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Review

Meteorological Applications Benefiting from an Improved Understanding of Atmospheric Exchange Processes over Mountains

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Abstract: This paper reviews the benefits of a better understanding of atmospheric exchange processes over mountains. These processes affect weather and climate variables that are important in meteorological applications related to many scientific disciplines and sectors of the economy. We focus this review on examples of meteorological applications in hydrology, ecology, agriculture, urban planning, wind energy, transportation, air pollution, and climate change. These examples demonstrate the benefits of a more accurate knowledge of atmospheric exchange processes over mountains, including a better understanding of snow redistribution, microclimate, land-cover change, frost hazards, urban ventilation, wind gusts, road temperatures, air pollution, and the impacts of climate change. The examples show that continued research on atmospheric exchange processes over mountains is warranted, and that a recognition of the potential benefits can inspire new research directions. An awareness of the links between basic research topics and applications is important to the success and impact of new efforts that aim at better understanding atmospheric exchange processes over mountains. To maximize the benefits of future research for meteorological applications, coordinated international efforts involving scientists studying atmospheric exchange processes, as well as scientists and stakeholders representing many other scientific disciplines and economic sectors are required.

Keywords: meteorological applications; mountain meteorology; land-atmosphere interactions; transport and mixing; atmospheric boundary layer processes; atmospheric exchange

1. Introduction

Mountains affect land-atmosphere interactions and atmospheric transport and mixing of mass, momentum, and heat over a wide range of temporal and spatial scales. Collectively, we refer to these as atmospheric exchange processes over mountains. Extensive recent reviews of this subject are available in [1,2]. Atmospheric exchange processes drive many aspects of weather and climate, including diurnal changes in atmospheric variables such as temperature, humidity, wind, and air pollutant concentrations near the surface. Good understanding, observation, simulation, and forecasting of these variables is important for meteorological applications related to many scientific disciplines and sectors of the economy, including the earth system sciences (e.g., hydrology and ecology), water resource management, agriculture and forestry, construction, urban and regional planning, renewable energy, transportation, air quality, and climate change. To emphasize that we discuss scientific disciplines and sectors of the economy in the context of meteorological applications, we will refer to these disciplines and sectors as 'applications'. The goal of this paper is to identify some of the benefits of an improved understanding of exchange processes in mountainous terrain to a selection of applications. We present some specific examples of applications that not only use current knowledge of atmospheric exchange processes over mountains, but also motivate their continued investigation. Therefore, our aim also is to stimulate discussion and a vision towards the future.

The paper is organized according to the structure depicted in Figure 1. From the bottom to the top of the figure, atmospheric exchange processes can be divided into two major components:

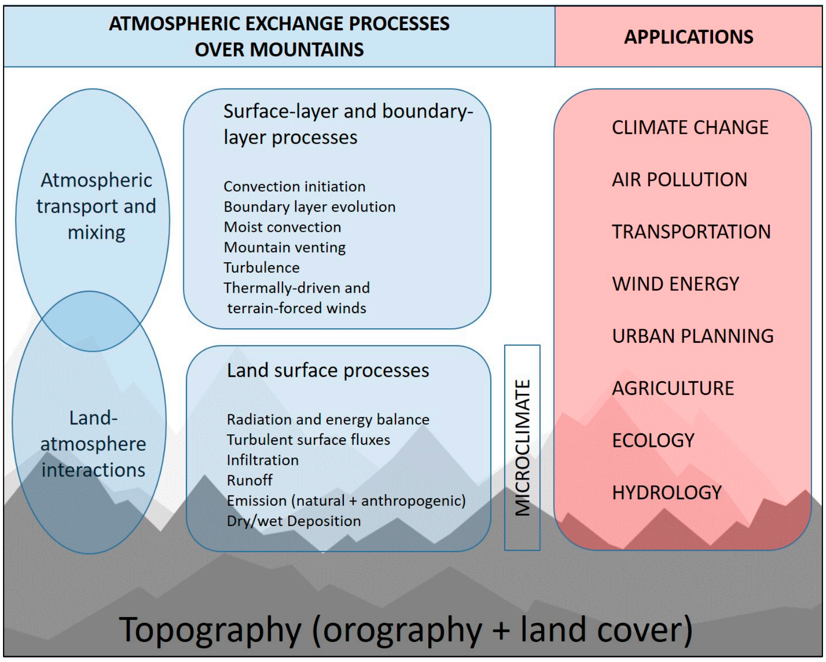

Figure 1. Atmospheric exchange processes consist of land-atmosphere interactions and atmospheric transport and mixing (blue ovals). These processes can be subdivided into land-surface, surface-layer, and boundary-layer processes (blue rectangles) that are relevant in meteorological applications in many scientific disciplines and sectors of the economy. The disciplines and sectors discussed in this paper, referred to here as 'applications', are listed in the right column (red rectangle).

(1) Land–atmosphere interactions, which include processes at the land surface and in the atmospheric surface layer. These processes have a substantial impact on weather and climate patterns and on the water, energy, and biogeochemical cycles of the climate system [3,4]. These interactions occur through complex dynamical, physical, biological, and hydrological processes, and are influenced by topography, soil properties, and land cover, including vegetation characteristics [5]. Mountain regions exhibit a strong variability in vegetation cover, snow, soil moisture, soil, and bedrock outcropping which span a wide range of scales, from meters to hundreds of kilometers. Albedo, slope, aspect, shading by the terrain, sky-view factor, and elevation create significant variability in short- and longwave radiation, and subsequently the amount of energy that is available for driving atmospheric exchange processes. Spatial patterns in the available surface energy, as well as in precipitation, soil moisture, and winds, affect the air temperature and humidity in microclimates that are important for meteorological applications in hydrology, ecology, and agriculture.

(2) Atmospheric transport and mixing, which include processes in the atmospheric surface and boundary layer. These processes have a significant impact on exchanges of mass, momentum, heat, dust and other aerosols, and trace gases within the atmospheric boundary layer (ABL) and between

the ABL and the free atmosphere. Field experiments over flat, homogeneous terrain have led to the development of theories and relationships that describe, for example, the variation with height of wind, temperature, and turbulence, and the diurnal evolution of the ABL. It is increasingly recognized that these theories and relationships need to be modified for application to the atmosphere affected by mountains. Research efforts have been made and our understanding has improved [2,6–8], but there are still many uncertainties and unknowns, and progress is hampered by many observational and computational difficulties. Advancements in addressing these uncertainties will provide more accurate characterizations and forecasts of flow and turbulence in the ABL over mountains, which will benefit meteorological applications in areas such as wind energy, transportation, and air pollution.

Land surface-, surface layer-, and boundary-layer-processes in mountainous terrain interact on many spatial and temporal scales, and many feedbacks exist. Some of these interactions and feedbacks are known, but many are still unknown or only hypothesized. Efforts to increase our knowledge of these interactions and feedbacks, and of the underlying basic atmospheric processes, constitute a major part of the research on atmospheric exchange over mountains. This research will lead to better understanding, observations, and simulations of weather and climate variables that ultimately benefit various applications. A selection of applications that benefit from a better understanding of atmospheric exchange processes over mountains (discussed in Sections 2–9) is listed on the right side of Figure 1. An attempt was made to order the applications such that from bottom to top in Figure 1, the applications increasingly emphasize transport and mixing processes higher up in the ABL. Climate change as an application, discussed in Section 9, does not fit this structure well because of the many potential topics that intersect with the previously discussed applications. Section 10 provides conclusions and some final thoughts.

2. Hydrology

Mountains are the water towers for the world, since they store water in the form of snow and ice at high elevations. At least one third of the world's population depends on melting snow and ice for their water [9]. Also, convection triggered by elevated terrain leads to the development of high intensity precipitation on steep terrain, which can result in flash floods [10–13]. Therefore, hydrologic processes in the mountains are critically important to humanity. Mountain hydrology is influenced by atmospheric exchanges in both directions. Precipitation is an important component of the hydrological cycle, and near the surface the deposition of this precipitation is strongly controlled by local turbulent processes, particularly when it falls as snow [14,15]. The resulting spatial variability has important hydrologic consequences including changes in runoff and changes in evaporation and sublimation to the atmosphere. While many land-surface models can approximate the details of hydrological processes, including evapotranspiration and infiltration, and, more recently, also the lateral flow of water, several aspects of mountain hydrology are still poorly understood and simulated in both numerical weather prediction (NWP) models and regional climate models. One outstanding example is our limited ability to estimate mountain snowpack [16]. The preferential deposition of precipitation combined with post-depositional wind redistribution [17,18] has an enormous impact on the spatial variability of snowpack [19,20]. This, in turn, affects the timing of runoff [21], the magnitude of rain-on-snow floods [22], the albedo [21,23,24], the climate change signal [25,26], and avalanche prediction [27,28].

While the spatial heterogeneity of the snowpack has a direct impact on hydrologic applications and turbulent exchange, the redistribution process itself results in a substantial loss of water from a basin through sublimation [29,30]. Blowing snow (Figure 2) has an exposed surface area that is orders of magnitude larger than snowpack's surface area. This combines with the highly turbulent environment to result in estimates of sublimation losses as high as 1000 mm of water along ridges [31]. However, very few measurements are available to constrain these estimates. While the importance of modeling redistribution as a component of alpine hydrology has been recognized for a long time [32–34], explicit modeling of snow redistribution has a much shorter history [35,36]. Explicit simulation of the complex wind fields controlling this redistribution [14,15,30,37] and an understanding of the coupling between the near-surface atmospheric turbulence in complex terrain and the snow transport dynamics [38] are only in their infancy. Understanding the transport and exchange of snow in the alpine boundary layer is crucial for helping water resource managers to better estimate the volume and timing of runoff expected in a given year.

Figure 2. Blowing snow at high elevations affects the spatial distribution of snow and wind loading of avalanche initiation zones. Simo Räsänen.

Blowing snow sublimation can potentially lead to large loss of water and has also feedbacks on the atmosphere through cooling and moistening of the stable boundary layer. These feedbacks are strong in Antarctica [39,40] but are also present in mountainous terrain [29,30].

Spatio-temporal variability in land surface and in meteorological variables influences all hydrologic applications from water resource management to avalanche prediction to flood forecasting. It is a critical aspect of all alpine catchment hydrology research. Measurements of turbulent exchange over regions characterized by large spatial variability would provide a key integration of evaporative losses in alpine environments in much the same way that streamflow measurements reveal the integration of subsurface hydrologic processes over entire catchments.

3. Ecology

Mountain ecosystems are characterized by large gradients in elevation and climate that affect the distribution of flora and fauna, and are therefore rich sources of biodiversity and ecosystem services (such as carbon sequestration, flood regulation, and pest control). Climate variables often have important covariances embedded in their spatial structure over mountains, which also affect vegetation distribution. For example, in water limited ecosystems, vegetation tends to grow on north facing slopes, while in energy limited systems, vegetation growth favors south faces. Among other factors, mean annual temperature is the main factor determining the range of different plants [41]. For example, the alpine tree line (Figure 3) occurs around the 10 °C summer isotherm [42]. Therefore, in tropical regions, the tree line may be above 4000 m, whereas at high latitudes it may be as low as few hundred meters [43]. Tree lines and snow lines occur at higher elevations in the interiors of mountainous areas than at the outer margins. This observation has been explained using the so-called "Massenerhebung" (mass elevation) effect [44], which is partly due to spatial variations in atmospheric heat exchange over the mountains. This effect has important implications in ecological studies but has so far not been quantified in terms of atmospheric exchange processes.

Mountains are subject to rapidly changing environmental factors of which land use change is the most important [45]. Mountain regions are affected by land abandonment due to a decline in traditional agricultural practices, which can be observed worldwide [46]. For example, this has led to forest regrowth increasingly replacing agricultural land in mountains. Mountains are also subject to impacts from climate change (see also Section 9), with changes occurring in the upper elevation limits of plant and crop growth, and in the start and duration of the growing season. These changes affect the spatiotemporal variations of vegetation and therefore also atmospheric exchange processes, including the surface exchange of heat, moisture, and momentum, thermally driven flows, and convection initiation.

Figure 3. Upslope migration of tree lines represents a land cover change that affects turbulent exchange processes over mountains. © William Demchick.

Changes in land cover and land use in mountains can have many impacts on components of the ecosystem that are relevant to atmospheric exchange processes, including the carbon cycle. It has even been suggested that mountain forest could explain the so-called missing carbon sink [47], which has motivated an increasing number of studies focusing on quantifying carbon sequestration in these ecosystems [48,49]. However, simulating and understanding mass fluxes in complex, highly heterogeneous terrain is fundamentally challenging [50].

Mountain ecosystems often include wildfires, which in many ways epitomize the complex relationships among weather, climate, atmospheric exchange processes in the mountains, the biosphere, and meteorological applications—in this case, methods and tools for fire management. A wildfire's size, intensity, and motion are shaped by weather, terrain, and fuel in the land cover [51]. There are multi-directional, nonlinear interactions among these factors over a range of spatial and temporal scales [52–54]. For example, on the high ends of those scales, low humidity and lack of rain for several months can desiccate dead fuel, leading to more large fires and greater area burned [55]. On the low ends of those scales, outflow from a pyrocumulonimbus generated by a fire can, in turn, modify that same fire's immediate environment [56,57]. To be most effective, modeling systems for simulating wildfires and the smoke they generate (see Section 8) must account for these interactions [58–60]. How well such interactions are represented depends on our understanding of the exchange processes, the surface and boundary layers, and the free atmosphere in and around wildfires.

4. Agriculture

Agriculture is an important economic driver in many mountainous regions of the world. Meteorological conditions determine the quantity and quality of agricultural products. Advances in our understanding of exchange processes support the improvement of meteorological forecasts at different spatial and temporal scales, which can help the management of crops, the planning of agricultural activities (such as plowing, seeding, watering, fertilizing, applying pesticides and herbicides, and harvesting), and the optimization of available resources. The continuous development of innovative technologies integrating different in situ sensors and remote sensing instruments allows for monitoring microclimatic conditions in the different growing stages with increasing precision. The collected data provide valuable support for targeted actions. Similarly, the improvement of forecasting systems facilitates planning such targeted actions and optimizing resources. For example, to protect crops from pests, suitable operations have to be performed, including the spraying of pesticides. Meteorological conditions are key drivers for such operations for two reasons: (1) many pests develop and proliferate only when particular micrometeorological conditions occur; and (2) the effectiveness of the operations depends on wind, turbulence, temperature, and humidity in and immediately above the planted volume. Therefore, every improvement in our capability to forecast the optimal meteorological conditions results in a better planning and management of these operations.

The optimization of agricultural practices is particularly important in mountainous areas that have an increased risk of natural constraints on crop growth, such as drought and frost. The availability of water is an important factor determining the success of agricultural practices. The correct forecast of both precipitation and evapotranspiration is complicated in mountainous areas, and is influenced by local and mesoscale exchange processes. For example, thermally driven flows can promote convective clouds and associated precipitation. Moreover, cloud and dew formation over mountain slopes may be beneficial as water supply to crops, especially in arid areas, as found in the Elqui Valley on the western side of the Andes range [61].

Frost is one of the most relevant damage factors for crops in mountainous areas and can destroy fruit and vegetable harvests. Radiation frost is produced mainly by local surface-atmosphere exchange processes in topographic depressions, while advection frosts are caused by the advection of cold air by local and larger-scale winds at higher elevations. The hazard posed by late frosts can be increased by early-blooming due to higher winter temperatures in a warming global climate [62]. Any improvement in our ability to forecast radiation and advection frost can support farmers in the management of frost protection systems. An example where understanding of microclimate and exchange processes in mountainous terrain has benefited agriculture is the existence of thermal belts [63,64]. These layers of relatively warmer air that occur over the slope at night at the top of the valley temperature inversion locally lengthen the growing season and enable crops to grow on slopes in regions where the climate is otherwise unsuitable (Figure 4).

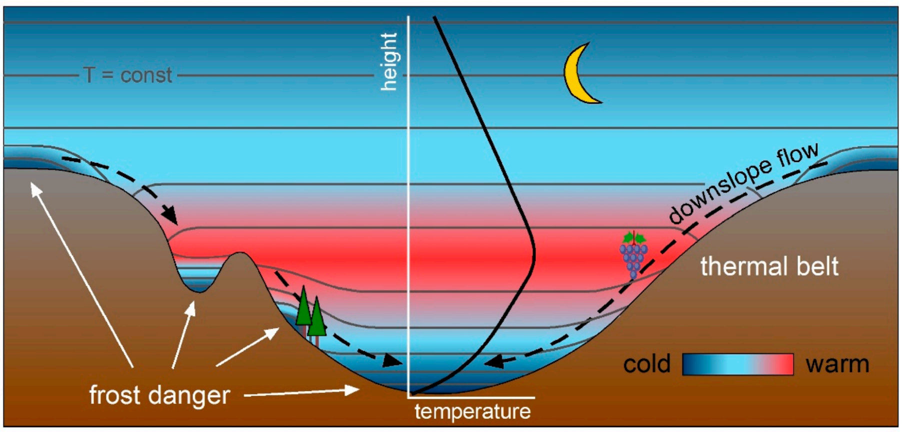

Figure 4. Illustration of airflow (dashed arrows) and air temperature distribution (isotherms and color shading) across a valley during a calm clear night. The grey lines depict the isotherms. The black solid line indicates the vertical temperature profile in the valley center. At night, the coldest air (indicated in blue) is typically found at lowest elevations in basins and valleys, in small topographic depressions along slopes, and in small areas upslope of dense vegetation. The upper slopes and ridge tops that are unaffected by cold air pooling can also be subject to frost. At the top of the temperature inversion, air is warmest (indicated in red). The thermal belt is the area on the slope around the height of temperature inversion top where it is relatively warm compared to the lower slopes and upper slopes. The thermal belt affects the growing season and agricultural management practices and provides ideal locations, for example, for vineyards.

5. Urban Planning

Many cities around the world are located within mountainous terrain. Their climates are strongly affected by dynamic, thermal, and radiative effects of the terrain, as well as by hydro-meteorological influences [65]. Cities in valleys and basins experience flooding caused by local heavy precipitation or by high river levels. Wind channeling effects and strong dynamically driven downslope flows (bora, foehn, etc.) affect human comfort in urban areas. In fair weather, cities frequently suffer from poor ventilation, resulting in various adverse effects including extreme heat and smog. Many of these effects can be alleviated by proper urban planning, which then contributes to nature conservation, healthful living conditions, prosperity within and around cities, and resilience to climate change. Examples of urban planning include the design of new water retention areas and improved rain water infiltration, improved facility siting, mitigation of heat load in cities, the delimitation of building or emission restriction zones, and the conservation or enhancement of urban ventilation under quiescent synoptic conditions [66–68].

While ventilation effects on air quality are discussed in Section 8, we focus here on the planning aspects of nocturnal cooling of cities by drainage winds. Cooler rural surrounding represents an area of compensation for urban heat islands. Under calm synoptic conditions, thermally driven mountain wind systems are the essential exchange mechanism between the urban and rural atmospheres to provide relief for a city (Figure 5). Important planning measures to ensure or improve urban ventilation are the conservation or enhancement of (1) nocturnal cold air production in the rural airsheds surrounding the city; and (2) urban ventilation paths with low aerodynamic roughness (and low emissions) to enable penetration of rural air into the city. Examples of cities where these planning measures were adopted include Stuttgart [69] and Graz [66]. To ensure consideration of urban ventilation in the process of urban development, urban climate maps have become a common tool [70].

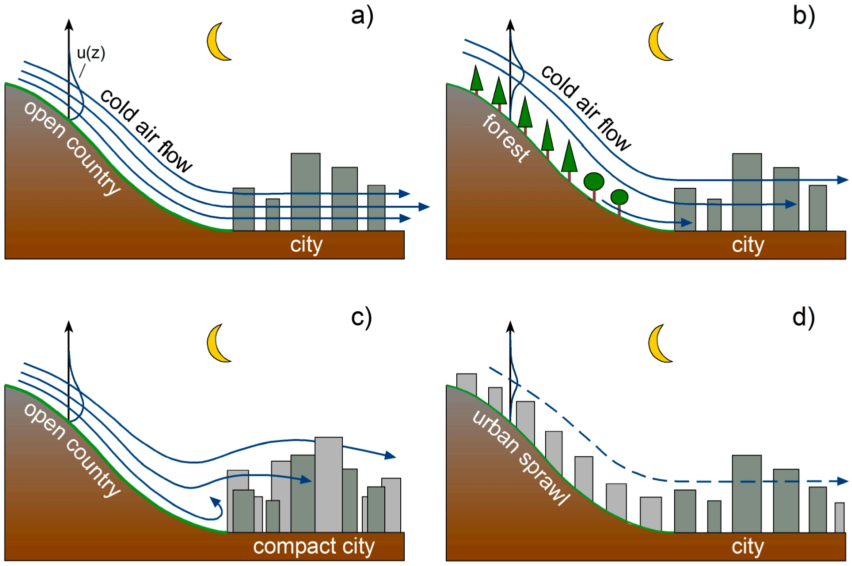

Figure 5. Schematic representation of nocturnal drainage wind ventilation in cities with different surrounding landscapes and urban planning scenarios. (**a**) Well ventilated city surrounded by open country with strong formation of local cold air; (**b**) Nocturnal ventilation of a city surrounded by forest with cold air formation at tree crown level; (**c**) A compact city with preservation of surrounding open country: the higher density among buildings causes blocking and lifting of drainage winds; (**d**) Urban sprawl scenario: strong reduction of rural cold air and drainage wind formation. Blue lines indicate stream lines and vertical profiles of nocturnal drainage winds. Green lines indicate low surface vegetation over the hillslope. Existing buildings and planned buildings are shown in dark and light grey, respectively.

Current limitations in understanding and simulating rural-urban exchange in mountainous terrain are causing many challenges for successful urban and landscape planning. Because simulated drainage winds often do not agree with observations of wind speed, vertical structure (e.g., jet-height), and flow oscillation or intermittency [71], many aspects of drainage winds are still under investigation, including the effects of slope steepness and land cover on their characteristics [72–76], their interaction with gravity waves and hydraulic jumps [77,78], and the determination of their ventilating speed and depth. Knowledge of these and other aspects of mountain exchange processes is often too limited to justify strict regulatory measures such as building and emission restriction zones, or to clarify whether urban sprawl or densification of the city are the better solution for creating additional living space in cities (Figure 5). Furthermore, many observational and computational difficulties exist to correctly capture the interaction of the small-scale drainage winds early in the night and the regional scale drainage winds later in the night with the building scale [65,79]. Numerical models need to explicitly resolve buildings and cope with extremely steep terrain, and measurements need to cover all relevant spatial and temporal scales, requiring high density of in-situ and remote sensing instruments in both the urban area and the surrounding rural landscape.

6. Wind Energy

Renewable energies, including wind energy, solar energy, and hydro power, have become an increasing fraction of the total energy supply in many parts of the world. They rely heavily on the weather, and, in the case of wind energy, primarily on wind and turbulence in the ABL. This makes wind energy an important application that benefits from an improved understanding of exchange processes over mountains. Wind and turbulence information is used in wind energy for siting wind turbines, estimating wind energy resources, and predicting wind power potential in the short term. While we focus on wind energy here, hydro power and solar energy depend on equally important effects of exchange processes over mountains—hydro power through the importance of understanding snowpack distributions and evapotranspiration, solar energy through the importance of the ABL on cloud formation.

The potential for wind energy in complex terrain is large, but complicated. Exposed sites such as ridges and escarpments, passes, and narrow valleys in mountainous terrain can be very windy and might seem suitable sites for wind energy. However, the flow in such situations is complex and associated with high levels of turbulence, making reliable energy and load predictions difficult, and in extreme cases damaging infrastructure. Vertical profiles of wind and turbulence can be very different in mountainous terrain compared to flat terrain. Ridges and valleys modify the existing flow, for example leading to speed-up of mean wind speeds and enhanced turbulence [80]. This enhanced turbulence could accelerate fatigue damage and premature failure, and the need for replacement of some components. Thermally driven mountain winds also contribute to wind power potential [81,82] and can modify wind and turbulence profiles [71]. Observing and simulating these vertical profiles in mountainous terrain continue to be a challenge.

Full-scale experiments of wind flow around hills and escarpments have been performed successfully [83,84]; there has also been a renewed interest in complex terrain field-experiments [85]. An important goal of these experiments is to provide measurement data for the validation of the models used, for example, to produce the "New European Wind Atlas" [85]. Numerical simulations and wind tunnels make it possible to study problems systematically in great detail [86], but the understanding gained from these experiments in controlled environments still needs to be verified in real situations.

For the purpose of wind power meteorology, landscapes can be divided into flat, hilly, and mountainous terrain [87]. In flat terrain, orographic influences are minimal, and the roughness length and nearby obstacles are the most important modifiers of the flow. In hilly terrain, linearized models provide accurate results of the flow and there are benchmark data sets for the testing of flow models in this type of landscape (single and isolated hills) [88]. In mountainous terrain, flow separation occurs and the entire ABL is strongly influenced by the terrain. Simple linearized models have numerous limitations in steep terrain, including an overestimation of the speed-up and the inability to predict strong turbulence. Given rapid advancements of computer performance, linear flow models are gradually being replaced by nonlinear numerical models that require more detailed field data for proper validation and further development. Reynolds-averaged Navier–Stokes and large eddy simulation (LES) models are now widely used for simulating flow over mountainous terrain [89,90].

Estimating wind speed and turbulence profiles at specific locations in mountainous terrain is challenging. Even minor changes in topography or ambient atmospheric conditions can have a large impact on the flow at the location of a wind turbine (Figure 6). The prediction errors in wind speeds and power production at locations in mountainous terrain have been expressed in terms of a ruggedness index, which is defined as the percentage of the terrain steeper than some critical slope [91]. When hills and mountains are forested, understanding of flow and turbulence profiles becomes even more challenging. Consequently, producing a wind atlas for mountainous areas is difficult [92]. All these challenges represent important areas for future research related to atmospheric exchange processes over mountainous terrain.

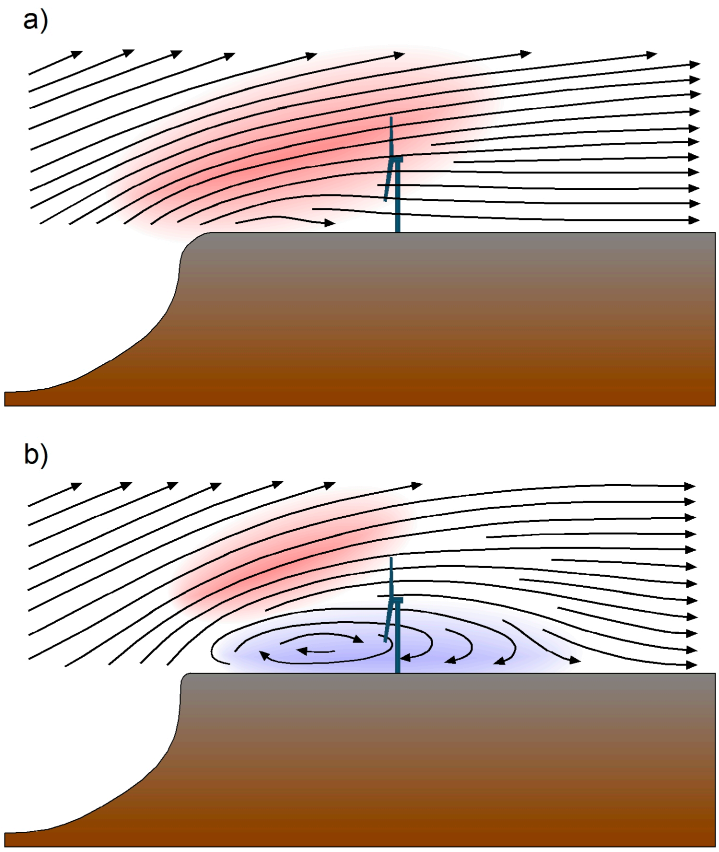

Figure 6. Airflow illustration of the mean flow field over topography with a rounded edge (**a**) and a sharp edge (**b**). Red and blue shading indicate areas with strong and weak horizontal winds, respectively. Adapted from [86].

7. Transportation

Influences from weather and climate pervade the transportation industry, including road, rail, and air transportation. Atmospheric conditions determine safety, operability, efficiency, and operational tactics on short time scales and can shape business plans, engineering, construction, and other more strategic efforts on long time scales. Many of transportation's sensitivities to weather and climate reflect basic challenges in understanding, modeling, and modifying operations in response to exchange processes in the surface and boundary layers. Prime examples of atmospheric conditions that affect the transportation industry and for which knowledge of mountain exchange processes is crucial include visibility, winds, and turbulence.

Clouds and precipitation that obscure visibility might be thermally or mechanically forced by local processes tied to orography and land cover. Fog is a serious problem in mountainous environments. Predicting precisely when and where it will form and dissipate still confounds the most advanced operational numerical models [93]. Snow on the ground can reduce visibility when lofted, transported, and deposited by wind that is often turbulent and directly influenced by land cover and topography. Small changes in surface roughness can translate to large changes in transport of snow crystals [94], as can changes in the cohesive properties of the top snow layers [95,96]. Snowdrifts obstruct roads and railways and can hinder operations around infrastructure at airports and seaports. More violent, unpredictable, and less easily managed obstructions include avalanches of snow and ice, and slides of rock and mud, which can necessitate very costly closures of critical transportation arteries through mountain ranges. In arid and semi-arid mountainous regions, dust and sand can also be lifted by strong thermally and/or dynamically induced winds, creating thick clouds of particles that reduce visibility. Local static stability, ground cover, soil composition, and soil moisture all play important roles in the exchange processes that give rise to visibility reduction by snow and dust.

Wet, snowy, and icy surfaces caused by moist atmospheric processes over and near mountains [2] reduce surface traction for vehicles [97]. Forecasting precipitation is a challenge by itself. Even more challenging is forecasting the freezing, melting, evaporation, and sublimation of precipitation on the ground, which are partly governed by local surface fluxes of energy and mass. Only a few examples exist of forecast models that have been developed specifically for road temperature and road condition in mountainous terrain [98]. Strong and gusty cross winds are also a major threat to ground transportation causing carriages or trucks to be blown off the track, cable, or road [99].

Wind and turbulence over mountains are very important to the aviation industry. The needs of commercial and general aviation have driven decades of applied research on atmospheric turbulence related to flight [100,101]. Turbulence in the free atmosphere has so far received more attention in aviation than turbulence in the ABL. However, the explosive proliferation of unmanned aerial vehicles (UAVs) will require a better understanding of low-level turbulence [102]. Not only does characterizing the responses of small airframes to turbulence present new challenges, at low altitudes local surface-atmosphere exchange processes and the structure (e.g., static stability) of the ABL are more important than at the flight levels of larger aircraft [102]. Even more demanding are cases of UAVs operating in or near urban areas in mountainous settings, where coherent structures and turbulence result from the complex superposition of phenomena across scales (Figure 7).

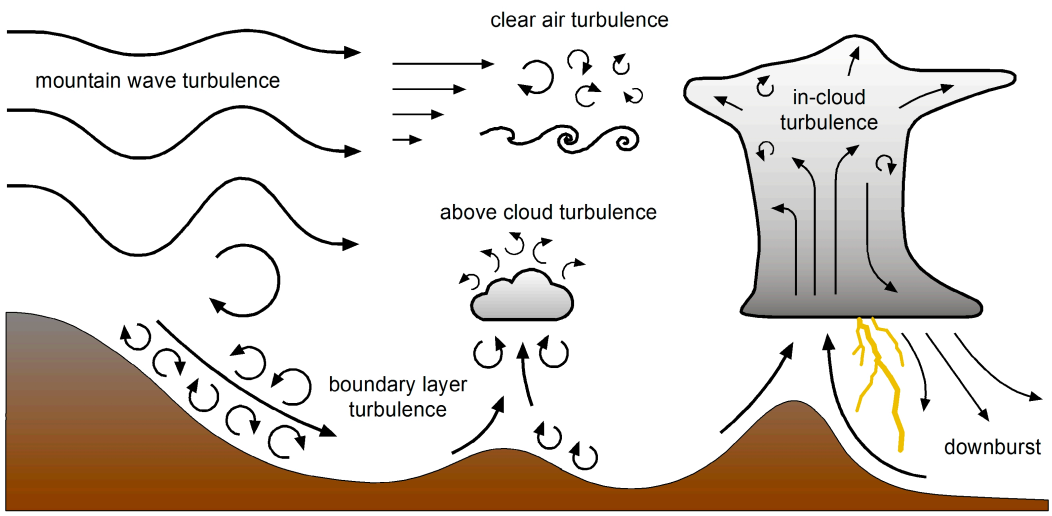

Figure 7. Some turbulence features over and near mountainous terrain relevant for aviation (adapted from [103]).

Even when wind and turbulence in mountainous terrain do not threaten to crash UAVs, these processes can still jeopardize flight missions. Navigating headwinds and maintaining controlled, level flight through flow and turbulence drains batteries and fuel tanks, limiting the times and distances small aircraft can travel. Basic research activities in atmospheric exchange processes over mountains that would lead to better forecasts of wind and turbulence in mountainous terrain would therefore be very beneficial for the transportation industry.

8. Air Pollution

Air pollution is an issue in many areas with complex topography. The need to better simulate air pollution concentrations in mountains has been a major motivation for many past field experiments. High pollutant concentrations are typically determined by reduced mixing in the lower atmospheric layers, especially of contaminants emitted close to the ground [104,105]. This reduced mixing may be the consequence of either strong atmospheric stability, calm winds, or both. Over complex terrain, a variety of dynamical and thermodynamical processes (shown in Figure 8) may affect stability and wind patterns and subsequently the transport of atmospheric pollutants in different ways [71,106]. Air pollution does not just comprise emissions from anthropogenic sources such as odour from pig farms [107], it also comprises natural sources such as aerosol dust [108] and smoke from wildfires [109,110] as described in Section 3. Air pollution in mountainous terrain is inextricably linked to transport and mixing processes.

Mountain valleys are often the main transit corridors connecting major cities, or even entire countries, leading to intense traffic flows and emission of pollutants at ground level. Other typical sources of air pollution are settlements, infrastructure, and industrial activities usually based on the valley floor. Up-valley winds may transport highly polluted air into the upper reaches of valleys during daytime, whereas down-valley winds may have a cleansing effect at the valley exit over the plain during nighttime. In addition, up-slope flows may transport primary pollutants, or precursors of secondary pollutants, to higher levels in the atmosphere where they are subject to synoptic-scale transport, or are simply carried over to adjacent valleys. Various mechanisms for transporting air pollutants from the surface to the free atmosphere over mountains have been summarized in [111,112]. The transport of primary pollutants, or even precursors, to higher elevations may lead to high concentrations of secondary pollutants (e.g., ozone) over elevated regions, where the different exposure to higher radiation levels and/or ambient conditions may affect chemical reactions and pollutant transformation [113–116]. High levels of ozone over elevated regions may also be favored by emissions of biogenic volatile organic compounds from forested areas [117]. Many monitoring stations for air chemistry and greenhouse gases are located on mountain tops, which can be affected by these mechanisms [118]. This has led to the development of approaches to distinguish local effects due to atmospheric exchange processes from background concentrations measured at mountain top locations [119,120]. These approaches would greatly benefit from new datasets to explicitly characterize these exchange processes.

The presence of an urban area in a valley can impact exchange processes and air pollution concentrations. In particular, urban areas can affect the development of the ground-based temperature inversion at night due to the presence of the urban heat island [121,122]. Moreover, Rendon et al. [123] showed that temperature inversion break-up in a valley can be significantly modified by urbanization, affecting air quality and the cross-valley wind system.

In closed basins, nocturnal radiative cooling favors the convergence of cold air towards lower areas, and the build-up of extended and deep cold pools [124–126]. These situations typically occur under anticyclonic weather conditions, with clear sky (favoring higher net losses of long-wave radiation, and therefore more surface cooling) and weak synoptic winds. While these cold pools typically break up during the morning in the summertime, they may persist for several days during winter, potentially leading to episodes with high levels of air pollutants [127,128]. Also, the persistence of ground-based thermal inversions over snow-covered areas may enhance photochemical reactions and ozone formation, due to the high reflection of incoming solar radiation [129]. An opposite situation may occur in narrow valleys with reduced sky-view factors, especially during wintertime, when the weak solar radiation input may inhibit ozone formation, leading to high levels of nitrogen oxides. The need to improve forecasts of episodes with high levels of air pollutants in urban valleys and basins has spurred a number of research projects [130–132].

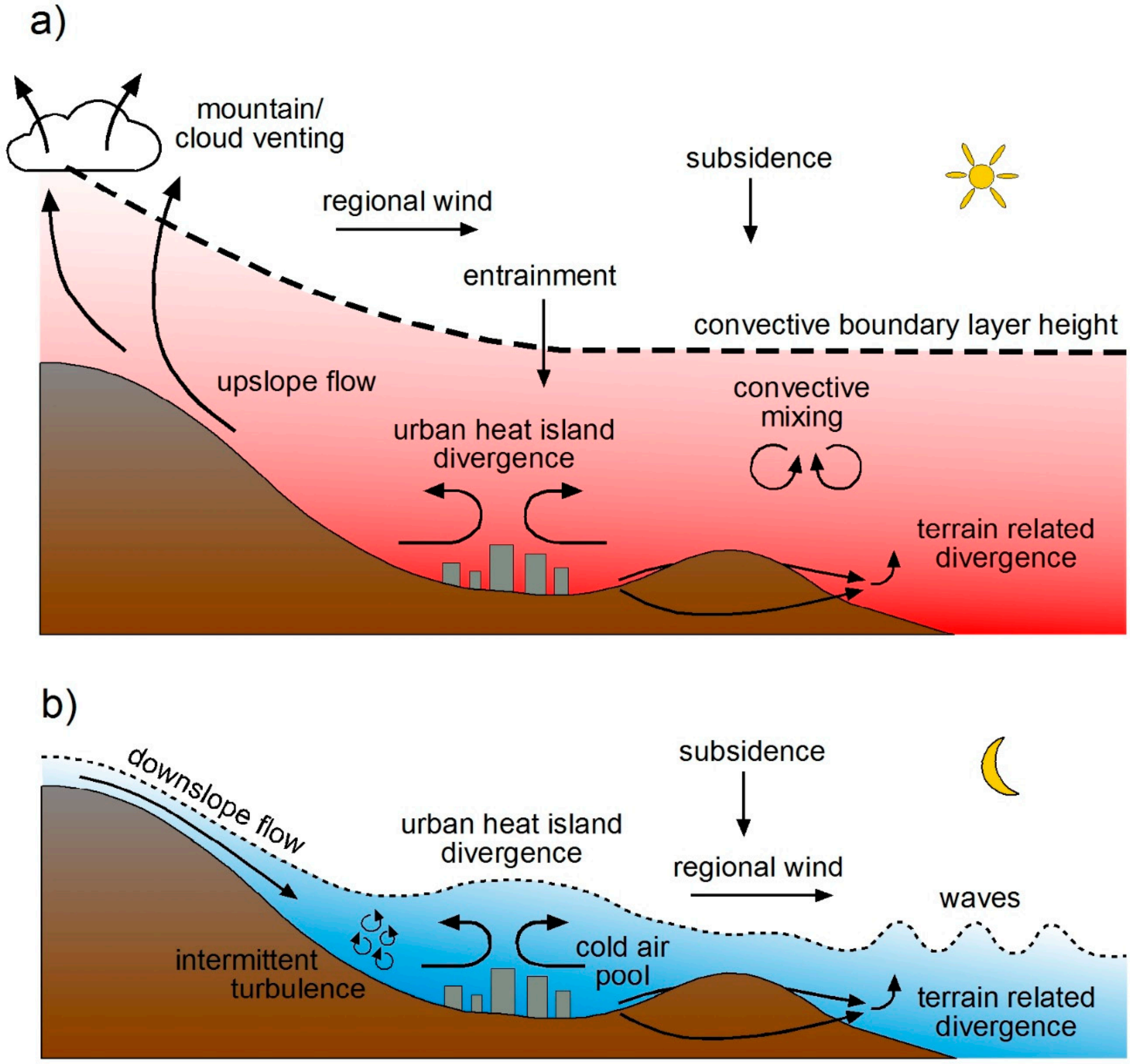

Figure 8. Schematic representation of processes affecting the dispersion of air pollutants in an unstably (**a**) and stably (**b**) stratified boundary layer over complex terrain. Note that similarities between daytime and nighttime situations are the synoptic-scale subsidence, the urban heat island divergence (caused by the relatively warm urban areas compared to the surrounding areas), the regional wind, and the terrain related divergence (caused by the westerly regional wind).

While the previous examples focused on how exchange processes affect air pollution, the relationship can also be in the opposite direction: pollution itself can affect exchange processes. Most natural aerosols and pollutants are concentrated in the ABL and reduce incoming shortwave radiation over the lower mountain slopes (surface dimming) potentially affecting the strength of thermally driven flows and atmospheric stability. The previously mentioned mountain venting can transport aerosols to high elevations, causing excessive levels, for example, of black carbon at 5 km in the Himalayas during the pre-monsoon season [133] and above 10 km over Tibet and much of central Asia during convective monsoon activity [134]. These elevated layers of aerosols absorb radiation, thereby changing atmospheric stability, and also decrease the surface albedo when deposited on snow [135]. Furthermore, land-use changes can cause dust to be transferred into the atmosphere and transported by wind into the mountains where it settles on snow, reducing albedo and leading to faster snow melt rates and enhanced warming at higher elevations [136,137].

Also, air pollutants may modify physico-chemical processes governing wet processes. High concentrations of air pollutants may significantly affect cloud microphysics, chemistry, and precipitation rate in cold clouds [138] or in fog-water [139] over elevated mountain regions. Air-pollution aerosols, incorporated in orographic clouds, slow down cloud-drop coalescence and riming on ice precipitation, and hence delay the conversion of cloud water into precipitation [140]. This mechanism explains the observed large loss of precipitation at the midlevel of the upwind slopes, smaller losses at the crest levels, and enhancement at the downslope side of the hills.

This section demonstrates that air pollution is yet another example of an important meteorological application benefitting from studies of atmospheric exchange processes over mountains. It is therefore not surprising that addressing issues relevant to air pollution has been and continues to be a major driving force behind these studies.

9. Climate Change

The order of the applications discussed in the previous examples was chosen such that the applications increasingly emphasize transport and mixing processes higher up in the ABL. We recognize that this categorization is highly simplified and that often an application is sensitive to the entire range of atmospheric processes from the surface to the ABL and beyond. One such application is climate change, to which mountain areas are particularly vulnerable [141]. Climate change in mountains is altering precipitation patterns, reducing snow levels, accelerating glacier and permafrost melting, intensifying floods, and increasing droughts [141–143]. Various aspects of climate change have a direct or indirect relationship with exchange processes in mountainous terrain. For example, higher temperatures cause tree- and snow lines to migrate upslope, reducing surface albedo. The larger available energy at the surface enhances warming of the ground and of the atmosphere around the retreating tree- and snow lines, causing a positive feedback. This albedo feedback has been suggested as a major reason for the observed amplified rate of warming with elevation (Figure 9). Numerical studies provide evidence of the importance of this surface-based feedback [144], but also illustrate the uncertainty in the strength of the feedback in current models [145]. Elevation dependent warming of the surface induces changes in atmospheric stability that can have an impact on thermally driven flows and ABL mixing [146]. These, in turn, have an impact on aerosol transport in mountainous terrain. Surface-atmosphere feedbacks involving reduced snow cover and soil moisture in early summer can also explain decreases in precipitation in alpine regions in future climate [147]. An improved understanding of atmospheric exchange processes in mountains could quantify the strength and importance of these feedbacks and improve their representation in climate models.

Local climates might not respond in the same way to global climate change as regional-scale climates. An example where the impacts of global climate change might locally be reduced are the cold air pools that were mentioned previously in this paper. At slope and ridge-top locations, air temperatures are highly coupled to changes in synoptic circulation patterns, contrary to temperatures in valley bottoms [148]. The cold air pooling in valley bottoms at night and during winter causes temperatures to be largely decoupled from synoptic flow variations. This decoupling causes local variations in temperature increase due to climate change that are less spatially coherent than the temperature increases predicted by global and regional models [148]. Because cold air pooling and consequent atmospheric decoupling occur in many valleys and basins, it is important to consider this process in efforts to understand the impacts of climate change in mountainous regions.

Many more examples of climate change impact studies benefitting from knowledge of atmospheric exchange processes over mountains exist, including the retreat of glaciers, changes in synoptic wind patterns, and increased frequency of droughts and floods. Addressing the many hypotheses that emerge from climate change impact studies strongly motivates future projects on atmospheric exchange processes over mountains.

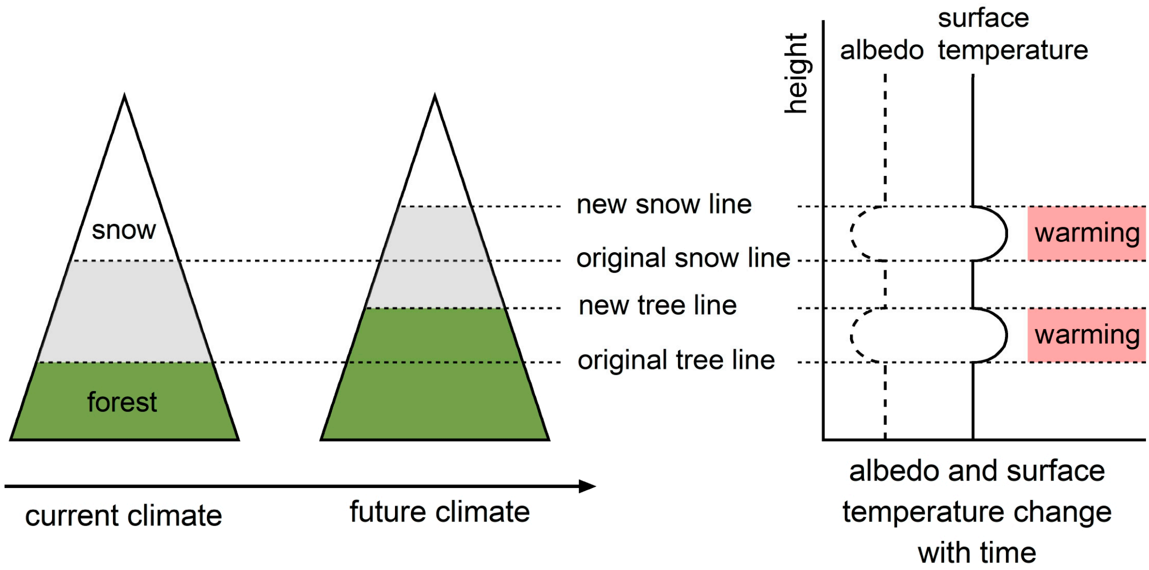

Figure 9. A positive albedo feedback mechanism to explain elevation dependent warming due to climate change. Climate change decreases albedo at altitudes with upslope propagating snow- and tree lines. A decrease in surface albedo changes the surface energy balance causing an increase in surface temperature (partially adapted from [26]).

10. Conclusions and Thoughts on Future Research

We asserted in this paper that improving our understanding, observations, and simulations of atmospheric exchange processes over mountains provides many benefits for a variety of meteorological applications. Our commentary followed the structure in Figure 1, with applications ranging from those with a focus on land-atmosphere interactions to those with a focus on transport and mixing processes in the ABL.

The benefits that were discussed are often not unique to a single specific application, but apply to several simultaneously, and collectively inform the needs for future research in atmospheric exchange processes. For example, an improved simulation of cold air pools can be considered a benefit to ecology, agriculture, urban planning, air pollution, and climate change impact applications, with the collective need for an improved representation of the effect of small-scale drainage flows in NWP models.

Research of atmospheric exchange processes over mountains must involve the investigation of processes occurring at many different spatial and temporal scales, ranging from turbulent transport and mixing to synoptic-scale winds, and their interaction with thermally induced and terrain driven flows. An improved comprehension of these processes helps us better understand and model complex temperature and precipitation patterns, snow redistribution, renewable energy and water resources availability, urban ventilation, air pollution concentrations, carbon budgets, and aviation turbulence, among many other applications of weather and climate.

This paper has touched on a few examples of how urban environments are a consideration in studies of exchange processes over mountains, including ventilation and air quality. Yet the topic is potentially much more complex and societally relevant than even those examples suggest. By 2030 60% of the planet's population are expected to be living in cities, 41 of which will host more than 10 million people [149]. Some of these cities will be among or near mountains. Yet, much remains unknown about the multiform interplay between atmospheric exchange processes characteristic of urban environments and those which are characteristic of mountainous environments. The planet's growing population and projected increases in environmental stressors will also heighten the importance of applications related to food security and water security [150].

The applications that were discussed in this paper use output from a variety of atmospheric models ranging from general circulation (or global climate) models (GCMs) with time scales of many years to microscale LES models with time scales of seconds to hours. Output from these models is used in applications such as hydrology, urban planning, transportation, wind energy, and air pollution studies to provide input to application-specific models. Parameterization schemes in atmospheric models are subject to many uncertainties and are often empirically tuned. These uncertainties need to be considered for various applications. For example, accurate forecasting of air pollution concentration requires simulations that can represent the effects of, or resolve explicitly, exchange processes at many spatial scales. Parameterization schemes for this purpose derived from experimental campaigns in flat terrain might be invalid over complex terrain [90]. The parameters in these schemes are therefore sometimes modified/tuned, or additional parameters are added. This has been done, for example, to represent some orographic effects in a surface layer scheme for improved simulations of surface wind speeds in complex terrain [151], and in an ABL scheme for an improved representation of dispersion processes in an alpine valley [152]. However, few if any large-scale datasets exist with which to evaluate these parameterizations in complex terrain.

Consequently, there is a critical need for observational data to support theory and model development. These data should come from long-term measurements at fixed locations as well as from short-term measurements at high spatial and temporal resolution. Observations in mountainous terrain are often sparse and unrepresentative of the surrounding region. Therefore, using data to initialize and provide boundary conditions to NWP models, to evaluate parameterizations, to verify forecasts, and for data assimilation provides many challenges in mountainous terrain [6,7]. Higher resolution, more accurate, and new types of surface and atmospheric data resulting from innovations in sensor technology combined with new satellite missions and the emerging use of autonomous vehicles, are providing opportunities for novel data sets that can be used in the various applications and in basic research. The increased use of autonomous ground and air vehicles, in turn, will require specific forecasts to ensure energy efficient and safe operations in complex terrain.

Many applications in the earth system sciences, including hydrology and ecology, use surface and near-surface data at high spatial resolution. An important question is the required spatial resolution to appropriately capture processes and their feedbacks with regional and global significance. This question is unanswered for atmospheric exchange processes over mountains [153–155]. Many interpolation methods have been developed to provide meteorological surface data at the appropriate resolution for specific applications. Some methods rely on observational data [156–158] while others use NWP model output or a combination of NWP model output and observations [159,160]. Some of these methods have also been developed with specific applications in mind, such as wildfire management [161] for which wind estimates at 10 m above ground are very important. Interpolating from the gridded output from models to the point of interest is challenging. Even for high resolution models, interpolation errors can be large in steep terrain with heterogeneous land cover, especially when model grid points are near the tops of ridges and mountains where the difference in actual and simulated altitude can be tens to hundreds of meters. Furthermore, it is often difficult to determine how accurate the interpolated point values are and how their accuracy could be improved by making observations at strategic/targeted locations. Surface observations are often made in mountain valleys and sometimes on mountain ridges, but less frequently on slopes. It is currently unknown what sampling strategy and station density would optimally balance practicality and utility, and how these factors depend on the surface and atmospheric variables needed for the various applications. In addition, the efficacy of statistical methods at representing changes at fine spatial scales is unknown, and better understanding of atmospheric exchange processes could aid in both the evaluation of such statistical models and in the development of physically based quasi-dynamical models [162].

Projection of climate change impacts was discussed as an application that benefits from an improved understanding of exchange processes in mountains. Studying the impacts of climate change requires accounting for interactions and feedbacks at many spatial and temporal scales, from the surface to the ABL and beyond. Currently, many of these interactions and feedbacks are only hypothesized and investigated with models that do not properly represent the effects of atmospheric exchange processes. The complexity of exchange processes over mountains is still only partly understood, and much research needs to be done to improve the representation of these processes in weather and climate models aimed at applications. We anticipate that better understanding of the impacts of climate change and reducing the uncertainty in climate projections will increasingly motivate more exploration of exchange processes in mountains, just as air pollution has traditionally been (and continues to be) a major motivation.

Increased awareness of the benefits of improved understanding of atmospheric exchange processes over mountains can be established by enhanced interactions between scientists studying these processes and stakeholders representing many other scientific disciplines and economic sectors. These efforts will ensure that the most important questions are addressed in new international initiatives that aim to improve our understanding of exchange processes over mountains.

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