BAMS
Essay

A Collaborative Effort to Better Understand, Measure, and Model Atmospheric Exchange Processes over Mountains

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ABSTRACT: In this essay, we highlight some challenges the atmospheric community is facing concerning adequate treatment of flows over mountains and their implications for numerical weather prediction (NWP), climate simulations, and impact modeling. With recent increases in computing power (and hence model resolution) numerical models start to face new limitations (such as numerical instability over steep terrain). At the same time there is a growing need for sufficiently reliable NWP model output to drive various impact models (for hydrology, air pollution, agriculture, etc.). The input information for these impact models is largely produced by the boundary layer (BL) parameterizations of NWP models. All known BL parameterizations assume flat and horizontally homogeneous surface conditions, and their performance and interaction with resolved flows is massively understudied over mountains—hence their output may be accidentally acceptable at best. We therefore advocate the systematic investigation of the so-called "mountain boundary layer" (MoBL), introduced to emphasize its many differences to the BL over flat and horizontally homogeneous terrain.

An international consortium of scientists has launched a research program, TEAMx (Multi-Scale Transport and Exchange Processes in the Atmosphere over Mountains–Program and Experiment), to address some of the most pressing scientific challenges. TEAMx is endorsed by World Weather Research Programme (WWRP) and the Global Energy and Water Exchanges (GEWEX) project as a "cross-cutting project." A program coordination office was established at the University of Innsbruck (Austria). This essay introduces the background to and content of a recently published white paper outlining the key research questions of TEAMx.

KEYWORDS: Mass fluxes/transport; Mesoscale processes; Orographic effects; Topographic effects; Turbulence; Climate prediction

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The atmospheric boundary layer (ABL) couples the Earth's surface and atmosphere, maintaining the exchange of energy, mass, and momentum between these two systems. On a global scale, processes in the ABL determine the efficiency of the water cycle, the global energy balance, and the carbon and momentum budgets. At regional scale, the relative efficiency of individual exchange processes contributing to the total exchange at different locations (see Fig. 1), together with the availability of the exchanged properties (e.g., latent heat exchange over the ocean versus that over land), lead to spatial differences in the energy, mass, and momentum distribution and hence affect atmospheric dynamics and composition.

Areas characterized by complex terrain cover up to 50% of the Earth's land surface, depending on how complexity is defined (Rotach et al. 2014), and they are unevenly distributed. Therefore, if mountainous terrain (which certainly *is* complex) should alter the exchange efficiency, this would impact not only our understanding of mountain weather and climate itself, but also the state of the atmosphere. In this contribution we argue that *we cannot a priori assume that the exchange over mountainous terrain is governed by the same processes as that over flat and homogeneous terrain*. In other words, if our current understanding of the exchange processes for energy, mass, and momentum is not appropriate (e.g., Rotach et al. 2015), or they are not resolved in numerical models, substantial errors can result—not only locally, but even on a regional to global scale. Even when compared to flat but inhomogeneous terrain, mountains add complexity to the processes by which exchange occurs. For example, gravitational flows require specific treatment, the radiation receipt varies depending on slope aspects, thermally driven flows with strong daily and seasonal cycles also generate 3D spatial variability, airflow is deflected around orography of a range of scales resulting in a variety of phenomena (e.g., rotors, gravity waves)—and there are interactions between these processes. Hence, we make a case for increased research efforts dedicated to improved observations, weather

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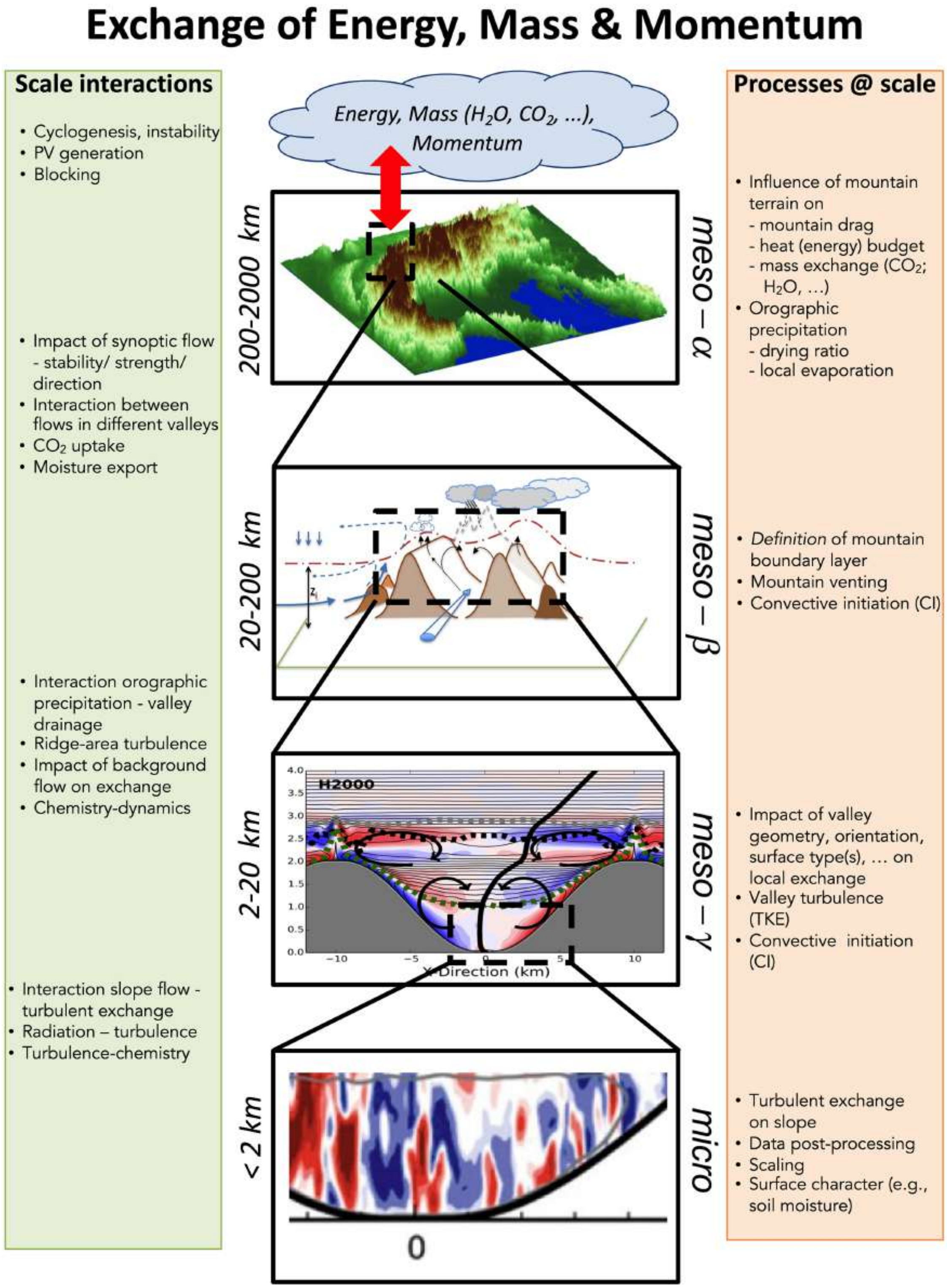

Fig. 1. Different scales in mountainous terrain, corresponding atmospheric processes at these scales (right bar), and scale interactions and multiscale processes (left bar). The top panel in the middle column shows the Alps at 1-km horizontal grid spacing in the WRF Model. Adapted from Lehner and Rotach (2018).

and climate modeling, and understanding of transport and exchange processes over mountainous terrain.

Our understanding of exchange processes in the ABL is to a large degree dependent on a theoretical framework (similarity theory) that assumes horizontally homogeneous (explicitly) and flat (implicitly) conditions (hereafter HHF). Similarity theory reasonably successfully

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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 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.

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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-α 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-γ" 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.

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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.

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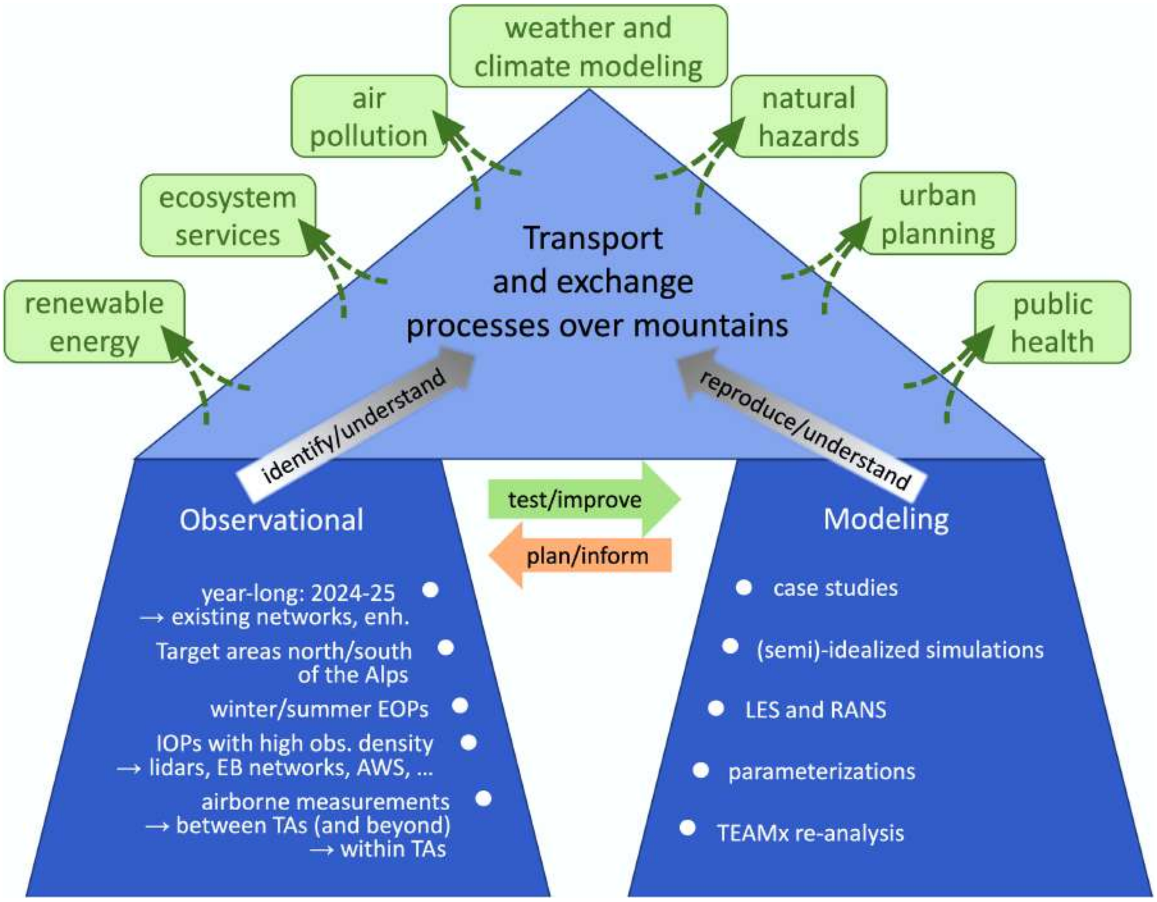

Fig. 2. Schematic representation of observational and numerical modeling activities planned within TEAMx. The TOC dataset is used to identify, characterize, and parameterize the relevant physical processes and to test and improve numerical modeling (different model types and parameterizations). Numerical modeling serves to optimize the experimental arrangements in the field, to specify the type of IOPs to be executed on a given day, and to improve data assimilation schemes and procedures in complex terrain, but it can also be used to identify the relative importance of different processes, assess uncertainties, and hence better understand the physical processes. "Case studies" refers to simulations with real terrain and atmospheric states close to reality (and thus includes short-term weather forecast simulations as well as climate time scales). LES denotes large-eddy simulation, RANS is Reynolds-averaged Navier–Stokes modeling (i.e., the typical framework for mesoscale atmospheric models), EOP is extended observation period, IOP is intensive observation period, TA is target area, EB is energy balance, AWS is automatic weather station, and "enh" is enhanced. Green boxes refer to typical areas of application for local atmospheric information.

Hand-in-hand with the TOC, a variety of numerical modeling experiments will be carried out across a range of scales and for different applications (Fig. 2). Central to TEAMx efforts is assessing the accuracy of model output with respect to understanding of exchange processes—it has become custom to call this "right for the right reason." To provide useful data for weather and climate services, we must have confidence that model output is sufficiently accurate for its purpose. For example, only with an adequate treatment and understanding of the surface energy balance in a complex valley can we correctly assess local evapotranspiration, the interaction of the locally driven slope flow with the mesoscale valley circulation, the interaction of the synoptic flow with both slope and valley flows, and hence the efficiency of the valley system's exchange of water vapor with the free troposphere. This improved representation of local evapotranspiration may in turn modify the abundance of water availability for precipitation processes at the mountain scale or even downstream. The key here is that the "right reason" (in this case, the correct

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surface energy balance, proper slope flow characteristics, etc.) not only yields the correct impact of the valley system on the atmospheric conditions aloft, but also allows for an adequate local forecast (or diagnostic), and even enables scientifically sound sensitivity studies, such as investigating the impact of forested versus non-forested slopes or urbanization in a valley.

Modeling of mountain atmospheres at high resolution can be done in at least two different ways: real-terrain (real atmosphere) simulations as in NWP or climate scenarios and idealized-orography simulations. The latter approach has been used widely to investigate idealized features of mountain landscapes, such as an infinite slope [e.g., the famous Prandtl (1942) model], the flow in a valley between two parallel straight ridges (e.g., Schmidli 2013), or the development of convective precipitation therein (e.g., Panosetti et al. 2016). In TEAMx both these approaches will be pursued in a coordinated manner.

Weather and climate services in the mountains

Point forecasts (and diagnostics) are an essential ingredient of weather and climate services. Many applied simulation tools in Earth system modeling (such as hydrological runoff modeling, pollutant dispersion modeling, sustainable energy potential assessment modeling, agricultural modeling) share a heavy dependence on meteorological input data and were originally developed, trained, and validated using meteorological station data. With the advance of computing power—and hence the increased resolution of meteorological models—these tools are being increasingly forced with the output of atmospheric models which dramatically extends their coverage. NWP model output (which is available every day, under any circumstance) is no longer exclusively employed for point weather forecasts, but also for a myriad of Earth system modeling applications used to make real-world decisions. Thus, the NWP output must be correct, or at least of sufficient accuracy, at every single grid point of application. The same is true if we use those Earth system models in conjunction with climate scenario simulations (which are also approaching convection-permitting resolution; e.g., Berthou et al. 2020; Ban et al. 2021), for example, to estimate the occurrence of high-impact weather (WMO 2017) under future climate scenarios, the availability of sustainable energy resources by the end of the century, or the possible impact of changes in agricultural practice.

Notably, a large portion of these Earth system modeling applications consider processes *that specifically occur in mountainous terrain*, despite difficulties in generating reliable point forecasts in the mountains (see below). This is true for

- surface runoff processes relevant for flash flood forecasts, hydropower planning, and operations;
- many hydrological processes involving snow and ice, such as planning for snow availability for tourism, securing drinking water availability downstream of major mountain ranges, avalanche forecasts, and road safety in icy conditions;
- processes affecting the siting of wind energy plants; and
- numerous air quality issues related to terrain, such as cold air pools and corresponding pollutant accumulation, and pollutant dispersion.

Overall objectives of TEAMx

Taking all of the above issues into account, TEAMx has four major objectives (Serafin et al. 2020), namely,

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- to improve qualitative and quantitative understanding of transport and exchange processes both between the surface and atmosphere and at multiple scales within the atmosphere,
- to provide a unique observational dataset which can be used to investigate the wide range of transport and exchange processes in mountainous terrain and their spatiotemporal variability,
- to evaluate and improve the performance of weather and climate models over mountainous terrain, and
- to reduce errors in impact models by transferring the knowledge gained to weather and climate service providers.

These broad objectives are based on the implicit assumption that our limited understanding of the exchange processes over mountains leads to *reduced forecast quality in the mountains*. Correspondingly, the third and fourth objectives could be reformulated as the goal to make weather and climate simulations over mountainous terrain at least as accurate as over flat terrain and that weather and climate services will no longer be limited by errors in weather and climate information. Issues with the accuracy of simulations over mountains may not, necessarily, impact everyday weather forecasts (if appropriately communicated) or even climate scenarios (if appropriately averaged, bias corrected, and communicated). They will, however, have an important impact on the applications in Earth system modeling. If the deviations are systematic, they will have a multiplying effect on possible enhancement/reduction in exchange efficiency over mountains and hence possibly a further modifying impact on larger-scale atmospheric states (see the orographic drag example in sidebar "Is exchange over mountains relevant?"). All the above conjectures will be critically examined through the research efforts of TEAMx—which hopefully will result in a more reliable estimation of the exchange of energy, mass, and momentum over mountains. Although the amount of relevant literature on the quality of weather and climate information over mountains and the underlying reasons remains limited, we show below that the existing evidence generally supports these ideas.

Is the quality of weather forecasts (climate diagnostics) worse in the mountains?

Although one might expect that mountainous regions may exhibit higher predictability due to the presence of a stationary obstacle in the flow (e.g., Anthes et al. 1985), in reality model errors likely dominate this effect to give lower forecast skill for many variables. It is clear, however, that the task of producing accurate forecasts in mountainous terrain is at least more challenging than over HHF terrain when it comes to properly representing exchange processes. Flat terrain can be inhomogeneous (e.g., a coastal area) or complex in terms of surface cover and form (e.g., a metropolitan area), which will impact the exchange. However, if substantial orography is involved we face additional numerical modeling issues (Chow et al. 2019) such as vertical coordinate definition, inconsistency of some physical parameterizations, a higher degree of nonlinearity and hence chaos, and, for very high resolution, the possibility of numerical instabilities due to too steep slopes.

But do these challenges impact forecast quality? Relatively little can be found in the scientific literature concerning systematic differences between forecast quality at mountain sites and in flat terrain. While virtually all operational national meteorological and hydrological services verify their weather forecasts, there are no systematic verifications for "mountainous" versus "flat terrain" sites even in countries containing significant mountains. Figure 3 shows a very straightforward comparison of this kind for the forecast model of ECMWF (IFS) using 3 years of data and a very simple definition of mountainous terrain [station height $>$ 1000 m

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above mean sea level (MSL)] and flat terrain (station height $<$ 500 m MSL). Clearly, this is only a very crude distinction between flat and mountainous terrain and hence a very first attempt, but still, the example shows that the flat terrain sites score substantially better than the mountainous sites. As this is only one example, it does not mean that the same results will be obtained for other models, or mountain ranges, or time periods. It is, however, a first step for the more systematic evaluation that will be performed within TEAMx.

A similar story applies to the assessment of the reliability of climate information over mountains: no systematic evaluation of "mountain versus non-mountain sites" can be found in

Is exchange over mountains relevant?

Four examples at different spatial scales demonstrate the relevance of surface–atmosphere exchange in mountain areas for the reliability of weather forecasts, climate modeling, and impact modeling.

Large-scale example: Momentum exchange

Orography slows down the large-scale flow through a number of processes such as orographic flow blocking, excitation of (non) hydrostatic gravity waves, or flow deformation (form drag) at turbulence scales—the impact of which is usually summarized as drag exerted on the flow. Numerical models used for weather or climate simulations cannot typically resolve mountains with horizontal scales less than a few tens to hundreds of kilometers and, thus, the orographic drag needs to be parameterized. Since their introduction in the 1980s, orographic drag parameterizations have played a major role for the accuracy of the models' momentum budgets (and hence wind forecast accuracy).

In an IUGG centennial event (100 Years of Atmospheric Research) in 2019, the Head of Research of ECMWF showed that orographic drag ("GWD O. Roughness" in Fig. SB1) was among the top 10 most important improvements in the history of numerical weather prediction—of similar importance as data assimilation procedures, satellite data, etc. The major impact can be seen on the Northern Hemisphere (full red line) where most major mountain ranges are found.

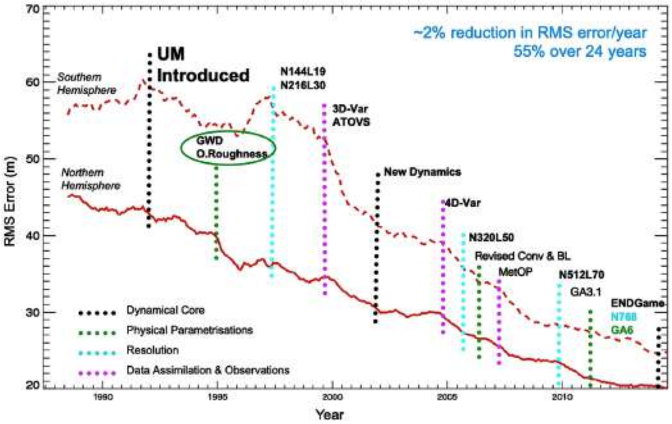

Fig. SB1. RMS error (vs analyses) of 500-hPa geopotential height, day 3 forecast by the Unified Model (UM) of the Met Office. Red dashed line for the Southern Hemisphere, red full line for the Northern Hemisphere. "GWD O. Roughness" (in the green ellipse) refers to the introduction of a gravity wave drag/orographic roughness parameterization. Figure courtesy Sean Milton from the Met Office, whose original work (Milton and Wilson 1996) is the basis of the shown impact.

Mesoscale example: Carbon budget

Due to its importance for many aspects of climate change, the global carbon budget is assessed every year by the internationally backed Global Carbon Project using the most up-to-date knowledge, data, and modeling tools to estimate anthropogenic emissions of greenhouse gases and their fate in the atmosphere and terrestrial/oceanic sinks. Every year, terrestrial processes—whether sources due to land-use change or sinks due to photosynthesis or other vegetative processes—are considered most uncertain (Fig. SB2). In fact, before 2016, the model-related uncertainties were considered so large that the terrestrial carbon sink was estimated as the residual of the carbon budget. More recently, the terrestrial sink is estimated based on atmospheric inversions with a resolution of atmospheric forcing of order $>$100 km. Note that the CO_2 flux data used are mostly not from orographically influenced sites (Rotach et al. 2014). Thus, at least part of the uncertainty may be attributed to the missing orography-related processes (Rotach et al. 2014), rendering the global budget compromised by uncertainties in mesoscale exchange processes.

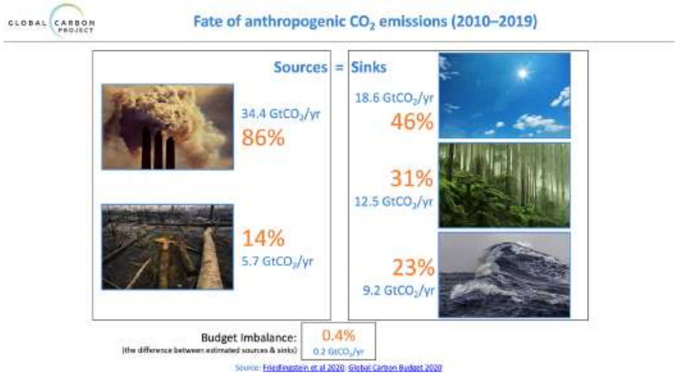

Fig. SB2. Summary of the fate of the anthropogenic CO_2 emissions (2010–19) from the Global Carbon Project (based on Friedlingstein et al. 2020). The sinks due to land surface exchange (middle panel to the right, 31%) are considered to be most uncertain. Source: www.globalcarbonproject.org/carbonbudget/20/presentation.htm, last accessed 1 Nov 2021.

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Small-scale example: Hydrological modeling

Runoff modeling (e.g., for flood forecasting or water resource management) is one of the applications for which the accuracy and appropriateness of local atmospheric information is most important (right for the right reason). While convection-permitting atmospheric ensembles are starting to become routine at operational centers, hydrological models, due to their highly parameterized character, still need to be specifically calibrated for use in every catchment. The example in Fig. SB3 shows the result of a combined atmospheric–hydrological ensemble (21 atmospheric members combined with 25 hydrological parameter settings, i.e., 525 simulations) of a flood event in the Verzasca Catchment in southern Switzerland. The darker turquoise shading around the blue runoff line depicts the uncertainty due to the atmospheric forcing and the difference to the total uncertainty (the hatched area) that of the hydrological model. Note that the "meteorological uncertainty" is mostly due to the chaotic nature of the atmosphere (and not due to the physical realism of the employed parameterizations in the atmospheric model). If the largest uncertainty in the hydrological forecast arises from the meteorological input, this example demonstrates the importance of correctly parameterizing the relevant processes (in this case, evapotranspiration, for which turbulence kinetic energy, advection of moisture or energy and the local flow conditions are critical) to provide an accurate atmospheric input for hydrological modeling.

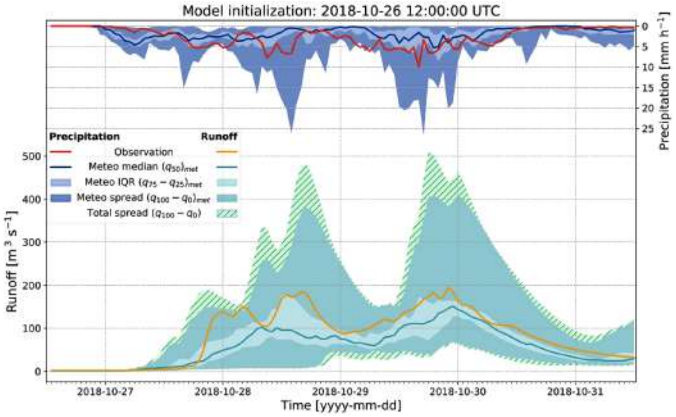

Fig. SB3. Runoff at Lavertezzo, Campiòi, in the small Verzasca Valley Catchment in southern Switzerland (left scale) and precipitation (right scale). Observations are compared to a meteorological–hydrological ensemble (a total of 525 ensemble members). Dark turquoise shading: runoff uncertainty due to the meteorological ensemble; green hatched shading: runoff uncertainty due to hydrological model uncertainty. Source: Giordani (2019).

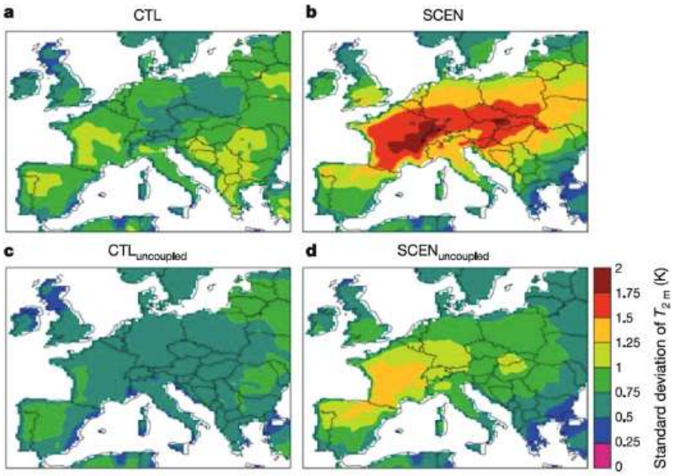

Fig. SB4. Simulated standard deviation of year-to-year 2-m temperature over Europe (color code) for (a) the control (1960–89) and (b) a scenario (2070–99) time window. (c),(d) As in (a),(b), but from a simulation in which the surface and the atmosphere are decoupled. For simulation details, see the source: Seneviratne et al. (2006).

Scale interactions example: Soil moisture

Climate change does not only lead to increasing mean temperatures but also to increasing interannual temperature variability. The simulations of Seneviratne et al. (2006) (Fig. SB4) compare the year-to-year T_{2m} (2-m temperature) variability between control (CTL, 1960–89) and scenario (SCEN, 2070–99). They find that the increased year-to-year variability under SCEN is largely attributable to Earth–atmosphere coupling ("uncoupled" in Figs. SB4c,d means that the soil moisture is artificially fixed at its climatological mean). Thus, the smallest, very local scales interact with the mesoscale and even synoptic-scale flow to produce a climate change signal. It can be seen that the area of highest projected T_{2m} year-to-year variability encompasses an arc ranging from the Pyrenees over the Alps to the Dinaric Alps. It is not suggested here that the mountain area produces the most reliable simulated surface exchange (56-km horizontal grid spacing!). Rather, this result emphasizes the need for better knowledge of Earth–atmosphere exchange over mountains to assess and interpret corresponding climate change results.

the literature. Results from pioneering regional climate simulations at convection-permitting resolution, however, suggest that the quality of climate information over a mountain range is different than over the surrounding flatter terrain (Fig. 4). Here we have deliberately chosen two examples in which, on the one hand, the Alpine area (and also the Pyrenees) show largest biases in daily precipitation totals—one would almost think the color coding shows the height contours—while on the other hand, the Alpine area has small biases in summer 2-m temperature in an otherwise much too warm European continent. Again, other models,

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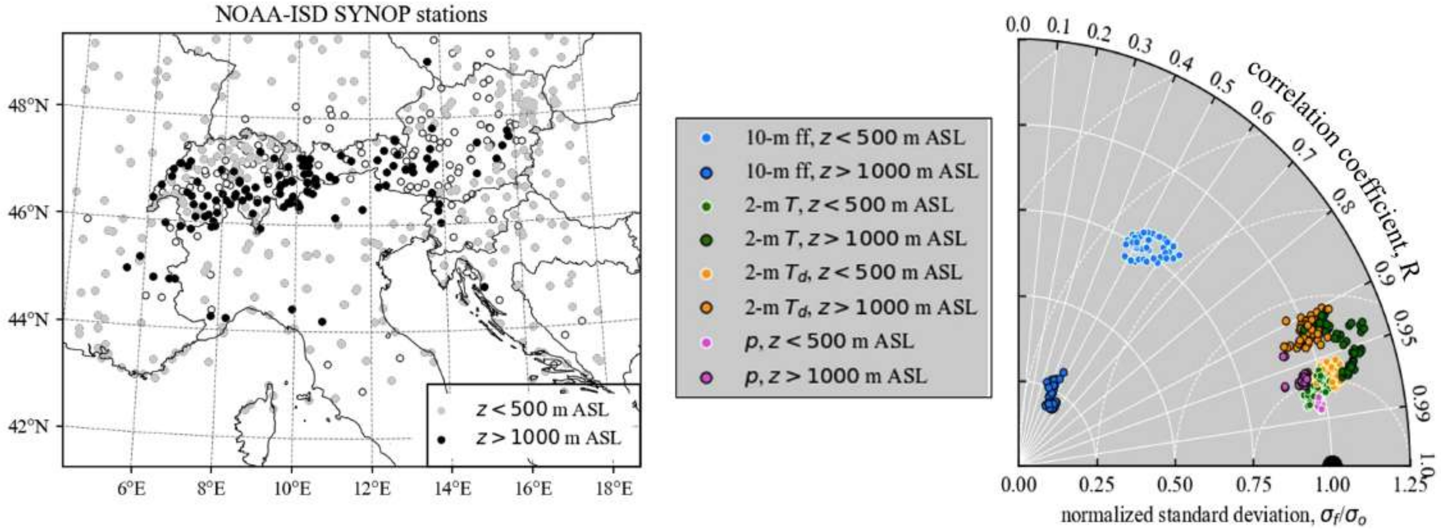

Fig. 3. **Verification of hourly forecasts of 2-m temperature (2-m T), dewpoint (2-m T_d), 10-m wind speed (10-m ff), and surface pressure (p) by the ECWMF IFS model (1200 UTC run) in the period 2016–19, for forecast ranges between 0 and 48 h. (left) Synoptic stations in and around the Alps, available in the NOAA Integrated Surface Database downloaded from the Global Hourly-Integrated Surface Database of NOAA (www.ncei.noaa.gov/products/land-based-station/integrated-surface-database, accessed on 4 Nov 2021; Smith et al. 2011). Black: station height $>$ 1000 m MSL (proxy for mountain site), gray: station height $<$ 500 m MSL (proxy for flat terrain site). (right) Taylor diagram contrasting mountain and flat terrain sites (as depicted in the left panel) for different variables (coloring: see inlet). Each point in the Taylor diagram refers to a specific forecast range and represents a spatially averaged score, i.e., the mean value across all observing sites in the set. Variability around the mean is large, especially in the case of wind speed forecasts (not shown). The Taylor diagram relates the correlation coefficient between observed and modeled values (R) to the respective standard deviations (σ_f for the standard deviation of the forecast, σ_o, for the standard deviation of the observations). Perfect forecasts and forecasts affected by a constant bias would have $R = 1$ and $\sigma_f/\sigma_o = 1$ (black half-dot on the horizontal axis); distance from this point is proportional to the root-mean-square error of debiased forecasts. For the model output of the deterministic IFS forecast, see data availability statement.**

other mountain ranges, other time periods (other variables, even) may show different results, but quite often, the mountain areas stand out with particularly large or small biases. If the forecast errors over mountainous and adjacent flat terrain differ systematically, this bears the possibility that better results over mountainous terrain are only due to compensating errors, thus compromising the "right for the right reason."

Conclusions

The TEAMx community has identified a major weakness in our ability to correctly understand and model the exchange of energy, mass, and momentum over large parts of the land surface, i.e., areas dominated by not horizontally homogeneous and flat (non-HHF) conditions, of which mountainous terrain is an extreme example. Paradoxically, many aspects of this weakness only emerged when computing power allowed mountains to be resolved in NWP models with small horizontal grid spacing. Traditional ABL treatments need to be transformed in order to handle sloping, irregular, and inhomogeneous terrain; the conventional ABL concept over HHF terrain needs to be extended to the mountain boundary layer (MoBL); and relevant processes with respect to the transport and exchange of energy, mass, and momentum and, in particular, the interactions between processes, need careful investigation. The TEAMx white paper (Serafin et al. 2020) has recently been published summarizing the current knowledge about mountain exchange processes and the most pressing remaining unknowns. In a concerted effort, the TEAMx community plans to conduct a major observational campaign as well as coordinated numerical modeling experiments to advance our knowledge toward a state where the output of numerical weather and

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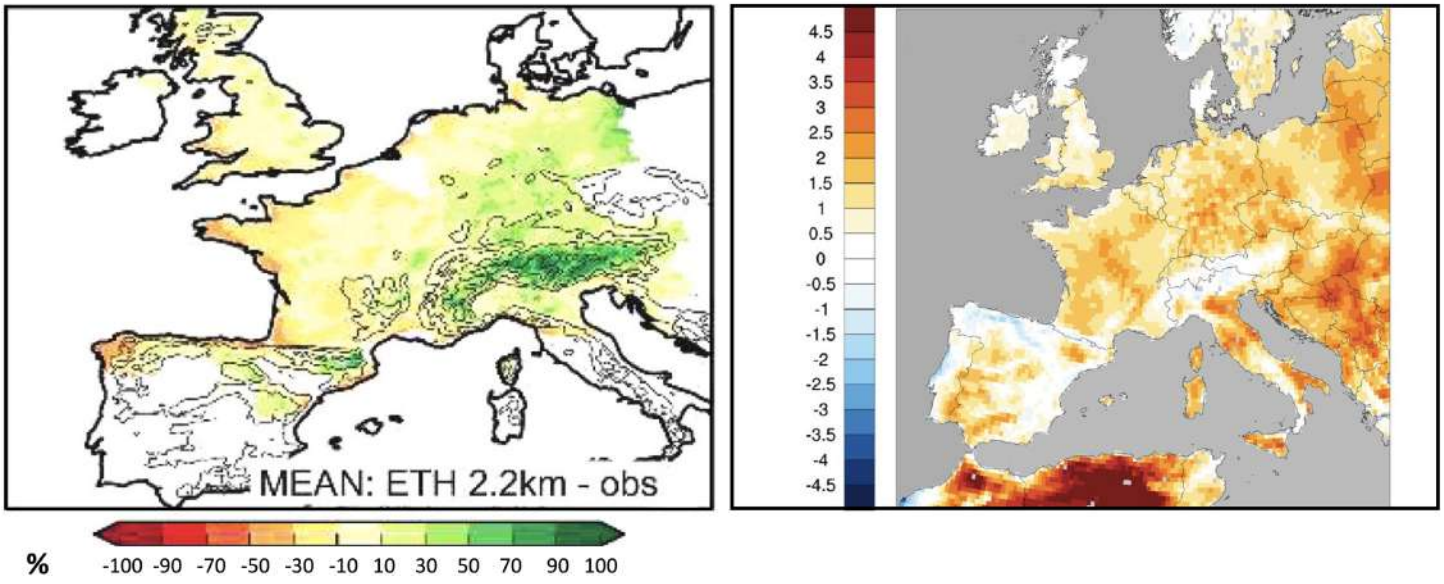

Fig. 4. (left) Percentage difference in (mean) daily precipitation totals for a 9-yr regional climate simulation for western Europe at 2.2-km horizontal grid spacing with the COSMO-CLM ("ETH 2.2 km" stands for the simulation of the Swiss Federal Institute of Technology with 2.2-km horizontal grid spacing). Thin black lines are orographic height contours and color coding corresponds to the bias (from Berthou et al. 2020). (right) Seasonal mean summer (JJA 2006) temperature bias (K), color code, with an early convection-permitting regional climate model, COSMO-CLM (Leutwyler et al. 2016).

climate models can safely be used as input for Earth system modeling applications—even over mountainous terrain.

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Data availability statement. Access restrictions apply to some of the data used in this study. Original data elaborations were needed only for Fig. 3. Measurements at SYNOP stations in the Alpine area were downloaded from the freely available Global Hourly-Integrated Surface Database of NOAA. The URL and literature reference are included in the figure caption. Model output from deterministic IFS forecast runs was downloaded from the Meteorological Archival and Retrieval System (MARS) at ECMWF and is available to licensed users based at institutions in ECMWF member states.

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