water, the riming and aggregation also increased.

The sensitivity of AOP interaction to the ST is observed by Muhlbauer et al. (2010) under different flow regimes (blocked and unblocked flow) by using simulations from three models (please refer to section 3.2.1). With a decrease in the surface temperature from 280 K to 273 K, the susceptibility of precipitation to the aerosol concentration also decreases because warm phase process become negligible and ice-phase process become the dominant precipitation forming method for both the flow cases. However, this decrease in precipitation susceptibility is higher in blocked flow case when compared to unblocked flow (discussed in the section 3.2.3).

Xiao et al. (2016) studied the AOP interaction modification with the change in the aerosol concentration under different freezing level/ST. The results show that for clean (less CCN) case when the ST is lowered from 291 K to 279 K (freezing level from 2.85 km to 0.9 km) the ice water content increases and the liquid water content decreases (similar to the findings of Colle, 2004). With the lowering of ST, the total precipitation and the fraction of ice-phase precipitation increases. With lowering of freezing level, the growth of ice crystals by vapour deposition (including WBF) and the rimming process becomes more efficient up to 1.4 km (ST = 282 K), below which the growth reduces because of less availability of liquid water content. For the polluted case with elevated values of CCN, the liquid water content and hence the growth of ice crystals is higher than that of a clean scenario, at a given freezing level (consistent with the results of Xiao et al., 2015) with the precipitation pattern shifting further downwind. With the decrease in the freezing level from 2.85 km to 0.9 km, the overall precipitation increases by 5–14%. The response of precipitation to the CCN concentration is insignificant when the freezing level is below 1.4 km (ST = 282 K), due to the limited availability of liquid water. The spillover effect also becomes less significant, and ice-phase processes modulate the precipitation in such a scenario dominantly. The maximum increase of precipitation caused by aerosols is found to be 14% when the freezing level is at 1.4 km (ST = 282 K) suggesting that it is the optimum freezing level for maximum effects of aerosol on precipitation.

Shrestha et al. (2017) discovered that the temperature perturbations resulted in a statistically significant effect ranging from −17% to +93% (at 95% significance level) for the sensitivity of cloud properties and precipitation over the foothills of the Himalayas, Nepal.

2.2.4. Impact of geometry

Muhlbauer et al. (2010) explored the response of orographic clouds and precipitation by aerosol perturbations in different mountain geometry and flow pattern. They considered two idealised mountain cases: one with maximum mountain height of 800 m representing a linear mountain wave (unblocked) flow and the other with height 3000 m representing blocked flow with same initial conditions and mountain half-width of 20 km. The simulated cloud is deeper for the case of blocked flow, and the total precipitation is several times larger than the unblocked flow case with increased contributions from ice-phase processes. Also, the spillover factor is significantly less for the blocked flow. The precipitation loss due to aerosol perturbations is relatively less in case of High Mountain implying that the precipitation susceptibility to aerosol loading may decrease with the increase in mountain

Table 1
The brief description of selected numerical simulations based AOP interaction studies.

Author	Model used	Orography considered	Response to increased aerosols
Muhlbauer and Lohmann, 2006 (WP)	2D Shortrange Local Model	Ideal Gaussian Mountain, a = 50 km, 250 < ho < 2500 m	Enhanced spillover effect and reduced OP for small mountains.
Lynn et al., 2007 (MP)	2D WRF	Sierra Nevada Mountain (ho ~ 3300 m)	Suppression of OP on windward slopes, with increase in moisture the suppression is reduced.
Muhlbauer and Lohmann, 2008 (WP)	2D COSMO	Idealised bell-shape mountain, ho = 1000 m & 3000 m, a = 10, 20, 30 km	OP is reduced but it can even increase depending on the flow pattern and mountain geometry.
Muhlbauer and Lohmann, 2009 (MP)	3D COSMO	Idealised 3D mountain, ho = 800 m, a = 20 km, b = 10 km	Mixing state of aerosols may impact the microphysical growth processes and OP
Saleeby et al., 2009 (MP)	CSU-RAMS	Complex Colorado Topography, ho ~ 3100 m	Net OP remain unchanged with a spatial redistribution of different type of hydrometeors.
Muhlbauer et al., 2010 (MP)	2D COSMO, WRF, UWNMS	Idealised bell-shape mountain, ho = 800 m and 3000 m, a = 20 km	No robust negative effect on OP. OP over small (high) mountains are more (less) susceptible.
Zubler et al., 2011 (MP)	2D COSMO	Jungfraujoch Mountain, Swiss Alps, ho = 3571 m	OP decreased by ~36%. Sign and magnitude of OP anomaly depends on ice-phase processes.
Xue et al., 2010 (WP)	2D WRF	Two bell-shape mountains ho = 800 m, a = 20 km	High solubility lead to activation of more CCN and GCCN. Effect on OP depends on moisture content.
Xue et al., 2012 (MP)	2D WRF	Two bell-shape mountains ho = 800 m, a = 20 km	Low aerosol solubility lead to broader drop size spectrum and thus high riming growth rate.
Saleeby et al., 2011 (MP)	CSU-RAMS	High terrains of Colorado (ho > 2700 m)	Overall OP did not change significantly while the spillover factor increased for high hills.
Xiao et al., 2014 (MP)	2D WRF	Ideal bell-shape mountain, ho = 1 km, a = 20 km	Decrease in net OP by ~ 23.4% and increase in spillover factor.
Saleeby et al., 2013 (MP)	CSU-RAMS	Park Range of Colorado, ho ~ 3200 m	OP loss by reduced riming is compensated by WBF growth.
Carrio and Cotton, 2014 (MP)	CSU-RAMS	Sierra Nevada Mountain, ho ~ 2300 m	In wet condition, more SLW lead to increase in OP (up to 4%).
Fan et al., 2014 (MP)	WRF	Sierra Nevada Mountain, ho ~ 2300 m	Presence of IN results in increase in OP even with elevated CCN.
Letcher and Cotton, 2014 (MP)	CSU-RAMS and WRF-Chem	Colorado Rockies, ho ~ 3200 m	Spillover effect is prominent but the total OP remains unchanged.
Xiao et al., 2015 (MP)	2D WRF	Ideal bell shape mountain, ho = 1.5 km, a = 20 km	Increase in OP (~10%) due to higher riming and WBF growth.
Xiao et al., 2016 (MP)	2D WRF	Idealised bell shape mountain, ho = 1500 m	Increase in OP by up to 14% due to enhanced riming for the freezing level at 1.4 km.
Shrestha et al. (2017)	WRF	Foothills of the Himalayas, Nepal, ho ~ 5900 m	No/less change in OP due to ice-phase processes compensation.
Fan et al., 2017 (MP)	WRF	Sierra Nevada Mountain, ho ~ 2300 m	Increase in OP by involvement of efficient ice phase processes.
Chu et al., 2017 (MP)	WRF	Medicine Bow Range, ho ~ 3500 m	Glaciogenic seeding supports development of ice phase particles and increases the OP over the target region.
Posse-Nottelmann et al., 2015 (WP and MP)	2D COSMO	2D bell shape mountain ho = 800 m, a = 20 km	Aerosol processing modulates its size and number distribution
Glassmeier and Lohmann, 2018 (WP and MP)	2D COSMO	Ideal bell shape mountain, ho = 800 m, a = 20 km	Possible buffered WP and MP processes in steady state with less or no change in OP.

Abbreviations.
WP = Warm Phase; MP = Mixed Phase; OP = Orographic Precipitation; ho = Maximum mountain height.
a = Mountain half-width in X-dir; b = Mountain half-width in Y-dir; WRF = Weather Research and Forecasting.
CSU-RAMS = Colorado State University Regional Atmospheric Modeling System; SLW = Supercooled Liquid Water.
COSMO = Consortium for Small-Scale Modeling; UWNMS = University of Wisconsin modeling system.

height. The results show that the OP is highly susceptible to aerosol loading for small mountain. The mountain height and precipitation loss relation may be due to increase in the advection time scale of orographic clouds past the mountain ridge (in case of high mountains), providing ample amount of time for the development of precipitation. The modelling studies for ACO interactions, discussed in the present manuscript, are summarised in Table 1.

2.3. Summary of modelling studies

The modelling studies have revealed several features of AOP interactions. For the warm clouds, the AOP interaction is comparatively simple and the study performed over different regions yield similar results. Almost all study reports an increase in spillover effect with an increase in aerosols due to the increase in cloud lifetime. The net precipitation under normal atmospheric conditions is found to decrease with increase in aerosols. However, this decrease is not observed in every case (Glassmeier and Lohmann, 2018). The atmospheric humidity, aerosol solubility, and aerosol processing within the clouds are identified to impact on the number and size spectrum of aerosols and therefore the AOP interaction (Xue et al., 2010; Pousse-Nottelmann et al., 2015). The physical property of orography has a significant role in AOP interaction (Guo et al. (2014). The increase in height and width of mountain favours the increase of advection time scale such that more time is available for the growth of cloud hydrometeors. This compensates the windward precipitation loss by increasing the leeward precipitation (Mühlbauer and Lohmann, 2006, 2008). Most of the studies for warm phase orographic clouds are performed using 2D idealised hills and thus the results cannot be generalised for real mountain cases.

The modeling results of AOP interaction for mixed phase orography clouds vary for different regions over the globe, because of the varying topographical characteristics, atmospheric dynamics and thermodynamics as well as the model framework. Some results show a decrease in overall orographic precipitation with an increase in CCN concentration because of suppression of warm rain processes and formation of smaller cloud droplets decreasing the collection efficiencies (C–C and riming) (Lynn et al., 2007; Saleeby and Cotton, 2009; Xiao et al., 2014). Most of the studies conclude the ice-phase processes to be the dominant precipitation forming process for mixed phase clouds (Zubler et al., 2011; Fan et al., 2014, 2017; Xiao et al., 2015; Ralph et al., 2016). By including the ice phase processes, studies have shown that even if the increase in CCN concentration suppresses the precipitation by decreasing the collection efficiency, the WBF ice phase growth process compensates for the suppression (Saleeby et al., 2011, 2013; Fan et al., 2014; Letcher and Cotton, 2014; Xiao et al., 2015). Thus the mixed phase clouds act as a buffered system such that the overall precipitation is less susceptible to aerosol perturbation (Mühlbauer and Lohmann, 2010; Saleeby and Cotton, 2009; Saleeby et al., 2011, 2013; Letcher and Cotton, 2014; Shrestha et al., 2017; Glassmeier and Lohmann, 2018). Recent studies also report an increase in net orographic precipitation due to increase in CCN concentration (Fan et al., 2014, 2017; Xiao et al., 2015, 2016) because of efficient collection and deposition ice phase growth processes. Such difference in results can occur due to many reasons e.g. the usage of different models, parametrization schemes, initial meteorological and topographical conditions. The orographic precipitation increases as an impact of the increase in IN concentration due to the formation of a large number of ice crystals which can grow more efficiently than liquid droplets (Mühlbauer and Lohmann, 2009; Fan et al., 2014, 2017; Xiao et al., 2015). The simulations of glaciogenic cloud seeding indicate a similar increase in orographic precipitation as a result of adding IN to orographic clouds (Chu et al., 2014; Xue et al., 2014; Xue et al., 2016). The AOP interaction also depends on the atmospheric conditions like humidity (Lynn et al., 2007; Carrio and Cotton, 2014), wind speed (Carrio and Cotton, 2014) and freezing level or surface temperature (Muhlbauer and Lohmann, 2009; Muhlbauer et al., 2010; Xiao et al., 2016; Shrestha et al., 2017), aerosol solubility (Xue et al., 2012), aerosol regeneration and processing within the cloud(Xue et al., 2012; Pousse-Nottelmann et al., 2015), cloud height and CTT (Fan et al., 2017), and mountain geometry (Muhlbauer et al., 2010). The understanding for riming and WBF growth processes for AOP interaction in mixed phase clouds (based on modeling studies) is represented by a schematic diagram in Fig. 1.

3. Understanding the effects of aerosols on orographic clouds based on observational analysis

The observation-based studies relating the aerosol-topographical impact on clouds are mainly utilizing the long-term rainfall data collected by rain gauges supported by observations of aerosols, visibility, cloud droplet number concentrations and ice nuclei. We can summarise the AOP interactions through observational analysis under the following categories:

3.1. Association of Orographic Enhancement Factor with aerosols

The rain gauge data analysis over a variety of orographic areas downwind of rural and urban locations commences understanding the enhancement/suppression of OP due to pollution. By considering an increase in anthropogenic pollution, as a proxy for an enhancement in CCN concentrations, it can be argued that the impact of CCN on precipitation will be more over the orographic regions downwind of urban locations compare to rural areas. Givati and Rosenfeld (2004) defined the Orographic Enhancement Factor (OEF) for the first time in an attempt to quantify the microphysical effect of aerosols by using rain gauge data. OEF is the ratio of the precipitation amounts at the hill to that over the upwind low land area. The trend analysis of OEF over California and central Israel shows a decreasing trend over the windward slope and an increasing compensatory trend over the leeward slopes on mountains downwind of polluted urban areas indicating the spillover effect. The leeward enhancement was found to be less than the windward suppression implying a decreasing trend in the overall OP. Such a reduction was significant only in shallow orographic clouds. A similar tendency was not observed downwind of pristine rural areas. The results advocate that anthropogenic aerosols serve as CCN and reduce the efficiency of coalescence and rimming process, thus delaying the conversion of cloud droplet to precipitation resulting in an increase in rainfall over leeward slopes (Givati and Rosenfeld, 2004).

However, in a study analysing the effects of anthropogenic aerosols and cloud seeding on orographic clouds over northern Israel by evaluating the rain gauge measurements for seeded and non-seeded days, Givati and Rosenfeld (2005) found that cloud seeding enhances the OEF while air pollution decreases OEF by up to 15%. The analysis shows that the OEF would further decrease by 12–14% without cloud seeding were stopped.

The OEF concept received broad approval in understanding the rainfall suppression by air pollution with orographic interactions and used by many researchers at different locations in the world. Griffith et al. (2005) extended the study of Givati and Rosenfeld (2004) for winter orographic clouds over the States of Utah and Nevada. They reported a similar decreasing trend of precipitation downwind of Lake City/Provo metropolitan complex over the windward slope of mountains. However, they also found that winter (Nov–Mar) precipitation in the Salt Lake Valley showed an increasing trend and questioned that this might be responsible for the reduction in the OEF over mountain regions. The rain gauge precipitation measurement along the Front Range of the Rocky Mountains found a decreasing trend in the OEF value downwind of polluted areas by up to 30%, whereas downwind of pristine regions did not experience such decreasing trend (Jirak and Cotton, 2006). These studies relating the OEF trend found a decreasing

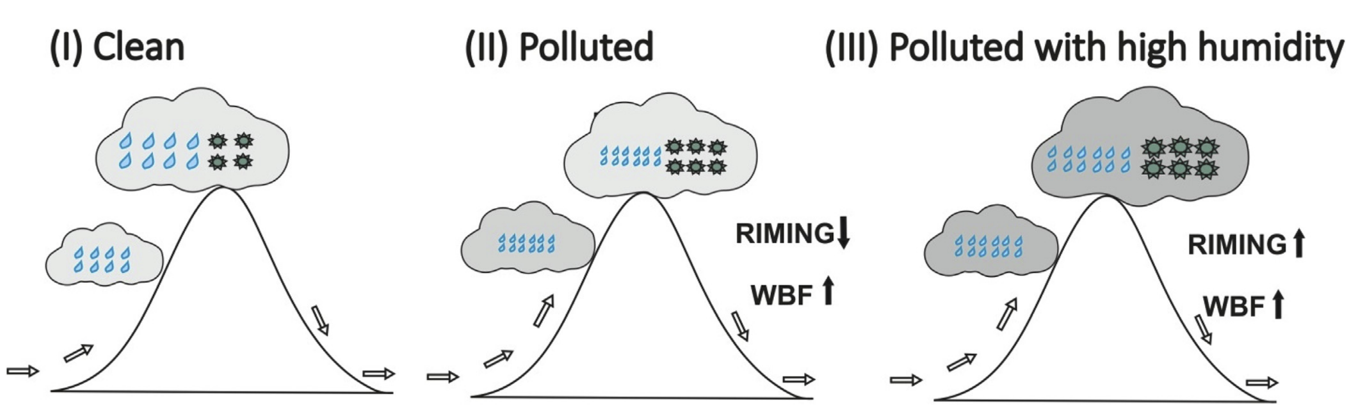

Fig. 1. Schematic diagram representing the growth process of raindrops and ice crystals in mixed phase orographic clouds for (I) clean, (II) polluted and (III) polluted with high moisture case. For the polluted case the spillover effect increases and the riming growth decreases due to the formation of smaller cloud droplets. The decrease in riming is compensated by the increase in WBF growth such that the change in net precipitation is negligible. For the case of high moisture content, both the riming and WBF process is enhanced leading to an increase in precipitation.

trend in OEF values for the region of study.

The OEF relation to precipitation over central Israel by Givati and Rosenfeld (2004) and over northern Israel by Givati and Rosenfeld (2005) was re-evaluated by including some more stations in the same location by Alpert et al. (2008). The results found no significant change in precipitation pattern; however, the pollutants concentration was not included in this study as well. The OEF between mountain and inland regions had a decreasing trend not necessarily because of the decrease in the OP but because of increase in inland precipitation. The factors responsible for increased inland precipitation may include urban heat island effect, indicating the limitation of OEF for analysing the anthropogenic aerosol impacts on orographic clouds, which may give a misleading impression of inverse pollution effects on OP. Griffith et al. (2005) also reported the OEF limitation for investigating the anthropogenic aerosol impact on orographic clouds. Alpert et al. (2008) suggested modifying the expression of OEF by comparing the precipitation over mountains with that over seashore (instead of inland regions). The revised OEF ratio found a slight increase in the rainfall over central Israel and no change over northern Israel over the years of their study that is contradicting to Givati and Rosenfeld (2004). They also compared the rainfall amount over windward (west) and leeward (east) side of the Galilee Mountains and found a decrease in rainfall over the leeward side, which is the site for Israel artificial cloud seeding and suggested that it may be due to adverse effects of cloud seeding on orographic rainfall. In continuation to findings of Alpert et al. (2008) over northern and central Israel, Halfon et al. (2009) analysed the rainfall pattern over Israel using rain gauge data. They adopted different methods based on GIS computations, multi-parametric regression, mean regional observed rainfall and OEF method. Halfon et al. (2009) found similar results as of Alpert et al. (2008) with no significant temporal change in the annual rainfall and no change in modified OEF ratio, except a slight increase over central Israel. The only hilly place where they observed a decrease in annual rainfall was on the leeward side or eastern slopes of Galilee Mountains, which is the target area for Israel artificial cloud seeding suggesting adverse effects of cloud seeding on rainfall. They also found an increase in the ratio of mountain precipitation to the coastal region downwind of urban polluted Tel Aviv region indicating the enhancement of OP by urban pollution. The studies mentioned so far relating the OEF with air pollution included only rain gauge data for the climatic periods and assumed that air pollution is increasing with the urbanisation over the area considered.

In a study relating the OEF from California to the entire western United States, affected by anthropogenic aerosol sources, Rosenfeld and Givati (2006) observed a decreasing trend in OEF by up to ~ 25%). Further, by analysing the Interagency Monitoring of Protected Visual Environments (IMPROVE) aerosol monitoring network measurements, an increasing trend of $PM_{2.5}$ over areas with decreasing OEF trend was discovered and thus suggested that fine aerosols may suppress the precipitation of short-term and shallow orographic clouds. However, such suppression did not appear in long-lived and deeper convective clouds (Rosenfeld and Givati, 2006). Study over a meteorological observatory at the top of Mt. Hua (32°23′N, 109°54′E, 2060 m), in central China suggested that the polluted air may be responsible for the reduction of the OEF downwind of urban areas by ~10–25% (Rosenfeld et al., 2007). By using visibility as a proxy for CCN, they observed a decreasing trend of OEF with decreasing visibility at the mountaintop by ~30–50% implying that air pollution may be responsible for such suppression.

Guo et al. (2014) analysed 40 years (1966–2005) long term visibility data (a proxy of aerosol concentration) and precipitation data at seven weather stations (3 over Taihang Mountain and 4 over upwind urban areas during summer months in north China. They grouped hourly precipitation into four categories: very low ($\leq$0.6 mm/h), low (0.6–2 mm/h), moderate (2–8 mm/h), and high ($>$ 8 mm/h), and focused mainly on the light rain case (very low plus low). For orographic regions, they found a decreasing trend of visibility implying an increasing trend in the aerosol concentration (air pollution). Coincidentally, the light rain intensity along with the OEF and precipitation efficiency showed a decreasing trend. They also calculated the trend of environmental parameters like the wind speed, precipitable water, convective available potential energy and vertical wind shear to check whether such factors are responsible for such decrease in light rainfall and found no direct links.

The OEF emerges out as a useful analysing tool for understanding the impact of aerosols on the precipitation pattern over any region but has its limitations of considering the inland precipitation changes in a long-term period. The results by various researchers show that to overcome these limitations; one should include the aerosol concentrations, urbanisation impacts on the inland precipitation, and considering the seashore areas instead of inland regions.

3.2. Relationship of OP with ground, aircraft and satellite based observations of aerosols

The exploration of the CCN impacts on the microphysics and precipitation over orographic locations through ground-based in-situ and remote sensing techniques are relatively less. Through statistical analysis of mixed-phase clouds in northwestern Colorado (elevation of 3210 m above MSL), Borys et al. (2000) found that the sulfate particles in atmosphere act as an efficient CCN and it is directly related to cloud droplet number concentration (CDNC), and CDNC and cloud droplet size are inversely related (Twomey effect, Twomey, 1974). Moreover, an inverse relation between cloud droplet size and snowfall rate was indicating the inhibition of riming process (which is a significant contributor to the development of cold phase precipitation). By combining the radar and mountaintop measurements over northern Colorado Rocky Mountains, Borys et al. (2003) found that by adding ~1 $\mu g\, m^{-3}$ of anthropogenic sulfate aerosols to clean background can reduce snowfall rate of winter orographic clouds by 50%. They suggested that increase in anthropogenic sulfate aerosols, which act as CCN leads to small size cloud droplets (shifting the Cloud droplet distribution towards smaller size) in the feeder clouds resulting in a decrease or sometimes complete shutdown of the snow particle riming process.

Using the aircraft measurement over Sierra Nevada, USA, it is found that precipitation decreases over central and southern parts of Sierra Nevada which are downwind of densely populated urban areas (Rosenfeld et al., 2008). Such suppression was not observed downwind of sparsely populated areas like the northern Sierra Nevada. However, the suppression was prominent in clouds that were triggered within the boundary layer (BL) and was maximum during the second half of the day (afternoon to evening) when the BL height was maximum. Clouds formed at the crest of mountains were least affected. In regions with high CCN concentration (polluted areas), the clouds had to grow greater depth to precipitate as compared to low CCN concentration regions.

Yang et al. (2013) investigated the impact of aerosols on orographic precipitation by considering the visibility data (1980–2009), the rain gauge precipitation data (1954–2009), ground and radiosonde wind data (1954–2009) for a total of 17 stations scattered over and nearby the Mt. Hua Mountain in central China. They observed a positive (inverse) correlation between visibility (aerosol concentration) and light precipitation intensity ($<$ 2 mm/h) for mountain stations. This trend was also observed for moderate rain case ($<$ 25 mm/h). The Mann-Whitney trend analysis of the daily averaged visibility measured at the top of Mt. Hua station indicated a decreasing trend for the period 1980 to 2001 and thereafter, an increasing trend up to 2009. The precipitation difference between mountain top and upwind plain stations showed similar decreasing and the increasing trend to that of visibility, because of a comparatively larger decrease in the OP than that of low land. The results proposed that increasing (decreasing) pollution is associated with the decrease (increase) in the OP. By analysing the wind strength, Yang et al. (2013) found a decrease (increase) in the wind speed in the upwind plain (Mt. Hua) region. The results suggest that the aerosols by virtue of their direct effect limit the vertical energy transfer and stabilise the atmosphere resulting in such decrease of plain winds. The increased wind speed at Mt. Hua reduces the advection time of air parcel across the mountain, thereby decreasing the OP. The results show that aerosols can suppress OP not only by the indirect effect but also the direct/radiative effect.

Kumar et al. (2014) compared the properties of clouds and precipitation over Western Ghats (WG) and Myanmar coasts (MY) for the monsoon months (June, July, August and September) by using satellite observations of precipitation (from TRMM), aerosol optical depth (from MODIS), total precipitable water and OLR (from AIRS and Kalpana INSAT), and vertical profiles of clouds (from CloudSat and MERRA). The results show that higher aerosol concentration and lower precipitable water over the WG form more number of small cloud droplets. This should decrease the C–C efficiency and suppress the warm rain process over the WG. In contrary, due to the availability of giant CCN formed by the sea salt from the Arabian Sea (Leena et al., 2016), the warm rain processes are rather enhanced. The formation of smaller particles should also increase the evaporation rate and thus the availability of more water vapour for depositional growth. However, the snow deposition for the case of WG may not be significant because of less convective available potential energy (CAPE) which results in weaker updrafts failing to lift the vapour above freezing levels. Riming process is also less efficient because of the decrease in collection efficiency (smaller droplets). However, the lower aerosol concentration and higher precipitable water over MY leads to less number of larger cloud droplets. While for MY, the lower aerosol concentration and higher precipitable water lead to less number of larger cloud droplets which favours the riming growth. The stronger updrafts over the MY tends to support the deposition growth. Kumar et al. (2014) suggested that the warm (cold) rain process is the dominant rain forming process over WG (MY).

Konwar et al. (2014) studied the cloud-aerosol interactions over the WG by considering two stations located at Pune (leeward side) and Mahabaleshwar (windward side) by using the data collected from Micro Rain Radar and X-band radar, disdrometer, CAIPEX observations (Kulkarni et al., 2012; Konwar et al., 2012b) and TRMM precipitation. The raindrop size spectra and radar reflectivity for the two stations show that for shallow orographic clouds the condensation growth is the dominant process in the windward slope where the forced lifting initiates the condensation. For light rain systems, the dominant microphysical process in the leeward side is the C–C process identified by the higher radar reflectivity. However, for heavy rain systems, a breakup process also occurs at lower altitudes with the C–C still being dominant at higher altitudes.

3.3. Orographic clouds and ice nuclei (IN) interactions

Ice nuclei (IN) are the tiny fraction of insoluble atmospheric aerosols that initiates ice-phase processes by the heterogeneous freezing. The concentration of IN are many orders less than the total aerosols mainly because of their requirements like the solid state; minimum size should be the size of an ice germ ($> \sim 0.1\,\mu m$) and lattice structure similar to that of ice with active surface sites (Stevens et al., 2009). The investigations between IN interactions with orographic clouds and resulting precipitation are still ongoing and not well understood. The reason for such less coverage may be due to the facts that exploration of IN is still under investigation and the concentrations of IN is decidedly less compare to CCN, which requires precise measurements for this investigation.

The oxygen isotopic ratios (del^{18}O) and sulfate concentrations studies in cloud water and cloud snow collected at the NW Colorado during winter show that the rimmed mass fraction sharply increased at mean droplet diameters above $10\,\mu m$ (Lowenthal et al., 2011). This increase is observed even for non-orographic clouds at different locations (e.g. Harimaya, 1975; Pitter and Pruppacher, 1974; Pitter, 1977). Lowenthal et al. (2011) found that the maximum amount of snow growth by riming and vapour deposition occurred in the low altitudes and the ice crystals form under liquid water sub-saturated conditions at high altitudes. When these ice crystals start to fall, they gain a significant fraction of their water content by riming and vapour deposition while passing through the low-level orographic clouds indicating the so-called seeder-feeder mechanism.

The study of the presence of insoluble aerosols in two extratropical storms on OP over the Sierra Nevada found that one of them was composed mostly of organic aerosols produced by biomass burning while the other one was composed of Asian dust (Ault et al., 2011). The measurements showed that the storm with Asian dust present in the higher altitudes of orographic clouds relative to the one without it produced 1.4 times more precipitation and 1.6 times more snowpack indicating the role of Asian dust serving as IN. They suggested that in the second storm, dust may have served as effective IN and may have resulted in enhanced heterogeneous nucleation process leading to the increased growth of ice crystals by collection processes like rimming and thus resulting in improved precipitation efficiency.

Creamean et al. (2013) showed the presence of dust transported from Sahara and Asia as well as biological aerosols in the mid-level clouds, which coincided with the presence of high amount of IN and ice-induced precipitation over the Sierra Nevada. They suggested that dust from Asia and Sahara, and biological aerosols may serve as efficient IN and can thus play an essential role in OP. Further enhancing the results of Creamean et al. (2013), Creamean et al. (2015) compared the observations of insoluble residues of aerosols in precipitation samples with the precipitation characteristics aloft during the winter season from 2009 to 2011 over the Sierra Nevada. They found that dust and biological aerosols most likely act as IN at the higher altitude while organic carbon acts as CCN at lower elevations near cloud bases. Also, the biological aerosols can, however, initiate the ice processes in relatively warmer cloud temperatures than dust particles implying that the former can serve as more efficient IN than dust. The impact of dust and biological aerosols on deep and shallow clouds also varies. For the deep storms (reaching higher altitudes) when dust and biological aerosols were dominant, larger quantities of ice-phase precipitation were observed implying that such aerosols may act as IN leading to enhancement in the ice-phase processes (consistent with the simulations of Fan et al., 2014). For shallow clouds which are not able to reach higher levels such that the IN concentration are low and organic carbon and other pollution aerosols are dominant, they found a negative relation between precipitation and organic carbon aerosols suggesting that such aerosols may serve as CCN and thus suppress the precipitation by decreasing the collection efficiency. For the case when both IN (dust) and CCN (organic carbon and other pollutants from biomass burning) were present, the cloud was reported to be shallow and produced less precipitation (similar to the simulations by Saleeby et al., 2009).

Including aforementioned studies, there are several projects and experiments that have produced similar results in terms of cloud seeding of orographic clouds. The results from Climax I and II experiments carried over Colorado Rockies for winter orographic clouds showed that the cloud seeding increased the precipitation for cases with CTT $> -20\,^{\circ}C$ (Grant; Mielke, 1967; Mielke et al., 1971; Chappell et al., 1971). The results from CLIMAX experiments were supported by the observational results of Colorado Orographic Cloud Seeding Experiment (COSE), Colorado River Augmentation Demonstration Program (CRADP) and the Sierra Cooperative Pilot Project (SCPP) in California (Reynolds, 1988). The experiments by Commonwealth Scientific and Industrial Research Organisation (CSIRO) over mountainous regions of Australia (especially the Tasmanian Mountains) showed that the precipitation is enhanced as a response to glaciogenic cloud seeding. However, such enhancement was only found for clouds formed in winter season with CTT falling in between $-12^{O}C$ and $-10^{O}C$ (Smith, 1974; Shaw et al., 1984). Such enhancement was not

Table 2
An overview of selected AOP interaction studies based on the observational analysis.

Author	Observation Data	Temporal Range	Area of study	Results
Borys et al. (2000)	SPL measurements, Cloud water samples for CCN conc., PMS-FSSP-100, HEGB	13 to 28 Jan 1995	Summit of Mt. Werner, NW Colorado, US.	A decrease in snowfall rate with increase in CCN concentration
Borys and Lowenthal (2003)	Same as Borys et al. (2000) including RADAR measurements	Feb 15 & 19, 2001	Northern Rocky Mountains, Colorado, US	An increase in CCN leads to a decrease in rimming rates and ultimately precipitation suppression
Givati and Rosenfeld (2004)	Rain gauge data	1920 to 2000	California and Israel	Precipitation loss in windward side and similar gain in leeward downwind of polluted areas
Griffith et al. (2005)	Rain gauge data	1949/1956 to 2004	States of Utah and Nevada, US	Precipitation reduction downwind of polluted urban regions and not in downwind of rural areas
Givati and Rosenfeld (2005)	Rain gauge data	1950 to 2002	Northern Israel	Cloud seeding increases OEF while anthropogenic pollution reduces OEF
Jirak and Cotton (2006)	Rain gauge data	1950 to 2002	Front Range of the Rocky Mountains	OEF decreased downwind of polluted areas and no such effect is observe downwind of pristine areas
Rosenfeld and Givati (2006)	Rain gauge and IMPROVE aerosol data	Rain - ~1950 to 2003 Aerosol - 1988 to 2003	Western US	Decrease in OEF associated with a decrease in coarse mode (PM2.5 – PM10) or increase in fine mode (PM2.5) aerosols
Rosenfeld et al. (2007)	Meteorological observatory measurements top of Mt. Hua (2060 m)	1954 to 2004	Mt. Hua, central China	Decreasing visibility coincides with decrease in OEF (30–50%)
Alpert et al. (2008)	Rain gauge data	1954 to 2004	Israel	No reduction in orographic precipitation is seen with increase in pollution except for leeward side of Galilee mountains
Rosenfeld et al. (2008)	SUPRECIP Aircraft measurements	Feb and Mar of both 2005 and 2006	Sierra Nevada, US	Precipitation suppression is evident in orographic clouds triggered within the boundary layer
Halfon et al. (2009)	Rain gauge	1952 to 2006	Israel	Similar to the results of Alpert et al. (2008)
Morrison et al. (2009)	Rain gauge	1960–2005	Tasmania, Australia	Cloud seeding has a positive impact on the orographic clouds
Konwar et al. (2010)	CAIPEX observations	May–Sept 2009	Western Ghats, India	Aerosol suppress warm rain process in the low altitudes.
Geerts et al. (2010)	WWMPP measurements	2008, 209	Medicine Bow Mountain, US	Seeding resulted in ~25% in snowfall below the target area
Manton and Warren (2011)	Rain gauge	May 2005 tp Jne 2009	Snowy Mountains, Australia	Seeding has a positive impact on OP but not statistically significant.
Lowenthal et al. (2011)	DRI SPL measurements	Jan and Feb 2007	Summit of Mt. Werner, NW Colorado, US	Significant decrease in the rimming growth in cloud droplets with size below 10 μm
Ault et al. (2011)	CalWater campaign measurements	22 Feb to 11 Mar 2009	Sierra Nevada, California, US	Storms with dust present produced higher precipitation and snowpack
Creamean et al. (2013)	CalWater campaign measurements	Jan to Mar 2011	Sierra Nevada, California, US	Presence of saharan dust and biological aerosols in clouds with elevated IN conc. and ice-induced precipitation
Yang et al. (2013)	Rain gauge, visibility, radiosonde	1954–2009	Mt. Hua, Central China	Aerosols can suppress light rainfall by means of both direct and indirect effect
Guo et al. (2014)	Rain gauge and visibility	1966–2005	North China	Increase in pollution suppress light rain
Kumar et al. (2014)	Satellite and Reanalysis data	1998–2011	Western Ghats, India, and Myanmar coast	Giant CCN from the Arabian Sea increases OP over Western Ghats
Konwar et al. (2014)	CAIPEX observations	2008, 2009, 2012, 2013	Western Ghats, India	C–C is the dominant growth process in light and heavy raining warm phase cloud
Pokharel et al. (2014a) & 2014b	ASCII experiments	21 Feb 2012 &13 Feb 2012	Sierra Madre, Wyoming, US	Seeding increase OP for shallow orographic cloud, ice particles of all sizes increased.
Creamean et al. (2015)	CalWater campaign measurements	Jan to Mar 2009 to 2011	Central Sierra Nevada, California, US	Deep clouds with dominant IN enhance precipitation; shallow clouds with dominant CCN suppress precipitation; clouds with IN and high CCN suppress precipitation
Pokharel et al. (2017)	ASCII experiments	Jan–Mar 2008, 2009, 2012, 2013	Sierra Madre, Wyoming	Increase in radar reflectivity is observed but not consistent for all cases. Needs larger observation sample size.
French et al. (2018)	SNOWIE measurements	March 2017	Payette Mountain, US	Seeding increased ice crystal concentration and hence OP in the

OEF = Orographic Enhancement Factor; DRI SPL = Desert Research Institute Storm Peak Laboratory.
FSSP = Forward Scattering Spectrometer Probe; HEGB = High-sensitivity Electronic Gravimetric Balance.
CSSL = Central Sierra Snow Lab, California; IMPROVE = Interagency Monitoring of Protected Visual Environments; SUPRECIP = Suppression of Precipitation.

prominent in clouds formed over plain regions of Australia. Ryan and King (1997) and Bruintjes (1999) have discussed the key cloud seeding experiments performed in the twentieth century. Morrison et al. (2009) analysed the rainfall patterns to investigate the impact of cloud seeding on the orographic precipitation for the period 1960–2005 over central Tasmania, Australia and found a positive impact of cloud seeding. Manton and Warren (2011) investigated the effect of cloud seeding on winter orographic clouds formed over the Snowy Mountains of south-eastern Australia as a part of Snowy Precipitation Enhancement Research Project (SPERP) (Huggins et al., 2008) using silver-chloroiodide as the seeding material and Indium (III) oxide as the passive tracer. They considered a total of 107 five hourly seeding experiments held between May 2005 to June 2009 and a total of 44 ground-based gauges to measure the precipitation (Manton et al., 2011). The results indicated a positive effect of seeding on the precipitation (7% increase) at 24% significance level. They found that the ratio of silver and indium concentrations within snow particles confirmed the seeding impacts on the cloud microphysics. Also, the effect of seeding depends on the duration of working of the seeding generators, and the seeding not only impacts on the supercooled liquid water content but also the physical parameters like wind field and temperature profiles.

Cloud seeding of summertime orographic clouds formed over hilly regions of Munnar, India was performed by Murty and Biswas (1968) for two summer seasons. The results showed an enhancement in orographic precipitation and they concluded that cloud seeding can be used over regions similar to Munnar so to prevent water shortage. Konwar et al. (2010) studied the cloud-aerosol interaction over the rain shadow regions of the Western Ghats, India, from the data collected by the Cloud-Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) from May–September 2009. The results indicate suppression of warm rain processes, due to the presence of thick aerosol layer up to the heights of 7 km, above which the phase of cloud was dominated by ice particles. Similar results are also reported by Narkhedkar et al. (2015). The clouds that did not exceed this height produced less precipitation due to the overseeding effect.

As a part of WWMPP, Geerts et al. (2010) studied the impact of glaciogenic seeding on winter orographic clouds. The study analysed the data collected from airborne profiling radar onboard flying aircraft over the Medicine Bow Mountains of Wyoming. Results of Geerts et al. (2010) indicated an increase in low-level radar reflectivity for seeded clouds which corresponds to around ~25% increase in snowfall rate. They further suggested that ground-based vertical pointing radars and probes should be used to measure the density and size distributions of ice particles. Pokharel et al. (2014a) studied the seeding impact on shallow orographic clouds with CTT of -22^{O}C, formed over the Sierra Madre, Wyoming, on 21 February 2012. The data was collected from the AgI Seeding Cloud Impact Investigation (ASCII) experiments with the help of Parsivel disdrometer and a system of radars (X-band scanning Doppler-on-Wheels radar, W-band profiling Wyoming Cloud Radar and a pair of Ka-band profiling Micro Rain Radars). The results show an increase in low-level radar reflectivity for the seeded region as compared to the control untreated region, resulting in an increase in snowfall rate near the seeded region. Further, the disdrometer measurements show that the number concentration of ice particles of all sizes increased after seeding with some time delay. Pokharel et al. (2014b) performed a second case study of seeding of a shallow orographic cloud formed over the same mountain on 13 February 2012. The results indicated that the change in radar reflectivity was influenced mainly by natural variability and not by the seeding. They also found an increase in ice particles concentration of all sizes. Further, Pokharel et al. (2017) estimated the impact of glaciogenic cloud seeding on the orographic clouds considering 27 case studies (Pokharel et al., 2016) in the four winters (January–March for years 2008, 2009, 2012 and 2013) over the Sierra Madre and Medicine Bow Mountains during the ASCII experiments. In this work, they compared the radar reflectivity of 2 h of seeded clouds with that of 2 h of non-seeded clouds just prior to seeding. This difference was again compared with the corresponding difference over control area so as to overcome the natural variability of cloud systems. The results indicated an increase in reflectivity over both the mountains for seeded regions, but this trend varied from case to case. They suggested that a larger sample size of such experiments is required before reaching to any conclusion.

By combining the radar and in-situ observations, French et al. (2018) studied the effects of AgI cloud seeding on the orographic clouds formed over the Payette Mountains for two cases in March 2017. The data was collected from the experiments of Seeded and Natural orographic Wintertime Clouds (SNOWIE). The results show that, for the target seeded area, the snow precipitation over the mountains increased as a response to cloud seeding. The concentration of ice crystals with diameter > 300 μm was found to be ~3 orders higher than the unseeded area at the same altitude. The seeding resulted in the formation of more ice crystals which continued to grow at the expense of supercooled liquid water by deposition, riming and aggregation resulting in an increase in snow precipitation over the target region.The observational studies for AOP interactions, discussed in the present manuscript, are summarised in Table 2.

3.4. Summary of observational studies

The observational study of AOP interaction is explored over several parts of the world by using many insitu and remote sensing data sets, e.g., long term rain gauge, visibility, radar (ground and airborne), satellite and re-analysis data sets. An inverse relation between anthropogenic aerosols and orographic precipitation is reported by many researchers by analyzing long term rain gauge data (Givati and Rosenfeld, 2004, 2005; Jirak and Cotton, 2006; Rosenfeld and Givati, 2006), visibility data (Rosenfeld et al., 2007; Guo et al., 2014), laboratory measurements (Borys et al., 2003) and aircraft measurements (Rosenfeld et al., 2008) over different parts of the world. Since OEF neglects the inland processes which may impact the precipitation trend like the urban heat island effect, Alpert et al. (2008) and Halfon et al. (2009) modified OEF by considering pristine coastal region in place of urban area found increasing trend over Israel. Studies have found that clouds with abundant dust and biological aerosols result in comparatively efficient ice phase processes resulting in comparatively higher precipitation (Ault et al., 2011; Creamean et al., 2013, 2015) supporting the modelling results. Results from the satellite measurements show the working of Twomey effect and role of aerosol direct effect in increasing the orographic precipitation (Kumar et al., 2014; Konwar et al., 2014; Leena et al., 2016). There are several glaciogenic cloud seeding experiments performed for orographic clouds with the help of radars (ground and airborne), disdrometers, aircrafts and many in-situ measurements. The results indicate an increasing in precipitation in the target region as compared to control no seeded region (Reynolds, 1988; Morrison et al., 2009; Ryan and King, 1997; Bruintjes, 1999; Huggins et al., 2008; Manton and Warren, 2011b; Manton et al., 2011a; Murty and Biswas, 1968; Konwar et al., 2010; Geerts et al., 2010; Pokharel et al., 2014a, 2014b, 2016, 2017; French et al., 2018). This further supports the hypothesis of IN increasing the orographic precipitation.

4. Summary and scope of future work

In the present article, we have reviewed the studies related to AOP interaction derived from the results of various observational and modelling studies over a variety of mountains. The primary goal for studying AOP interaction is to understand the modulations of precipitation by aerosols in different mountain scenarios to advance our current forecasting quality and prepare necessary mitigation plans. Realising the difficulty of re-examining all published works, we have summarised this article centred on the aspects of AOP interaction for physical, geometrical and simulation-based findings.

Based on our understanding, we propose an idealised conceptual

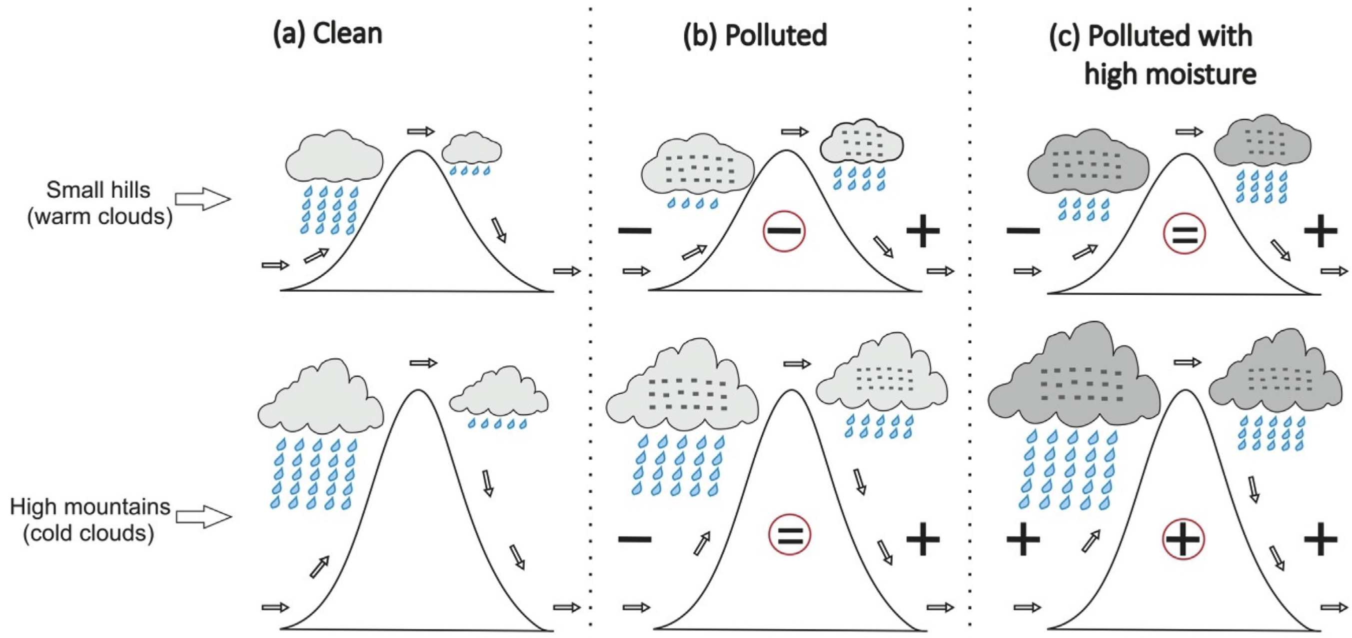

Fig. 2. Schematic diagram of AOP interaction for warm and cold phase orographic clouds with (a) clean/pristine scenario, (b) Polluted scenario and (c) Polluted scenario with high moisture content. For panel (b) and (c), '+' and '-' symbols are indicating increase and decrease in precipitation over windward or leeward side of the mountain. The '+','–' or ' = ' symbols inside the circle indicate a change in net precipitation over the mountain.

picture of the AOP interaction under different mountain height and moisture content regimes, considering only the amount and distribution of OP (Fig. 2). For warm clouds, which generally form over small hills, the increase in aerosols acting as CCN results in the formation of larger clouds. However, due to growth in cloud lifetime (because of the creation of a considerable number of small cloud droplets), the hydrometeors cannot grow large enough to fall as precipitation. Mostly, these hydrometeors may not precipitate in the windward side and transferred along with the wind to the leeward side of the hill, which increases the spillover effect. But the net precipitation may decrease because of high evaporation caused by subsidence in the leeward side.

Situations with higher moisture content can subjugate this suppression, thereby eliminating the overseeding effect and decrease evaporation rate in the leeward side. For cold clouds, formed over high mountains, the overall precipitation may be less susceptible to the increase in aerosol concentration, mainly because of two reasons:

(i) The involvement of ice-phase processes which compensates for the loss of precipitation by the reduction in liquid phase processes, and,
(ii) An increase in the mountain height implies larger advection timescale such that the clouds can grow large enough to overcome the leeward subsidence. The spillover factor is increased but is less as compared to the small hill case. Increase in moisture content results in higher super-cooled liquid water content and reduced leeward evaporation, thus increasing the net orographic precipitation.

At the current stage of research, it is clear that if not the amount, the distribution of precipitation over orography is highly dependent on the aerosols. All the models show an increase in spillover effect with an increase in CCN concentration for both warm and mixed-phase clouds, with the overall precipitation either increased or decreased depending on the geometry of orography and environmental conditions. Due to rapid growth in industrialisation, urbanisation and population, the anthropogenic pollutants (and hence CCN) are increasing day by day, which may result in a net precipitation pattern shift further downwind of mountain ranges, affecting the local water reservoirs on a larger timescale. The AOP interaction studies are developing and improving the understanding of weather events in a changing climate. However, there are areas, which need to be comprehensively studied, before reaching at any conclusion about AOP interaction. Since with an increase in aerosol concentrations, the IN level is also increasing, the impact of IN on the distribution and amount of OP needs to be well understood. The effect of chemical properties of aerosols (e.g. solubility) on the orographic precipitation requires a comprehensive study for quantifying the indirect effects of aerosols in such regions. Most of the AOP studies are focused on the indirect effect of aerosols. Since aerosols by virtue of their direct effect can impact the OP by modulating the atmospheric circulation and moisture transport towards the mountains, the ARI effects of aerosols should also be considered when studying AOP interactions. We can conclude the findings as follows:

1. The observational studies have constraints mainly because of limited temporal and spatial coverage due to various factors (e.g. results from sparse and spatially fixed rain gauge data or aircraft measurements may not apply to whole mountain region). However, the modelling studies can overcome these limitations, and the model simulation based results are showing an overview for the entire area.
2. Aerosols have a dominant role in shifting the precipitation pattern further downwind of orography resulting in an increase (decrease) in the leeward (windward) precipitation by its second indirect effect, i.e., increasing the cloud lifetime.
3. For particular mountain geometry, the traditional concept of precipitation suppression with an increase in CCN concentration is applicable only under certain environmental conditions when the atmosphere is relatively dry, and the orographic clouds are shallow. For cases with humidity high enough to prevent overseeding and rapid leeward evaporation, or freezing level low enough for the ice processes to be dominant, an increase in CCN may not significantly affect the amount of orographic precipitation.
4. Since the geometry of the mountains governs the advection time scales of orographic clouds limiting the microphysical time scale, the aerosol impacts on the distribution and amount of precipitation highly depend on the height and width of the mountain. For high mountains, the susceptibility of orographic precipitation to aerosol perturbations is less because more time is available for the growth

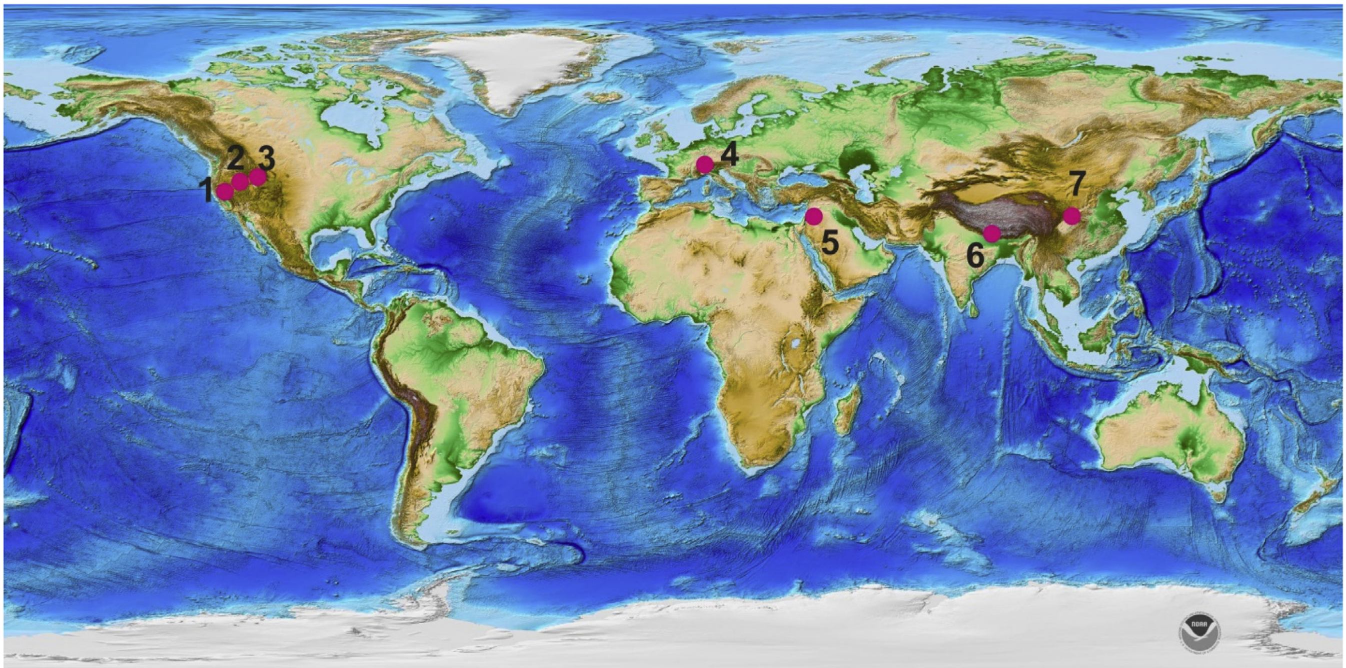

Fig. 3. Mountainous regions around the world with an exploration of AOP interactions. The legends are 1. Sierra Nevada Mountains, US; 2. Utah Mountains, US; 3. Colorado Mountains, US; 4. Jungfraujoch Mountain, Swiss Alps; 5. Israel Mountains; 6. The Himalayan foothills, Nepal; 7. Mt. Hua, China (background Image Source: etopo1, National Geophysical Data Center, NOAA).

of hydrometeors, while this susceptibility increases for low hills.

5. Warm phase orographic clouds that formed over low mountains suffer a loss of overall precipitation due to increase in CCN concentration due to the formation of more small cloud droplets resulting in reduced growth of hydrometeors by collection process. Consequently, the microphysical time scale of the cloud increases, and because of limited advection time scale (Small Mountain), it advects past the mountaintop where the rapid evaporation leads to a loss in net precipitation. Thus, the spillover effect increases, but the gain in leeward precipitation does not compensate for the loss of windward precipitation.
6. Mixed-phase orographic clouds formed over considerably high mountains like that of Colorado, Sierra Nevada and Himalayan mountain ranges, may act as a buffered system in response to CCN perturbations due to the involvement of dominant ice-phase processes because of the following reasons:

(i) The increase in aerosol concentration leads to suppression/growth of warm rain/ice phase processes, due to more availability of supercooled liquid water.

(ii) High mountains provide larger advection timescale for the growth of cloud hydrometeors and thus are associated with more CWP and IWP so that the growth of ice phase hydrometeors by riming and WBF process is high enough to withstand the leeward subsidence.

(iii) Increase in aerosol concentration also favours the resaturation in the leeward side and thus reduces the precipitation loss by slowing down the ice-crystals sublimation.

Therefore, in this case, even if the spillover factor increases, the loss of OP over windward regions is compensated by the leeward enhancement resulting in no significant change in the overall OP. Increasing the humidity in such case may also increase the OP due to the availability of more super-cooled liquid water and may result in enhancement of ice phase growth processes. The growth of hydrometeors by ice-phase processes is thus the dominant process, which determines the sign of overall precipitation anomaly for the case of increased aerosol concentration.

7. The orographic precipitation is highly sensitive to aerosols, especially for mountains located downwind of urban cities. The responsible factors may be the aerosol indirect effect, aerosol radiation interaction by absorbing aerosols and urban heat island effect.

AOP interaction study is in the early stages of understanding. Based on the review of various works in the present study, we can identify a few mountain ranges, where most of the studies are venturing (Fig. 3). Several regions with major mountains like the Himalayas, the Western Ghats of India, the Andes, the Appalachians, the Rwenzori, the Pyrenees, the Alborz, the Atlas, the Alaska Range, the Great Dividing Range, the Zagros, the Karakoram, the Hindu Kush, the Brooks Range are still left uncovered and needs attention of researchers. Even for the mountain ranges like the Himalaya, we feel that there is a need to explore the AOP interactions with more observations to support the proposed theories given the high amount of pollution in the foothills regions. The existing studies are mostly exploring AOP interaction with clouds generation due to orographic lifting. The investigations for the clouds originating at other place and moving over an orographic region, assisted by orographic clouds formed in the lower altitude (favourable for seeder-feeder mechanism) and has a dominant contribution to the world orographic precipitation (Houze, 2012) are infrequent. Most of the studies are concentrated on the mid-latitudes whereas AOP interactions over tropical mountains like the Himalayas, which is climatologically very important, are relatively less explored. The aerosol effects on OP largely depend on mountain geometry, the flow pattern and the environmental conditions along with aerosol properties.

Since these conditions vary with the geographical location, the AOP interactions for one region over a specific period may not be viable for others. Thus, the AOP interaction should be studied independently over all the major mountains before reaching any general conclusion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Conflicts of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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