describes turbulent exchange between the surface and atmosphere over HHF terrain[1] and is used in almost all weather and climate models. Vertical turbulent transport dominates the exchange over HHF terrain (e.g., over the plains of Kansas, where one of the major ABL experiments took place in the late 1960s). Early theoretical concepts of Reynolds, Prandtl, and Taylor (and many others) grew out of laboratory experiments and naturally could make the assumption of horizontal homogeneity. In turn, the concept of “a homogeneous grid cell” in numerical models corresponds to the essential numerical assumption of discretization. In the early days of numerical modeling, when grid cells in numerical weather prediction (NWP) models typically had dimensions on the order of 100 × 100 $\text{km}^2$, subgrid horizontal homogeneity was naturally assumed, and parameters characterizing the efficiency of the ABL exchange did not have much in common with their actual physical counterparts but were mere tuning parameters. Correspondingly, and owing to available observational technology, atmospheric observations focused for many decades on the vertical characterization of the atmosphere, thus failing to capture the local horizontal inhomogeneity.

What is certain with respect to exchange processes over mountainous terrain is that the surface forcing cannot be horizontally homogeneous since the surface is not flat. Any imaginable terrain configuration would induce some degree of heterogeneity owing to the influences of differential insolation on opposite sides of a valley, background cross-valley or cross-mountain winds, or variations in soil moisture and land cover, for example. Mountainous terrain inevitably leads to non-HHF surface conditions, therefore we cannot a priori assume our current description and understanding of turbulent exchange to be appropriate or adequate. Furthermore, over non-HHF surfaces turbulent exchange is not necessarily limited to the vertical, so that simple one-dimensional similarity theory is unlikely to be appropriate. This means that when numerical models use surface exchange parameterizations based on the HHF paradigm, they are unlikely to correctly capture the exchange of energy, mass, and momentum over mountainous terrain.

If deviations from the “truth” were systematic (e.g., if exchange was generally more efficient over complex than HHF terrain) this would mean that the large-scale distribution of energy, mass, or momentum would be biased, thus leading to systematic errors. Conversely, if the differences were only random this would lead to an inadequate description of the local atmosphere over mountains, but possibly not to systematic differences in the global (or regional) budgets of energy, mass, and momentum.

In a recent survey (Reynolds et al. 2019), WGNE (Working Group on Numerical Experimentation, one of the interdisciplinary bodies of WMO) identified the largest sources of errors in atmospheric modeling and reported “surface fluxes/surface temperature diurnal cycle” as the second most critical issue (after convective precipitation). These errors probably do not solely reflect the difficulties faced in modeling surface exchange in mountainous terrain, but the mountains certainly contribute their share.

Given the central role of the ABL in effectuating the exchange of energy, mass, and momentum in the climate system, and the likely inappropriateness of our traditional HHF-inspired treatment of ABL processes, we emphasize the importance of the mountain boundary layer (MoBL) and highlight the need to systematically investigate its characteristics. The sidebar “Mountain boundary layer” summarizes some of the pertinent properties of the MoBL.

## The scope for TEAMx

Based on the importance of the ABL in governing exchange between the land surface and the atmosphere and the large uncertainties still associated with exchange over complex terrain, the time has come for a collaborative effort to improve our understanding of MoBL

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[1] Clearly, there are remaining challenges in the application of similarity theory even over flat terrain, such as the very stable boundary layer. These challenges can, however, at least be addressed from a solid theoretical basis—which is not the case for complex terrain.

processes and their description in numerical models, thereby exploiting recent advances in both observational techniques and numerical modeling capability (e.g., Emeis et al. 2018).

TEAMx stands for Multi-Scale Transport and Exchange Processes in the Atmosphere over Mountains–Programme and Experiment. TEAMx is a bottom-up financed international research program, based on the hypotheses that (i) *transport and exchange of energy, mass and momentum over mountainous (complex) terrain are critical to weather and climate*, yet (ii) *the corresponding processes are not well understood*. The first hypothesis is supported by various examples pertaining to different scales and their interactions—see the sidebar "Is exchange over mountains relevant?" More detail can be found in a series of review papers (Zardi and Rotach 2021), which were solicited on topics ranging from "the boundary layer structure and processes over mountains" and "orographic convection" to "numerical modeling, observations and applications in Earth system modeling [over mountains]." Based on this review effort, a white paper has recently been published in which the different scales (from near-surface turbulence to the meso-$\alpha$ scale of a mountain range, and from short-range weather to climate time scales), their interactions, their relevance for surface–atmosphere exchange over mountains, and our ability to model them are discussed in detail (Serafin et al. 2020). Naturally, the white paper also identifies the

## The mountain boundary layer (MoBL)

Lehner and Rotach (2018) have defined the mountain boundary layer (MoBL) as "the lowest part of the troposphere that is directly influenced by the mountainous terrain, responds to surface and terrain forcings with timescales of about one to a few hours, and is responsible for the exchange of energy, mass, and momentum between the mountainous terrain and the free troposphere."

We first note that the definition based on time scales overlooks the relevance of length scales that characterize the orography. The reason for this is the attempt to modify the definition of the traditional (i.e., HHF) ABL (Stull 1988) as little as possible. However, due to the relevance of diurnal and semidiurnal processes (e.g., thermally driven winds and corresponding advection), the "one hour or less" time scale from Stull (1988) for HHF surfaces was extended in order to include the relevant processes—and their interactions—at the various time and spatial scales.

Second, the traditional definition of the ABL does not specify its role in the climate system, while the MoBL is defined as *the layer that is responsible for the exchange between the mountainous terrain and the free troposphere*. While it is implicit that exchange in the ABL over HHF is turbulent, exchange in the MoBL is not the result of turbulence alone. Taking the "meso-$\gamma$" panel of Fig. 1 as an example, we see that mesoscale motions (such as slope-flow or along-valley flow) are influenced by the terrain and strongly contribute to the exchange, but they cannot be characterized as pure "turbulent exchange." Thus, it does not simply suffice to extend similarity theory to spatially inhomogeneous conditions (which prevail over most parts of the Earth's land surface). Rather, a crucial ingredient of the MoBL is *interactions of processes at different spatial and temporal scales*. Near the surface there is generally a turbulent layer, which we may call the "*local boundary layer*" and the characteristics of which we might assess based on traditional boundary layer methodology. The total exchange of energy, mass, and momentum between the surface and free troposphere, however, is the sum of the exchange in the local boundary layer, the contributions of the mesoscale processes and the interactions between them. This is a formidable four-dimensional problem.

The height of the traditional ABL can conveniently be defined as the level where turbulence strength (measured, for example, in terms of turbulence kinetic energy) diminishes or its turbulent mixing is no longer detectable. Common detection algorithms for ABL profiling observations typically yield the local boundary layer height. The height of the MoBL, conversely, is not tied to turbulence alone. Determining the height up to which mixing is noticeable in mountainous terrain requires a suitable tracer and measurement strategy which reaches high into the atmosphere (e.g., De Wekker and Kossmann 2015). The spatial variability of the MoBL height, criteria to diagnose it, and processes that determine it are important challenges that will be addressed in TEAMx.

Note that the investigation of the lowest portion of the atmosphere over mountainous terrain has a long and rich history. Thermally driven mountain flows like valley or slope winds (e.g., Zardi and Whiteman 2013), dynamic modifications such as gravity driven currents, or stagnant situations like cold air pools have been investigated in depth [see Whiteman (2000) for an excellent overview]. Turbulence characteristics in the ABL have been investigated over complex terrain corresponding to the smallest scales of Fig. 1 (Finnigan et al. 2020), but less for steep mountainous terrain and interactions with the larger (sub)mesoscales. MoBL investigations extend this precious knowledge and will focus more strongly on the role of the lowest layer as a mixing agent in the climate system.

most relevant gaps in knowledge. Figure 1 illustrates some of the spatial scales, exchange processes, and interactions discussed.

Mountains have been known to impact the atmospheric state—and hence weather and climate—for a long time. Processes such as lee cyclogenesis, orographic precipitation, downslope windstorms ,or gravity waves have therefore been studied in previous international mountain meteorology programs such as the Alpine Experiment (ALPEX; GARP 1986) or the Mesoscale Alpine Programme (MAP; Bougeault et al. 2001). These programs have typically addressed questions such as "how is the atmosphere [as a whole] modified by the presence of a mountain?" However, given the relatively large dominant atmospheric scales of interest, near-surface exchange processes continued to be treated with the traditional (HHF) concepts.

Since computing power has reached the point where we are now employing convection-permitting numerical models for operational NWP and even some pioneering convection-permitting regional climate simulations (e.g., Ban et al. 2021), our focus has naturally shifted to smaller scales. It is no longer sufficient to know how the presence and shape of a mountain together with the atmospheric conditions impacts, for example, the predictability of the onset of foehn (weather) or the long-term distribution and intensity of precipitation (climate). Rather, we are *additionally* interested in accurately knowing the local atmospheric state when these mountain-induced atmospheric phenomena occur—and due to advances in observational technology we can start to properly address the relevant physical processes. The objective of TEAMx is thus to gain a better understanding and consequently an improved representation in numerical models of the near-surface exchange of energy, mass, and momentum resulting from processes at different spatial scales (Fig. 1) and, importantly, the interactions between these scales.

Traditionally, in atmospheric sciences this would motivate the call for denser and more detailed observations to assimilate into high-resolution numerical models as well as to improve process understanding. While it is certainly appropriate to address the need for high-resolution information with high-resolution observations, there are four important challenges in mountainous terrain. First, setting up and maintaining observations is more demanding due to harsh environmental conditions, limited accessibility, or poor network coverage for data transfer, for example—and hence more expensive. Second, the spatial inhomogeneity makes it even more difficult to select "representative locations" than in flat terrain (for each of the processes a different setting may be representative). Third, to assess the local state of the atmosphere, three-dimensional turbulence information is required. Fourth, many experimental techniques have been established based on HHF terrain and may not be directly applicable to more complex settings.

Fortunately, recent advances in observational technology are providing solutions to some of these challenges. For example, arrays of surface-based lidars combined with high-resolution satellite-retrieved information and/or airborne data can be used to characterize the spatial structure of the near-surface atmosphere in unprecedented detail (e.g., Fernando et al. 2019; Adler et al. 2021). However, the high costs for the needed personnel and instrumentation call for collaborative efforts with common measurement platforms and shared algorithms, as well as for a coordinated observational plan and research agenda.

Altogether, this means that the fine structures of the variability in complex terrain must be explored in a concerted effort among many institutions. Only with the required large number of instruments and infrastructure can we learn more about processes and their interactions at the relevant scales over certain characteristic features of mountainous terrain (the valley floor, the slope, the ridge/crest, etc.). This will be achieved through the TEAMx Observational Campaign (TOC), a year-long effort (spring 2024–25, Fig. 2) to study the atmosphere over a number of target areas in the central Alps.