TEAMx is an international research programme that aims at improving the understanding of exchange processes in the atmosphere over mountains and at advancing the parameterizations of these processes in numerical models for weather and climate prediction. TEAMx is a bottom-up initiative promoted by a number of universities, research institutions and operational centres, internationally integrated through a Memorandum of Understanding between interested parties. It is carried out by means of coordinated national, bi-national and multi-national research projects and supported by a Programme Coordination Office at the Department of Atmospheric and Cryospheric Sciences of the University of Innsbruck, Austria.

The present document, compiled by the TEAMx Programme Coordination Office, provides a concise overview of the scientific scope of TEAMx. In the interest of accessibility and readability, the document aims at being self-contained and uses only a minimum of references to scientific literature. Turquoise boxes at the beginning of chapters list the literature sources that provide the scientific basis of the document. This largely builds on review articles published by the journal *Atmosphere* between 2018 and 2019, in a special issue on *Atmospheric Processes over Complex Terrain*. A few other important literature pieces have been referenced where appropriate. Interested readers are encouraged to examine the large body of literature summarized and referenced in these articles. Orange boxes have been added to most sub-chapters. Their purpose is to highlight key ideas and proposals for future collaborative research.

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1 Motivation

Meteorological processes of all scales are significantly affected by orography. Mountains impact atmospheric flows by generating planetary waves, modifying synoptic-scale advection, producing mesoscale organized motions and internal gravity waves, altering micro-scale motions and turbulent mixing. Major advances in the scientific understanding of these phenomena often originated from large-scale internationally coordinated research programmes, culminating in field campaigns. Notable examples in Europe include ALPEX (1981-1982), PYREX (1990), MAP (1999) and COPS (2007).

These programmes investigated atmospheric processes of progressively smaller scale, from lee cyclogenesis (ALPEX) and gravity wave drag (PYREX) to orographic precipitation, potential vorticity streamers, gap flows (MAP) and orographic convection (COPS). However, besides impacting the flow characteristics and phenomena in the atmosphere aloft, mountains also strongly modify the exchange processes responsible for the transfer of heat, momentum and mass (water, trace gases, aerosols, pollutants) between the ground, the planetary boundary layer and the free atmosphere. Since about 30% of the land surface consists of complex orography (Fig. 1), exchange processes over complex terrain may be expected to have a major impact on the global cycles of water, energy or carbon. Furthermore, their understanding and accurate representation in numerical models is crucial for determining and forecasting the local state of the atmosphere, and hence for the quality of weather forecasts and climate change diagnostics or projections.

In the last few decades, technological and scientific progress extended the range of atmospheric motions that can be accurately observed and modelled towards smaller and smaller scales. Today, this potential can be exploited in a large internationally coordinated program to study exchange processes over orography, their interaction with meso-scale processes and their role in the climate system. Long-standing shortcomings in the observation and modelling of the atmosphere over mountains urgently need being addressed. From the experimental perspective, terrain heterogeneity is responsible for several problems connected to the practical use of observations. These include the possibly limited representativeness of point measurements; the limited testing of retrieval algorithms for remote sensing (e.g., for satellite observations); and special requirements in data post-processing (e.g., for turbulence measurements). From the modelling perspective, the imperfect representation of flow over mountains contributes to systematic model errors in both numerical weather prediction (NWP) and climate simulations. These errors remain one of the major sources of structural uncertainty for Earth-system models despite the ever-increasing resolution.

In recent years, the societal demand for meteorological and climate information has largely increased in knowledge areas beyond meteorology and climatology. End-users and stakeholders require weather forecasts or climate-change projections in sectors such as air pollution science, renewable energy harvesting, hydrology and water resource management, agriculture, ecology, health, and tourism. Meteorological and climatological information referring to mountains is also indispensable in dealing with natural hazards and weather extremes (hail, flooding, droughts) and their impacts, which are relevant not only to the population of mountainous regions (about 10% of the world’s total), but also to that of adjacent low-land areas (a further 15%).

All these considerations demonstrate the need for increased, internationally coordinated efforts to improve the understanding of exchange processes between the surface and the atmosphere over mountains. TEAMx aims at combining joint experimental and numerical modelling efforts towards better scientific understanding of these processes. This White Paper provides a concise overview of the outstanding scientific issues and of the expected outcomes of the programme (Tab. 1, Fig. 2). It also outlines the basic elements of a strategy towards the implementation of TEAMx collaborative research, and describes the foreseeable impacts of coordinated experimental efforts.
Figure 1. Global distribution of mountainous areas (data source: Global Mountain Explorer).

<table>
<thead>
<tr>
<th>Objective</th>
<th>Primary focus</th>
<th>Target</th>
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<tr>
<td><strong>Process Understanding</strong></td>
<td>Micro- and meso-scale processes within and above the <em>mountain boundary layer</em> (MoBL); Interaction between scales.</td>
<td>Quantitative understanding of water, energy and mass exchange over mountainous terrain.</td>
</tr>
<tr>
<td><strong>TEAMx Joint Experiment(s)</strong></td>
<td>Collaborative use of multi-platform instrumentation to sample the spatial heterogeneity of turbulence and mesoscale circulations over and near mountains.</td>
<td>Quality-controlled observational data pool, available for process investigation, high-resolution model verification, parameterization development.</td>
</tr>
<tr>
<td><strong>Improving Weather and Climate Models</strong></td>
<td><em>Models right for the right reason</em>, i.e., identification and reduction of model biases and uncertainties over complex terrain.</td>
<td>Weather forecasts and climate simulations over mountains as good as over flat terrain, and less reliant on model output post-processing.</td>
</tr>
<tr>
<td><strong>Support to Weather and Climate Service Providers</strong></td>
<td>Air pollution, hydrology, climate change scenarios (e.g., elevation-dependent warming).</td>
<td>Smaller uncertainty of impact models, due to reduced errors in weather and climate information.</td>
</tr>
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</table>

Table 1. Summary of scientific issues and expected outcomes of TEAMx.
Figure 2. Objectives of the TEAMx programme. Better models, based on better process understanding and on TEAMx data for validation, will lead to more accurate information for weather and climate service providers (grey boxes are examples of application areas).
2 Scientific Objectives

- Exchange processes in the atmosphere include land-atmosphere interactions, as well as transport and mixing within the atmospheric boundary layer and between the atmospheric boundary layer and the free atmosphere. Decades of mountain meteorology research have shown that these processes are more complex over mountains than over flat and homogeneous terrain, in terms of the relevant scales of motion (Fig. 3). It remains unknown (i) whether the larger spectrum of relevant scales of motion generally enhances land-atmosphere exchange over mountains, in terms of spatially aggregated fluxes; and (ii) whether modified exchange efficiency explains the observed stronger sensitivity of mountainous areas to climate change. There is a critical need for novel observations to support theory and model development.

Figure 3. Sketch of exchange processes over complex terrain. Exchange processes govern the transfer of heat, momentum and mass between the ground, the planetary boundary layer and the free atmosphere. Over mountainous terrain, exchange processes include turbulent mixing, breeze systems, gravity wave propagation and moist convection. Vertical transport towards the free atmosphere is conjectured to be on average more intense over mountains (thicker black arrow).
2.1 Understanding exchange processes within and above the MoBL

The atmospheric boundary layer (ABL) is typically defined as the portion of the atmosphere that responds to variations in surface forcing at time scales on the order of 1 hour or less. A distinctive feature of the ABL is turbulence, which causes effective mixing of atmospheric properties, in particular in the vertical direction. The Mountain Boundary Layer (MoBL) is persistently subject to processes other than turbulence, e.g., thermally-driven local wind systems. These determine complex patterns of variability in three dimensions, which are hard to observe and predict and have a direct impact on surface exchange. Organized air motions also impact exchange between the MoBL and the free atmosphere, in addition to other meso- and synoptic-scale motions (deep moist convection, frontal systems) that cause intermittent deep exchange. This chapter briefly reviews the overall structure of the MoBL (Sec. 2.1.1), the properties of its lower and upper boundaries (Sec. 2.1.2 and 2.1.3) and the phenomena that lead to deep coupling between the MoBL and the free atmosphere (moist convection in Sec. 2.1.4, gravity waves in Sec. 2.1.5). Furthermore, it extends the scope of MoBL research towards climatological time scales (Sec. 2.1.6) and towards connecting dynamical and chemical processes (Sec. 2.1.7).

Relevant literature:

2.1.1 Three-dimensional structure

The theory of land-atmosphere exchange over horizontally homogeneous terrain accounts mostly for the role of mixing due to small-scale turbulent processes. A prominent approach in this context is the boundary-layer approximation: turbulent mixing is mostly effective in the vertical direction, and horizontal advection can be neglected. Quantitative description of 1D vertical mixing affected by buoyant turbulence production or loss is well rooted in theory (e.g., Monin-Obukhov Similarity Theory, MOST, see Sec. 2.1.2) and is incorporated in virtually all land-surface-atmosphere parameterizations for NWP and climate models. Other scaling principles based on the boundary-layer approximation (e.g., mixed-layer scaling for the convective ABL, or z-less local scaling for the stable ABL) are used extensively in ABL parameterizations.

Where landforms or land cover are spatially heterogeneous, the validity of the boundary-layer approximation breaks down. Baroclinicity due to differential heating or cooling generates local wind systems, which are connected to substantial spatial variability in the boundary layer. The interaction between turbulence and thermodynamically driven mesoscale flows determines both the spatial extent of the MoBL and its efficiency in exchanging energy and atmospheric constituents between
the mountainous surface and the free atmosphere. Also the dynamic response to flow over terrain, such as wake formation, creates intrinsic spatial heterogeneity. In these conditions, land-atmosphere exchange is determined not only by vertical mixing, but also by horizontal mixing and three-dimensional advection.

Advective processes have an impact on several aspects of MoBL flow. First, the MoBL responds to surface forcing on time scales considerably longer than one hour (i.e., the commonly accepted scale over flat terrain). It may also contain regions with small levels of turbulence (for instance, daytime mid-valley subsidence areas), or where turbulence is advected instead of being generated locally (for instance, atmospheric rotors). Finally, atmospheric kinetic energy spectra from complex-terrain sites often do not exhibit a clear energy gap between synoptic and turbulent scales of motion—a challenging aspect for ABL parameterizations, which are generally based on evident separation between resolved and unresolved scales.

- Experimental evidence of the three-dimensional distribution of turbulence in the MoBL is currently very limited. Novel in-situ and remote-sensing observations and experimental strategies are required to strengthen the existing knowledge, which is mostly based on numerical results (often idealized simulations).
- Precise definition of the vertical extent of the MoBL is elusive. Objective methods to determine the spatially inhomogeneous MoBL height must be developed and tested.
- Theoretical and modelling work is needed to relate the intensity of thermally driven slope-, valley- and plain-to-mountain flows to the respective forcing factors and to quantitative descriptors of orographic variability.
- In view of improving the existing parameterizations of exchange processes, research should be oriented towards quantifying the upscale impact of turbulence and organized mesoscale motions on the total exchange in the MoBL.

2.1.2 Land-atmosphere exchange

Measurements of the surface energy balance are often plagued by lack of closure. That is, the sum of the measured sensible, latent and ground heat fluxes is less than the measured net radiation. At ideal sites, lack of closure is often connected to inadequately sampled mesoscale motions, causing significant horizontal and vertical advection. Complex terrain sites are systematically affected by such motions, and therefore they often exhibit substantial underclosure. In addition, significant uncertainty in the estimation of the surface energy balance terms derives from the lack of consolidated approaches to handle basic data-processing tasks (as further detailed in Sec. 2.2.1). Besides the complexity of the terrain height itself, mountainous areas often display dramatic soil and land-cover (vegetation) heterogeneity. Due to changes in elevation, different climate zones occur across short horizontal distances in mountainous environments. As ecosystems adapt to this variability, spatial heterogeneity in ecosystem structure and functioning impacts exchange processes (e.g., through varying soil properties, vegetation, roughness, etc.). Implications include not only marked spatial variability of the measured turbulent fluxes, but also directional variability of the fetch at a single point. It follows that point measurements over complex terrain generally have limited representativeness.

An important consequence is that, over complex terrain, models of exchange processes are not as well constrained by observations as they are over flat and homogeneous terrain. For instance, no universal scaling behaviour replacing MOST or other scaling regimes has been reported over complex orography so far. The limited applicability of existing turbulence theory over complex terrain also stems from frequent violation of its basic assumptions (e.g., stationarity and isotropy of small-scale turbulence).
Increasing efforts should be devoted to developing and evaluating footprint models for turbulence measurements in complex terrain, and to understanding the factors that determine the lack of closure of the surface energy balance.

Progress in theoretical models of land-atmosphere exchange over complex orography (in particular, flux-profile scaling laws needed in parameterizations) requires generalizing similarity theory by accounting for horizontal heterogeneity in landforms and land-cover.

Surface exchange is heavily affected by the state of soil and vegetation, which can display marked spatial variability. Improved experimental characterization of soil properties and canopy should be pursued, as well as better modelling of their impact on surface fluxes at spatial scales comparable to the grid elements of a NWP model.

2.1.3 Heat and mass exchange with the free atmosphere

Over flat terrain and in weak synoptic flow, the upper boundary of the ABL depends primarily on the thermal structure of the atmosphere and on the intensity of turbulence. In dry convective conditions, exchange across the top of the flat-terrain ABL is limited to the turbulent entrainment caused by overshooting thermals. Over complex orography, the dry convective MoBL often features a layered structure, in which stable layers (e.g., temperature inversions) alternate with more turbulent elevated mixed layers. Thermal plumes on mountaintops are generally connected to horizontal convergence-divergence patterns responsible for mountain venting. This, in connection with synoptic advection, provides a powerful mechanism to redistribute heat, water vapour, aerosols and trace gases both vertically and horizontally. Due to horizontal transport and mixing, the upper boundary of the convective MoBL generally does not follow smoothly the shape of the terrain. Diagnoses of its height from temperature and aerosol concentration profiles generally do not coincide.

Under stable conditions, exchange between the boundary layer and the free atmosphere is strongly reduced, except for sporadic mixing events caused by high wind shear and internal gravity waves. Mixing in the stable boundary layer (SBL) is observed to be intermittent and affected by sub-mesoscale motions, but is artificially enhanced in surface-layer parameterizations (for instance, using long-tail similarity functions). Intermittent mixing occurs over flat terrain as well, but may be more frequent over complex orography, where both cold air pooling and gravity wave generation are favoured. Over mountains, the likely orographic origin of many sub-mesoscale disturbances affecting the SBL offers some hope of enhanced predictability, at least in a stochastic sense.

Combined use of in-situ airborne observations and remote-sensing profiling instruments is necessary to observe phenomena at the interface between the MoBL and the free atmosphere in a variety of weather conditions.

Most of the knowledge on exchange mechanisms at the top of the MoBL is based on numerical studies that neglect synoptic forcing. Interactions with meso- and synoptic scales of motion urgently need to be investigated.

Coordinated numerical and observational experimentation can help develop better parameterizations of turbulent entrainment and advective transport at the top of the daytime MoBL; and of intermittent mixing in the stable MoBL.

2.1.4 Boundary-layer control of convective pre-conditioning and initiation

Flow over and past mountains aids the development of deep moist convection by mechanical displacement of the airflow and by generation of thermally-induced circulations. Besides providing the uplift required for convection initiation, heat and moisture exchange in the MoBL and at the surface plays a role in convection preconditioning: it prepares the environment for moist convection
by favouring localized humidity build-up, removing convective inhibition and enhancing convectively available potential energy. However, exchange processes can also inhibit convection by making the environment less favourable for its onset, particularly through enhanced mixing with dry free-tropospheric air above the higher terrain.

While the mechanisms of convection triggering and preconditioning related to orographically-induced airflow are qualitatively clear, it remains challenging to quantitatively describe their dependence on the characteristics of the orography and their effects on the mesoscale moisture and temperature fields. This knowledge is required, for instance, to appropriately parameterize the sub-grid-scale orographic forcing for convection initiation in global models, which are not yet convection-permitting and will lack the resolution to adequately capture orographic convection for some time.

On a more fundamental level, correlations and feedbacks between soil moisture and convective precipitation over mountains are still largely unclear, and may be affected both by mountain dimensions and by spatial variability in vegetation and soils (and the resulting soil moisture heterogeneity). Finally, the role of katabatic flows, topographically-induced internal gravity waves and other lifting mechanisms in the initiation of nocturnal convection near mountains still has to be firmly established.

- Observations of moist orographic convection should target a broad range of scales, combining high-density in-situ measurements of surface energy exchange (soil moisture, sensible, latent and ground heat fluxes) with retrievals of the wind, temperature, water vapour and precipitation fields from different remote-sensing methods.
- Progress in forecasting moist orographic convection crucially depends on reducing initial-condition error at the smallest resolvable scales. This demands upper-air observations of the wind, temperature and moisture fields with higher density and frequency, and improved assimilation of existing and novel high-resolution observations.

2.1.5 Turbulent exchange due to low-level gravity-wave processes

Gravity-wave dynamics governs a range of orographic flow phenomena, including föhn, atmospheric rotors and modulation of the stable boundary layer. The impact of these phenomena on near-surface exchange is only partially understood and hard to describe quantitatively.

For instance, a subtle interplay between föhn-induced turbulence and low-level stable layers governs whether föhn reaches low terrain, locally enhancing sensible and latent heat fluxes. Where accelerated föhn flow detaches from the surface, atmospheric rotors can develop; the high levels of near-surface turbulence encountered in rotors are not produced locally, but rather advected from regions of shear instability upstream.

Föhn and atmospheric rotors, affected by gaps and peaks in the upstream orography, generally cause sharp horizontal variations (both along and across the flow direction) in the vertical profiles of stability and wind shear, and hence in turbulent transport. Finally, gravity waves can affect the surface energy balance, especially at night, for instance by intermittently dissipating radiative fog.

- Parameterizations of the effects of gravity-wave processes on the large-scale flow typically account for wave momentum fluxes and for turbulent form drag. The available evidence suggests the need to also represent the turbulent fluxes of heat, moisture and other atmospheric constituents that can result either directly from gravity wave breaking, or indirectly from wave-induced enhancement of the wind shear and the resulting dynamic instability.
- Sampling the three-dimensional variability of gravity-wave-driven turbulence requires the coordinated deployment of in-situ and remote-sensing measurement platforms, both ground-based and airborne.
Climate variables and processes in mountain regions

The characterization of climate and climate change in mountainous areas is affected by major uncertainties. Surface observations are sparse or lacking due to the remoteness of high-altitude regions, while climate model simulations suffer from major limitations due to the imperfect representation of complex orography and its effects.

One important question related to climate change in the mountains is whether mountain environments are warming more or faster than the lowlands, or compared to the global mean. Elevation-dependent warming (EDW), i.e., the altitudinal dependence of warming rates, has been analysed using both observations and model simulations. According to the current understanding, EDW is largely determined by feedbacks in which surface exchange processes play a central role. For instance, changing surface albedo (particularly in connection with snow cover changes) turns out to be a main driver of EDW in several mountain areas, such as the Alps and the Himalayas. However, evidence for EDW is not equally conclusive in all mountain ranges worldwide and the extent to which regional differences in elevation-dependent trends depend on the global circulation is largely unexplored.

Evidence for elevation-dependent climate change signals in other variables, such as rainfall, snowfall or wind, is less solid than for temperature, partly because of the inherent difficulty of determining meaningful trends from sparse and poorly representative observations. Accordingly, progress in understanding climate change in mountains depends on improved accuracy and representativeness of the observations of essential climate variables in complex orography. Observational efforts should focus primarily on the temporal and spatial variability of temperature and liquid/solid precipitation (which are key variables due to their influence on the high-altitude cryosphere), but also on all variables affecting the surface energy balance (among others: shortwave and longwave radiation, surface albedo, specific humidity, clouds, aerosols and soil moisture).

Better scientific understanding of elevation-dependent climate change also depends on improved modelling of the Earth system components involved in the relevant climate feedbacks (e.g., snow cover and mountain glaciers, orographic clouds, vegetation). Relevant parameterizations include land-atmosphere exchange models (in particular their snow component), but also microphysics, boundary-layer and convection schemes, which affect the modelling of orographic clouds.

- Long-term observational capabilities in mountain regions should be improved by increasing the number of in-situ stations that measure essential climate variables, including the surface energy budget components, up to the highest elevations. Special consideration is required by measurements of precipitation, in particular snowfall.

- In addition to monitoring climatic change, dense networks of in-situ stations would also serve the purposes of validating satellite Earth observations, evaluating climate model simulations, correcting model biases and training statistical and/or stochastic downscaling methods. The latter are nowadays essential for the formulation of high-resolution climate-change scenarios for extreme precipitation.

- Besides statistical approaches, downscaling research should invest in the advancement of physically-based methods. This may involve the further development of intermediate complexity models, which are not based on numerical integration of the time-dependent governing equations but on simple steady-state models of airflow over mountains and orographic precipitation.

- Knowledge of systematic model errors arising from parameterized processes (e.g., the components of the surface energy balance) in mountainous areas, as well as their dependence on model resolution, is still largely lacking and urgently needs to be established.
2.1.7 Aerosol, trace gases and air pollution

The fate of near-surface emissions, both natural and anthropogenic, crucially depends on near-source chemical transformations, which are in turn affected by transport and exchange processes. Hence, the distribution of pollutants from local to global scale is a fundamentally coupled dynamics/chemistry problem. In mountainous terrain, inhibited vertical exchange leads to local pollution episodes (e.g., wintertime trapping of pollutants in valleys), while enhanced vertical exchange between the surface and the free atmosphere contributes to regional pollution episodes (e.g., build-up and long-range transport of ozone, fed by precursors emitted at the surface).

At present, the optimal architecture of dispersion models for applications over complex terrain consists of coupled high-resolution meteorological simulation and Lagrangian Particle Dispersion Models (LPDM). LPDM are preferred to Eulerian models because, if properly generalized to account for horizontal exchange, in principle they allow better simulation of plume rise in the near-source region and where the assumption of horizontal homogeneity cannot be made. Sub-km grid spacing in the meteorological simulations is necessary in order to make the effective model resolution enough to properly represent small-scale orography and its impact on the mean flow.

While technically feasible, sub-km resolutions lie within the grey zone of ABL parameterization schemes. This implies that any property of the sub-grid-scale turbulence used to inform LPDMs may be only poorly representative. Skipping the grey zone is possible in research applications by coupling LPDM and LES, but is unfeasible for operational purposes. For the latter, progress in turbulence parameterization design and in the determination of scaling parameters (such as the MoBL height) seems to be mandatory. A further challenge is represented by the inclusion of chemical reactions, especially those with high-order kinetics, in LPDMs.

At the surface, the estimation of emission fluxes in complex-terrain areas is affected by similar complications as that of momentum, energy and water fluxes (Section 2.1.2).

- High-resolution atmospheric models coupled with LPDM are presently the most appropriate tool to simulate pollutant dispersion. Application over complex terrain requires good-quality mean flow and turbulence fields from the meteorological component, as well as LPDM that account for horizontal exchange.

- Further research on the representation of reactive tracers in LPDM is necessary.

- Model validation efforts should be supported by tracer experiments conducted at sites with different degrees of orographic complexity.
2.2 Measurement of MoBL processes

Measuring microscale and mesoscale transport and exchange processes in the atmosphere over mountainous terrain poses great challenges, due to the large degree of spatial heterogeneity that needs to be sampled with sufficiently high resolution over sufficiently large areas. This requires coordinated use of in-situ and remote-sensing measurement platforms. Generally, turbulent fluxes are not measured directly, but rather estimated from high-frequency measurements of field quantities. This is true both for turbulence-resolving in-situ measurements (Sec. 2.2.1) and for remote-sensing retrievals (Sec. 2.2.2). In either case, flux estimation relies on assumptions and methodologies whose applicability over complex orography is questionable. The limitations of fixed measurement platforms can be partially overcome by airborne systems (Sec. 2.2.3).

The material in the following three sections focuses exclusively on known criticalities in the collection and processing of measurement data, having a quantitative impact on the experimental characterization of exchange processes. At present, it mostly deals with measurements in clear-sky conditions. Challenges related to precipitation measurement, as well as to aerosol and trace gas measurements over complex terrain, require further consideration.

For a discussion of the concrete planning of field activities and of the optimal strategies to combine different measurement platforms, please consider Ch. 4.4.

Relevant literature:

2.2.1 Turbulence data processing

The standard approach to evaluate turbulent fluxes is to use a sonic anemometer to measure the three wind components and (sonic) temperature, plus sensors allowing high-frequency measurements for other scalars, followed by application of the eddy covariance method. For complex terrain applications, possible anemometer tilt and local streamline deformation need to be accounted for by rotating the coordinate system that defines the wind components. The choice of the coordinate system has a non-negligible impact on flux estimation. Additional complications arise if the aerodynamic characteristics of the upwind terrain vary with upwind direction; sector-dependent processing algorithms have been developed to handle these cases. Also the separation of turbulent fluctuations from the mean flow properties is handled with a variety of methods. This task is complicated by the fact that atmospheric processes over complex terrain seldom attain steady states and, as a consequence, the appropriate cut-off timescale cannot be easily determined. Despite extensive testing, there doesn’t seem to be general consensus on a single best approach for all sites and conditions.

In the case of stable boundary layers, propagating internal gravity waves can contaminate eddy covariance measurements, so the ability to disentangle turbulent fluctuations from other kinds of atmospheric motions is essential for an accurate estimation of fluxes. Several methods to distinguish wave motions from turbulence were suggested, considering their differences with respect to dominant wavelengths or frequencies, energy transport speed, mixing efficiency, ability to transport scalar quantities, correlations between pressure, temperature, and wind speed fluctuations, and potential vorticity. In practice this is an unsolved issue, and no straightforward and universally accepted approach to the problem exists at present.

Alternative approaches to obtain turbulence information include for instance the use of wavelet transforms in data processing. This method has been used to study canopy flows and airborne turbulence measurements, but its potential for micrometeorological research over complex terrain is largely unexplored. Nowadays, measurement principles alternative to the eddy covariance method are available too (e.g., scintillometry, see Sec. 2.2.2).
Progress in understanding turbulent exchange over complex terrain with the eddy-covariance method depends on thorough understanding of the implications of data processing (e.g., anemometer tilt correction and the determination of the turbulence averaging scale) on the estimate of turbulence statistics.

Collaborative research systematically testing and comparing alternative approaches to measure or process turbulence data is mandatory.

2.2.2 Surface-based remote sensing

The spatial heterogeneity of the atmosphere over complex terrain limits the representativeness of in-situ measurements to relatively small spatial and temporal scales. Surface-based remote sensing can increase the temporal resolution (e.g., vertical temperature and humidity profiles from passive microwave radiometers at intervals of minutes) and spatial coverage (e.g., three-dimensional wind fields from scanning Doppler lidars) of measurements. Nowadays, the increased commercial availability of these technologies provide potential for routine measurements. Another available option to extend measurement coverage is scintillometry, which yields spatially averaged turbulent fluxes in the surface layer and is hence potentially interesting for model verification. Despite this progress, current remote sensing technologies have only limited ability to resolve small-scale spatial heterogeneities. For example, the vertical resolution of microwave radiometers is insufficient to observe complex vertical structures in valley atmospheres, such as shallow elevated inversion layers.

Besides resolution, even other factors may restrict the applicability of remote sensing techniques over complex terrain. In some cases, the basic assumptions on which the measurement principles rely are not necessarily valid in this setting. One example is that horizontal homogeneity has to be assumed for the derivation of three-dimensional wind vectors from conical Doppler lidar scans, as well as for the boundary-layer scans done with passive microwave radiometers to improve the vertical resolution of temperature profiles in the lower atmosphere. Another example is that turbulence characteristics derived from scintillometer measurements implicitly assume the validity of MOST, in addition to spatial homogeneity within the measurement path. Despite their limitations, remote sensing observations provide new means for determining turbulence characteristics on a larger scale than the point measurements from traditional eddy-covariance systems. However, only few studies have determined profiles of turbulent fluxes so far, which require simultaneous measurements with a Doppler lidar and a Raman lidar or Differential Absorption Lidar (DIAL).

A thorough evaluation of the use of surface-based remote sensing in complex terrain is necessary, including a quantification of potential errors produced by invalid assumptions, such as horizontal homogeneity.

Capturing small-scale mountain-specific processes (e.g., slope winds) and determining turbulence characteristics with surface-based remote-sensing instruments requires a coordinated and optimized strategy based on multiple instruments.

2.2.3 Airborne measurements

Adequate sampling of the spatial and temporal variability of exchange processes over mountains requires the ability to cover large areas. Remote-sensing observations from satellites would in principle be an option, but geostationary satellite observations do not have sufficient horizontal and vertical resolution while orbiting satellites do not allow continuous monitoring. An effective way to sample the three-dimensional spatial variability of the MoBL with adequate resolution and coverage is to perform in-situ measurements with a variety of airborne platforms.
Airborne platforms include balloons (radiosondes), tethered balloons, remotely-piloted aircraft systems (RPAS; also known as unmanned aerial vehicles, UAV) and aircraft. Most of them are only partially suited for operation in the MoBL. For instance, the typical frequency of release of radiosondes, even during intensive observation periods, usually allows only very coarse temporal resolution. Large aircraft have comparatively limited manoeuvrability and are not designed for low-elevation flight, while also being subject to restrictions on operation imposed by air traffic control for safety reasons (e.g., flight allowed only above a certain altitude). Their operation is costly and thus limited to short field campaigns. Usability of RPAS is excellent for the purposes of vertical profiling and sampling horizontal transects over short distances, but is otherwise limited by their endurance, their ability to carry only small payloads and the requirement of special flight permits. Small aircraft, ultra-light or motor gliders might be a more appropriate solution, provided they can carry enough payload.

- Stacked horizontal flights of small aircraft or RPAS are a possibility to obtain spatially distributed measurements of mean quantities as well as turbulent flux profiles. Combined use of several airborne platforms is necessary and requires detailed evaluation of operation strategies, possibly with dedicated campaigns.

- Limitations in the processing and interpretation of airborne turbulence measurements, due to inhomogeneity along flight legs, should be taken into account. Data processing should also correct any interference introduced by the measuring platform.
2.3 Numerical modelling of the atmosphere over complex terrain

The ability of atmospheric models to represent mesoscale phenomena and the impact of fine-scale terrain depends critically on model resolution. Current operational weather prediction limited-area models (LAMs) are non-hydrostatic and adopt a grid spacing on the order of 1 km. Most regional climate models, on the other hand, still adopt hydrostatic dynamical cores and a grid spacing on the order of 10 km. Model resolution determines not only the magnitude of numerical errors, but also the applicability of parameterization schemes, which are typically designed with a specific range of grid spacing in mind.

Factors limiting the skill of high-resolution forecasts include the lack of mesoscale detail in their initial conditions, the fast growth of small-scale forecast errors, and the rapid downscale propagation of large-scale initial errors. Consequently, an important pathway for the advancement of high-resolution weather forecasts is the improved specification of boundary and initial conditions, a task that entails special challenges over complex terrain (Sec. 2.3.1 and 2.3.2).

Regardless of their resolution, atmospheric models rely on parameterization schemes, which generally oversimplify the atmospheric behaviour over orography, or are empirically tuned to flat-terrain observations. Deficiencies in parameterizations (Sec. 2.3.3) are an additional source of uncertainty for LAMs. They may also be the cause of systematic model errors, limiting the quality of both short-range weather forecasts and climate simulations regardless of model resolution. In the latter case, the impact of even small model biases is potentially amplified by the very long model integrations.

Relevant literature:

2.3.1 Representation of the surface

Numerical weather prediction models have historically been developed using curvilinear grid systems in which the lower boundary coincides with the Earth’s surface. Such terrain-following grids allow for a simple specification of the surface boundary conditions, while making the formulation of the governing equations only moderately more complex. At km-scale resolutions, traditional terrain-following grids encounter problems in resolving correctly the pressure gradients near steep orography, making models more prone to error and numerical instability. Non-conforming grid systems, in which the model grid is not transformed to adjust to the terrain, are an area of ongoing research: immersed-boundary and embedded-boundary (or cut-cell) methods, whose use is commonplace in engineering, have been recently introduced into NWP codes. However, their development has only focussed on micro-scale simulations and is still at an experimental stage due to difficulties in specifying surface boundary conditions in high-Reynolds-number flow.

Challenges determined by the increasing resolution of LAM are not limited to the specification of model orography and to the related implications on the grid design. Accurate specification of high-resolution surface boundary conditions depends on the availability of sufficiently resolved global databases of surface properties. While this precondition is currently met for digital elevation models, it is not for other type of land data (e.g., roughness length, land-use, vegetation cover). Even when high-resolution land information is available (e.g., the CORINE database in Europe), it is not straightforward to map categorical land information into physical soil properties (required in land-atmosphere exchange models), and to aggregate high-resolution information to the scale of
the grid. The operational monitoring of the soil moisture and temperature fields is also suboptimal: especially in complex terrain, the monitoring relies on sparse and poorly representative observations and on low-resolution remote-sensing retrievals (see also Sec. 2.3.2).

In addition, there is some uncertainty about the most appropriate strategy for specifying surface fluxes over sloping terrain, both in terrain-following grids and in Cartesian grids with immersed or embedded boundaries. Most operational models (based on terrain-following grids) only specify the vertical flux components, in accordance with the boundary-layer approximation. Increasing evidence of the relevance of horizontal fluxes calls for a revision of the current paradigm, at least over complex orography. Theory developed from observations over flat terrain (MOST) may not be applicable over complex topography either (see also Sec. 2.1.2).

- Immersed-boundary and cut-cell methods show promise to improve the forecast accuracy of near-surface atmospheric fields, but require further research directed to improving the specification of surface momentum and energy fluxes.
- Due to the extreme spatial heterogeneity of the physical properties of the land surface in complex terrain, accurate specification of surface boundary conditions is not possible in the absence of high-resolution information and of effective flux aggregation methods.
- Near-surface turbulence is often of non-local origin over complex terrain. Hence, the development of non-local parameterizations of surface fluxes is necessary. Such schemes should incorporate information about the lateral variability of physical land properties, like surface roughness or soil moisture, over spatial scales determined by the orography.

### 2.3.2 Initial conditions

The specification of the initial state of NWP model integrations relies on data assimilation (DA). A few of the basic assumptions of modern DA approaches (e.g., small departures between observations and background field; Gaussian error statistics; unbiased model and observations) are hardly met over mountains.

Systematically large departures from the background (due to model biases, unresolved processes or poor observation representativeness) can cause observations in complex orography to be frequently discarded from the assimilation process. In addition, the models of the observation error covariance needed in variational DA methods can prove inaccurate over mountains. Potential consequences include fitting observations more closely than would be appropriate; or rejecting observations because of large departures (too large relative to an underestimated background error). Ample margin for progress in both variational and ensemble DA still exists, in particular regarding the assimilation of observations critical for surface exchange modelling (e.g., turbulence and soil moisture).

- Examining analysis increments from DA over mountains allows highlighting systematic biases in observations and/or models, offering useful information to improve ABL and land-atmosphere exchange parameterizations over mountains, and consequently DA products themselves.
- Improved mesoscale analyses of the atmospheric state may result from coupled DA. In mountainous areas, high-resolution land-only DA may be a useful alternative to low-resolution coupled DA, due to the high degree of correlation between atmospheric and land variables over mountains (e.g., between atmospheric temperature and soil temperature, or between atmospheric humidity and soil moisture).

### 2.3.3 Parameterizations of sub-grid-scale processes

Atmospheric processes that occur on spatial scales too small to be captured by a model’s computational grid are parameterized. Parameterized processes in NWP and climate simulations
include boundary-layer turbulence, land-atmosphere exchange and, depending on the model resolution, orographic drag, shallow and deep moist convection. A parameterization represents the bulk effects of a sub-grid-scale process using simplified models that rely on the resolved quantities. As the horizontal resolution of atmospheric models steadily increases with time, the explicit representation of atmospheric processes of progressively smaller scale becomes feasible. Therefore, traditionally parameterized processes (e.g. moist convection, turbulence) become at least partially explicitly resolved. However, for any given process, there is no sharp resolution limit between explicit representation and mandatory parameterization. The range of model resolutions that lies between the large-scale limit beyond which parameterization is warranted and the small-scale limit beyond which the process is fully resolved on the model grid is referred to as the grey zone.

Parameterization schemes are usually developed with a specific grid resolution in mind, that is, they are not designed for a proper transition across the grey zone. For instance, the underlying logic of ABL parameterizations for RANS mesoscale NWP models largely differs from that of turbulence parameterizations for LES models. In the current modelling paradigm, high-resolution simulations are only made in nested domains, where specific sub-grid-scale models designed for small grid spacing are adopted. In fact, this is a pragmatic way of avoiding running models at grey-zone resolutions. More often than not, fine-scale structures in nested domains do not develop in a realistic manner, because they cannot be properly initialized and advected from the outer domains, and they are affected by spurious wave motions originating along the lateral boundaries. The limitations of current parameterization schemes, especially of turbulence and convection, call for further investigations on improving their scale adaptivity.

Besides grey-zone issues, boundary-layer and surface-layer parameterizations for complex terrain fundamentally suffer from oversimplified treatment of horizontal exchange (for instance: purely local parameterization of land-atmosphere exchange or, in the case 1.5-order ABL schemes, neglecting horizontal derivative terms in the turbulent kinetic energy equation).

Inaccurate parameterizations of SGS processes can introduce distinctive model biases. These can be aggravated by extended integration times, e.g., in climate modelling. For instance, latent heat exchange modelling based on concepts for flat terrain may not decisively deteriorate a weather forecast, but it might systematically yield too much or too little evaporation, so that a particular location (not necessarily only the one affected by the largest evapotranspiration bias) gets too dry or too wet over the years of a climate simulation, altering the meso-scale flow patterns and feeding back to the larger-scale flow.

Another example relates to orographic drag. Climate models suffer from biases in the hemispheric circulation due to an imperfect treatment of orographic drag. The partitioning between parameterized and resolved orographic drag varies greatly between different models, as it is mostly determined by ad-hoc tuning of the parameterization schemes. Orographically-induced momentum fluxes have undergone careful scrutiny because of their obvious impact on the global circulation. Knowledge on the global-scale effect of orographically-induced energy and mass fluxes, and on the adequacy of their parameterization in models, is instead largely lacking.

- Future research should be devoted to testing and improving scale-adaptive parameterizations, especially unified mixing schemes that represent simultaneously the local effect of turbulent mixing and the non-local effect of convective and terrain-induced transport. The further development of nesting methods that allow the realistic development of fine-scale structures in high-resolution grids should also be pursued.
- While the biases related to the modelling of momentum exchange over mountains have been studied extensively, justifying the urgency of improved orographic drag schemes, the possible impact of imprecise modelling of heat and moisture exchange over mountains has so far eluded investigation.
2.3.4 Forecast uncertainty and predictability issues

Imperfections in initial conditions, numerical approximation, imperfect parameterization schemes and non-linear error growth are the primary sources of uncertainty in numerical weather predictions. Forecast uncertainty evolves during the forecast range and, in practice, it is generally estimated with ensemble prediction systems (EPSs). The first operational ensemble forecasts were based on global models and date back to the early 1990s, but limited-area ensembles with convection-permitting grid spacing gained increasing popularity in more recent years. Limited-area ensemble forecasting has its own specific challenges. First, handling of lateral boundary conditions is an additional source of uncertainty in this case. In addition, it remains unclear whether the various perturbation methods used in convection-permitting ensembles are equally effective as those adopted for global EPS. Recent scale-dependent predictability studies suggested that outputs from individual members of convection-permitting ensembles become fully de-correlated at the smallest resolved spatial scales in a matter of only a few hours. This implies low practical predictability at the small scales, likely due to a perturbation design that is not sufficient to fully model the initial-condition uncertainty.

Uncertainty due to imperfect model formulation is estimated in EPSs using model error schemes. These schemes, which primarily serve the need of inflating ensemble spread, are presently based on the introduction of spatially and temporally correlated stochastic perturbations either into the parameterized tendencies of prognostic variables or in the least well-constrained free parameters of the parametrization schemes. However, the current understanding of the dynamical impact of these perturbations remains rather limited.

- Predictability issues in convection-permitting EPS are not specific to complex-terrain modelling, yet it can be intuitively expected that explicitly resolved orographic forcing is a source of predictability. The weather conditions and the spatial and temporal scales at which orography effectively enhances atmospheric predictability are not known in detail.
- Useful developments of stochastic parameterizations of turbulent mixing and moist convection may result from physically based schemes aware of sub-grid-scale orographically-induced air motions (e.g., inherently stochastic treatment of surface-layer exchange over non-homogeneous terrain, as opposed to universal use of MOST).
3 Impact

3.1 Better understanding

Current atmospheric models use theoretical understanding valid over flat and homogeneous terrain to parameterize the turbulence-related part of Earth-atmosphere exchange, even over steep and complex orography. Due to this ill-defined foundation, weather forecasts are expected to be more difficult in complex terrain than over plains.

The practical aim of weather forecasting may be considered to meet sufficient quality standards in the forecasts of basic weather elements (precipitation, temperature, wind), and one may argue that nowadays the quality of these forecasts is not significantly different between mountainous and plain regions. However, a number of additional atmospheric variables, often related to turbulence and exchange processes, are routinely used in applied meteorology (Sec. 3.3). These include surface heat exchange, turbulence kinetic energy, Reynolds stresses and turbulent fluxes throughout the ABL. In forecast models, these are parameterized quantities. Simulations of these quantities are not routinely verified, but rather tuned in order to optimally reproduce empirical evidence, often deriving from temporally and spatially limited observational datasets.

Climate change scenarios fundamentally depend on the assumption that the accuracy of climate models, and in particular of physical process parameterizations, does not change over the temporal horizon of the projection. Evidently, this cannot be taken for granted if parameterizations are subjected to extensive tuning towards present-day climate, potentially leading to simulations plagued by unclear error compensation effects.

In light of this, it is necessary to work towards making weather forecasts and climate simulations right for the right reason (that is, based on physically sound principles, subjected to minimal tuning and free of error compensations). Improving the understanding and the representation of atmospheric processes over complex orography is an important part of this general overarching aim.

3.2 Useful observational data

Field observations will be an integral part of TEAMx to answer the scientific questions outlined in Sec. 2. Data collected from a spatially dense and multi-scale network of diverse observational platforms will provide a basis for improved understanding of the relevant processes and for evaluation of modelling systems and existing model parameterizations, including their underlying assumptions. New theories for parameterizations and new benchmark simulations for MoBL-specific processes can be developed based on this observational dataset.

The combination of high-quality observations, numerical experiments and new theoretical models may help identify needs for the future establishment of additional routine measurements, e.g., for improving error statistics in the assimilation of surface data or for improving the estimates of MoBL depth used in pollutant dispersion modelling. Recommendations resulting from the identification of potential needs can then be implemented by national weather services and environmental agencies. Finally, testing new remote-sensing techniques against more traditional observations can lead to improvements in their use over complex terrain and thus to the extension of current measurement capabilities in terms of spatial/temporal resolution and coverage.
3.3 Better models

Relevant literature:

Nowadays, almost all the weather forecasts conveyed to the general public are based on some kind of modelling product. Improvements in parameterization schemes developed during TEAMx will contribute to providing more accurate weather and climate information at the local scale in complex terrain, resulting in generally better numerical forecasts and more timely weather warnings. Weather and climate information is relevant not only to forecasting, but also to many scientific disciplines and weather-sensitive sectors of the economy. Air pollution studies were dealt with in Sec. 2.1.7, but accurate knowledge of atmospheric properties strongly affected by exchange processes is essential in a number of other disciplines. For instance:

- Forecasting extreme weather (deep convection, hail and flooding) and weather-related natural hazards (e.g., landslides) is of capital importance for civil protection. Complex-terrain areas are particularly exposed to such risks, in particular small catchments where flooding can occur over extremely short timescales. In fact, providing precipitation fields for hydrological run-off modelling is one of the most crucial meteorological services.
- Forecasting the distribution, density, albedo and evolution of the snowpack in mountainous areas, including its redistribution by the wind and its sublimation, is critically important for avalanche warning and, on longer time scales, for water resource management.
- Wildfires, whose propagation depends primarily on fuel availability, can be reinforced by specific weather conditions caused by mountain-wave dynamics, e.g., extremely low near-surface humidity and high wind speeds. Fire forecasting is made challenging by the fact that wildfires are affected by the environmental conditions but also modify them, as is made visible by pyrocumulus clouds.
- Several tasks in agriculture (e.g., irrigation, fertilizing, applying pesticides, operating frost protection systems) can be optimized if good forecasts of the surface weather are available. Information about winds, temperature and moisture is also critical in dealing with public health issues like pollen dispersion or disease spreading.
- Some aspects of urban planning, for instance ensuring nocturnal cooling and ventilation of the urban atmosphere, can benefit from the knowledge of local breeze circulations induced by the orography or by urban/rural land-use contrasts.
- The extrapolation of measured wind energy potential to nearby sites is generally based on flat-terrain paradigms, which have numerous limitations over complex orography. Optimal micro-siting often has to deal with meteorological considerations related to near-surface momentum exchange (e.g., topographically-induced wind speed-up and turbulence).
- Surface exchange of heat and moisture (including snowmelt, evapotranspiration and cloud formation) affects other renewable energy industries too (e.g., hydropower, solar energy).
- Transportation (primarily air traffic, but ground transportation as well) is affected by atmospheric conditions, in particular by visibility, icing, wind and turbulence. Some of the most adverse conditions for traffic in mountainous areas (mountain-wave turbulence, downslope windstorms, fog, low visibility, road-surface freezing) are intimately connected with one or another form of exchange process.
- Since major transportation routes are typically confined in valleys, these are particularly exposed to traffic-related air pollution. Partial relief might result from regulatory systems adopting measures (e.g., speed limits or bans of certain vehicle types) depending on traffic count data and on forecasts of boundary layer depth and mixing, before critical concentration thresholds are reached.
Meeting these needs requires providing forecasts on a broad range of space and time scales, which is only possible using different tools, from general circulation models to large-eddy simulation codes. Regardless of model resolution, virtually all the relevant model output is critically affected by the accuracy of a few key parameterization schemes, which are known to suffer from strong limitations over complex orography (e.g., radiation, turbulence, land-atmosphere exchange, etc.).

The necessity of reducing the uncertainty of observations and forecasts to the benefit of end-users demands acquiring application-oriented observational data over orographically complex regions. Since the weather parameters of interest, the optimal observation strategies, the most relevant forecast ranges and the admissible observation and forecast uncertainties are all application-dependent, involvement of weather service users in the planning of any dedicated observational effort is essential.
4 Implementation (preliminary considerations)

4.1 Organization

TEAMx activities are spearheaded by a Coordination and Implementation Group (CIG) established in September 2017 and consisting of 13 members. A Memorandum of Understanding (MoU) has been signed among the institutions that support TEAMx, which initially coincide with the home institutions of the CIG members. The TEAMx partnership welcomes new members.

In August 2018 a TEAMx Programme Coordination Office (PCO) was created at the University of Innsbruck. As of August 2019, the TEAMx PCO has received financial support from the Karlsruhe Institute of Technology, Meteo France, MeteoSwiss, the National Center for Atmospheric Science, the University of Innsbruck, the University of Trento, and ZAMG.

It is envisioned that funding for TEAMx research will be acquired through a bottom-up approach. Participating scientists and institutions are supposed to gather the necessary financial resources through projects supported by national and international research funding agencies after successful peer-review.

In the future, collaborative research within TEAMx will be organized in Scientific Working Groups and coordinated by a Scientific Steering Committee where all working groups are represented.

4.2 Phases and indicative timeline

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Definition of working groups
Numerical experimentation
Observation phase
Analysis phase

4.3 Numerical experimentation

A recent survey of systematic errors in weather and climate models (WMO Working Group on Numerical Experimentation, Oct. 2018), receiving 35 answers from 14 different modelling centres, defined a ranking of the model errors that need to be addressed with the highest priority. Processes tightly related to surface exchange are on top of the list, and include convective precipitation, surface fluxes, diurnal cycles. Albeit with lower priority, orographic precipitation and surface drag found their place in the ranking too. A coherent plan to identify and possibly reduce systematic model errors over mountainous terrain should be based both on idealized, process-based numerical experimentation, and on the routine verification of operational NWP.

4.3.1 Idealized numerical experiments

Idealized simulation has been widely used to explore the underlying mechanisms of a variety of processes related to atmospheric exchange over orography (thermally-driven flow, mountain waves and atmospheric rotors, convection initiation). Drastic simplifications are introduced in several aspects of these simulations (initial state, topography profile, treatment of surface-layer exchange).
Future research should work towards reducing the level of idealization by incorporating at least some elements of complexity, which are known to greatly affect the intensity of exchange in the real world (e.g., background flow variability, small-scale terrain irregularities, land-cover heterogeneity, spatially- and temporally-variable solar forcing). Collaborative research based on idealized simulations may serve in particular the purposes of model evaluation and parameterization development, through studies designed to simulate well-constrained processes and track any model deficiency back to specific features of parameterization schemes or dynamical cores.

In fact, intercomparison of idealized simulations has already been used to evaluate the ability of models to simulate certain mesoscale processes. For instance, systematic comparison of idealized mountain-wave simulations, evolving from identical initial states but performed with different models, led to identifying considerable spread in the vertical flux of horizontal momentum, mostly imputable to differences in dynamical cores. Similar analyses of simulations of thermally-induced breezes revealed that the parameterizations of land-atmosphere exchange and boundary-layer turbulence were the major sources of spread in this case, while diversity in dynamical cores had comparatively minor influence. Useful knowledge may be gained by replicating the approach of idealized intercomparison for additional mesoscale processes, e.g., the initiation of deep moist convection due to thermally-induced or mechanical destabilization.

While observational data have typically not been a concern in intercomparison studies dealing with mesoscale phenomena, they have been central to those addressing boundary-layer and surface-layer processes. For instance, the GEWEX Atmospheric Boundary Layer Study (GABLS), which mostly focussed on stable boundary layers, included a sequence of model evaluation studies with increasing complexity. The first GABLS benchmark case focused on turbulent mixing in a moderately stable boundary layer driven by uniform geostrophic wind and cooled by contact with an ice surface. Subsequent studies dealt with increasingly complex problems (simulation of the complete diurnal cycle, low-level jets, very stable boundary layers) and introduced additional model elements (e.g. parameterizations of radiative transfer and land-surface exchange). All studies included intercomparisons between observations, large-eddy simulations and single-column versions of NWP codes. Results emphasized for instance overestimated nocturnal mixing in ABL parameterizations or considerable inter-model differences in the representation of transition phases, spawning subsequent research to solve these issues.

All GABLS intercomparison studies considered flat and homogenous terrain. Designing complex-terrain benchmark cases with an overarching logic similar to GABLS is a useful way of pushing research on the modelling of complex-terrain exchange forward. While the GABLS approach can largely be exported to the study of complex-terrain phenomena, a few adaptations will prove necessary. These include: i) Design of benchmarks addressing separately the role of orographic and land-cover complexity; ii) Extension of the pool of participating models, to include different types of model grids and treatment of the surface, including immersed and embedded boundary methods; iii) Replacement of single-column models by small-sized regional domains, in order to retain a level of terrain complexity and explore the problems posed by horizontal exchange parameterization.

Several past field campaigns can provide observational data for the design of the initial benchmarks cases. At a more advanced stage, focus on the three-dimensional distribution of turbulence or on boundary-layers affected by mesoscale disturbances (e.g., föhn penetration) might require the use of observations from the TEAMx field phase (Sec. 4.4).

4.3.2 Performance of operational NWP models over complex terrain

Considering the limitations of the representation of orographic forcing in NWP and climate models (Sec. 2.3), the hypothesis that numerical simulations are plagued by larger systematic errors over or near mountains than over flat terrain seems justified. However, no systematic proof of this
conjecture has been provided so far. In some studies, on the contrary, better model performance was reported over mountains than over plains. However, since different weather parameters and verification metrics were considered, it is practically impossible to generalize results. Systematic comparison of model performance over flat and complex orography is out of the scope of routine forecast verification, and can become the subject of renewed collaboration in LAM verification. A study focussing on complex-terrain verification should consider a temporal range of a few years, a broad set of measurement stations covering a major mountain range with homogeneous density, and possibly also small clusters of neighbouring stations located at morphologically different sites (e.g., valley floor/mountain top pairs). The investigated parameters should not be limited to precipitation, temperature and wind, but include quantities related to surface exchange (e.g., surface energy budget components, low-level cloud fraction, mixing heights). Stratification of the dataset by the expected intensity of exchange (e.g., by daily total global radiation) may prove useful. Additional aspects whose implications should be considered are observation uncertainty, which is generally significant in mountainous areas due to the poor representativeness of measurement sites, and the possibly large differences between modelled and true orography. Model-independent gridded analyses of observations, possibly covering entire mountain ranges, may be a useful tool for verification. Gridded observational datasets can also be exploited for data assimilation and nowcasting purposes or, if made available for extended temporal periods, for climate change studies.

Identifying systematic model errors from forecast/observation comparisons might require using model diagnostics that are more sophisticated than the traditional scoring rules, which only focus on quantifying the average distance between paired observations and forecasts. Alternative approaches could include, for instance, diagnostics based on physical links between various observable parameters, or diagnostics derived from data assimilation (e.g., statistics of the deviations between observation and background fields at specific sites).

4.4 Observations

A major goal of TEAMx is to conduct co-ordinated experimental activities in order to:

i) characterize the structure and spatial/temporal variability of the MoBL (Fig. 4);
ii) better understand and hence model the relevant exchange processes.

iii) verify current NWP models and validate or train post-processing and downscaling algorithms for weather and climate simulation.

The specific challenges of the field experiment will be:

- **High observation density.** The processes that contribute to the exchange between the mountain surface and the free troposphere have a high degree of spatial variability. Sampling this variability requires a large number of available instruments, which can only be achieved through cooperation between different groups.

- **Common procedures for data processing.** Having different groups active in the same target area makes it necessary to coordinate the measurement strategies, retrieval algorithms, post-processing options, etc.

- **Extended temporal coverage.** The typical duration of field experiments (up to a few months) is not appropriate for climatological studies and poses interpretation challenges even for meteorological investigations. In particular, the interaction of processes at different spatial scales (e.g., convection initiation occurring in a specific configuration of synoptic flow and thermally driven circulation) makes it unlikely to encounter similar conditions during a sufficient number of days within a single campaign. Existing long-term observational platforms are therefore
important for assessing the representativeness or generality of the intensive observations made on individual days, as well as bridging the gap towards climatological time scales.

- **Concentration of measurement efforts.** Different exchange processes may be better observed at different sites. For instance, mountainous regions next to high-emission areas are intuitively better suited for pollutant transport studies. Study of orographic convection might require a target area in the vicinity of a climatological maximum of convective rainfall. However, logistical aspects and the necessity of overall scientific coordination require concentration of resources in a limited number of sites.

The coordinated experimental activities are planned to culminate in a field experiment, tentatively planned for 2023. An earlier field phase does not appear feasible at this stage. This is in part due to the desired deployment of the US National Science Foundation (NSF) observational facilities and the involvement of the North American scientists. Given the existing NSF funding procedures, for a large deployment of NSF observing facilities to happen in 2023, an NSF application, including a science proposal and an experimental design, will need to be submitted by January 2021, that is two years before the planned field phase.

At least one target area of the field experiment will be in the European Alps. This is because most of the institutions that initiated TEAMx are based in Europe and because the high-density surface measurement network available in the Alps (which includes semi-permanent micrometeorological observatories) is an asset not available in other mountainous regions. Consideration of other target areas, motivated by scientifically sound reasons, is not excluded a-priori.

One major concern regarding the European Alps is that they are extensively covered by vegetation and receive precipitation more or less continuously throughout the year. Other major mountain ranges worldwide, like the Andes or the Himalayas, are under very different climatic conditions and generally mark a sharp transition between relatively moist and very arid regions. Given the marked impact of soil and vegetation on exchange processes, observational efforts in climate areas other than the mid-latitudes might prove necessary, in coordination with TEAMx.

### 4.4.1 Target areas

A prototypical target area for the experimental study of exchange processes influenced by orography may be a deep alpine valley system (i.e., valley floor, sidewalls and mountain tops; see Fig. 4) with length on the order of 100 km, elevation difference between floor and mountain tops on the order of 1000 m or more and crest-to-crest width of a few tens of km. Tributary valleys may be considered too, as well as nearby forelands.

The ideal aim of the experimental design would be to cover at least one major alpine valley with an approximately regular grid of surface measurements, flux stations and profiling sites, with density comparable to the resolution of current operational NWP models. This is not feasible in practice, even under the most optimistic assumptions about the availability of measurement platforms. Therefore, surface and profiling sites must be chosen at characteristic locations, all within a short range (e.g., a cross-valley transect consisting of sites at the valley floor, slopes of differing steepness and altitude, and mountain tops). Redundant measurements at individual sites should be made.

Valley orientation is an important concern. On the one hand, it affects the spatial heterogeneity of surface forcing through the dependence of the energy budget on slope orientation relative to the sun. On the other, it determines whether the valley atmosphere is shielded from or exposed to the prevailing synoptic flow, and therefore the dominant interacting exchange processes. Optimally, instrumentation should be distributed in a limited number of valleys with similar morphological features, but different orientation.

The search for the optimal target area may be based on different strategies, including: i) concentrating all field efforts in a complex valley system, with a major valley and a few tributaries; ii) searching for individual valley systems with similar morphology but different orientation, possibly...
also in different climatic zones (e.g., North and South of the Alps); iii) focussing on one or more prominent mountain massifs (i.e., well-delimited portions of a major range), surrounded by easily accessible major valleys and featuring pronounced land-cover variability, including glaciers. Availability of long-term observations is an important pre-requisite, for the purpose of assessing the representativeness of IOP observations. Given this consideration, the i-Box in the Inn Valley, a more or less E-W oriented major valley in the Alps, is a candidate environment. Its current instrumentation would require quite substantial extension. Other long-term installations exist or are being installed in the Pyrenees (P2OA) and in the Apennines (ADAMO).

Whatever the final choice for the target area will be, the instrumentation layout will approximately follow the scheme illustrated in Fig. 4-5 and in Sec. 4.4.2.

**Figure 4.** Schematic draft of an experimental outline in a valley system.

**Figure 5.** Different instrumentation at different levels to assess the three-dimensional structure of mean quantities and turbulence.
### 4.4.2 Essential instruments

The following list of essential instrumentation is neither a final plan nor a survey of what is available among potential TEAMx contributors. It is merely an aid to the planning of what and how to measure in a generic potential target area. The overall concept of the instrumental deployment is sketched in Fig. 4, while the use of different platforms to sample different layers of the valley atmosphere is depicted in Fig. 5.

<table>
<thead>
<tr>
<th>Parameter/process</th>
<th>Measurement platform</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic state variables at the surface</strong></td>
<td>Mesonet/transects of automatic weather stations</td>
<td>Extend from valley floor up to mountain tops</td>
</tr>
<tr>
<td></td>
<td>Portable weather stations/data loggers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DTS, Distributed Temperature Sensing</td>
<td>Sensing of wind speed &amp; direction possible as well with heated optic fiber (experimental)</td>
</tr>
<tr>
<td><strong>Near-surface turbulence</strong></td>
<td>Multi-level flux-towers</td>
<td>Mostly 10-m towers, possibly one 100-m tower</td>
</tr>
<tr>
<td></td>
<td>Advection sites</td>
<td>At least one mountain-top tower, possibly upwind/downwind towers</td>
</tr>
<tr>
<td></td>
<td>Surface energy balance</td>
<td>Single-level flux sites for spatial variability</td>
</tr>
<tr>
<td><strong>Vegetation state</strong></td>
<td>Webcams, narrow-band radiometers (NDVI)</td>
<td>Redundant measurements of soil moisture and heat flux</td>
</tr>
<tr>
<td><strong>Vertical profiles and three-dimensional structure of basic state variables and turbulence</strong></td>
<td>Wind lidars</td>
<td>Several valley sites, coordinated vertical scans</td>
</tr>
<tr>
<td></td>
<td>Raman and DIAL lidars</td>
<td>Mountain-top sites, coordinated horizontal scans</td>
</tr>
<tr>
<td></td>
<td>Microwave profilers</td>
<td>At least one mountain-top site, vertically pointing</td>
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<td></td>
<td>Sodars</td>
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<td></td>
<td>Radiosondes</td>
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<tr>
<td></td>
<td>Tethersondes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ultra-light aircraft</td>
<td>Variances of T, RH and w required</td>
</tr>
<tr>
<td></td>
<td>RPAS</td>
<td>Variances of T, RH and w required</td>
</tr>
<tr>
<td></td>
<td>Scintillometers</td>
<td></td>
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<tr>
<td><strong>PBL/MoBL height</strong></td>
<td>Ceilometers</td>
<td></td>
</tr>
<tr>
<td><strong>Exchange with the free atmosphere</strong></td>
<td>Airborne in-situ measurements</td>
<td>High-rate (~100 Hz) measurements required</td>
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<tr>
<td></td>
<td>PTR-TOFS for tracer measurements</td>
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<tr>
<td></td>
<td>Fluorescence tracers</td>
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<tr>
<td><strong>Precipitation</strong></td>
<td>Rain gauges</td>
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<td></td>
<td>Disdrometers</td>
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<tr>
<td></td>
<td>Network of X-band radars</td>
<td>Potentially airborne</td>
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<td></td>
<td>Cloud radars</td>
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<tr>
<td></td>
<td>Microwave radiometers</td>
<td>For liquid water path</td>
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<td></td>
<td>Oxygen isotope measurements</td>
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<tr>
<td></td>
<td>Runoff</td>
<td></td>
</tr>
<tr>
<td><strong>Regional-scale surface fields</strong></td>
<td>Satellite retrievals</td>
<td>Soil temperature and moisture, energy fluxes, precipitation, vegetation state</td>
</tr>
</tbody>
</table>
4.4.3 Observation periods

The minimum conceivable duration of an Extended Observation Period (EOP) is one full year, or longer for any activity taking place at long-term observatories. During the EOP the core surface instrumentation will be kept permanently in the field in order to sample at least one yearly cycle. Since continuous availability of aircraft cannot be given for a full year, a number of Alert Periods (APs) will be defined, during which aircraft is available for flight missions, soundings are released and any special operations with surface instrumentation take place. APs would optimally be at least one per season and last several weeks each, depending on available funding for aircraft operation. During APs, individual Intensive Observation Periods (IOPs) will take place. IOP start will be decided based on the state of the atmosphere. Weather conditions deserving IOP status could include for instance:

i. Thermally-dominated exchange (prospective valley wind days in a levelled pressure field).
ii. Dynamically-modified exchange (e.g., prefrontal conditions with föhn occurrence, still significant surface fluxes).
iii. Synoptically-dominated exchange (e.g., frontal passages, weak surface forcing).

Distributing APs and IOPs over a full year will permit sampling and comparing conditions with markedly different Bowen ratio (from 0.1 over 1 to 10).

If operations (flight, soundings, lidar scanning strategies) need to follow different procedures depending on weather conditions, an operations coordination centre may be necessary.

4.4.4 Monitoring on climatological timescales

Typically, continuous observations over a 30-year period are considered necessary in order to characterize climate. Monitoring of near-surface turbulence on a comparable time-scale is performed only in a handful of sites worldwide, while mapping the 3D structure of the MoBL on a decadal time scale is simply not possible with the current technology. Existing long-term observational platforms (e.g. i-Box, P2OA) may at least partially bridge the gap between an EOP and climatologically relevant time scales, but they should be operated and upgraded according to a specific coordinated strategy.

Climatological investigations of exchange processes at sites where permanent observatories do not exist require, beyond observations, model-based and theoretical approaches. The optimal strategy may lie in a combination of long-term installation of low-cost sensors for essential climate variables and shorter-term field experiments with full deployment of turbulence-resolving instrumentation. For instance, one-year monitoring of turbulent fluxes at any given site of interest could serve as the basis to establish local scaling laws, which could then be used to infer estimates of the surface energy budget components over a considerably longer time period, from cheaper or possibly already available measurements of the mean quantities.

4.5 Links to other initiatives

**AQUARIUS** is a future aircraft campaign, planned in the winter of 2021/2022 to investigate wintertime PM in mountain basins of the western U.S.

**GEO-GNOME** is a working group that aims at addressing the paucity of observation data and information on mountains. GEO-GNOME is working on compiling and providing data, both related to historical conditions and to future projections that support examination of the drivers, conditions and trends at a variety of different scales.

**PROBE** is a recently approved COST Action on PROFiling the atmospheric Boundary layer at European scale. It aims at enhancing networking and coordination between researchers that deploy and manage temperature, humidity, wind, aerosol and cloud profilers.
### Appendix: Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABL</td>
<td>Atmospheric Boundary Layer</td>
</tr>
<tr>
<td>ADAMO</td>
<td>Apennine Distributed Atmospheric Mesoscale Observatory</td>
</tr>
<tr>
<td>AP</td>
<td>Alert Period</td>
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<tr>
<td>ALPEX</td>
<td>Alpine Experiment</td>
</tr>
<tr>
<td>AQUARIUS</td>
<td>Air Quality Research in the Western US</td>
</tr>
<tr>
<td>CIG</td>
<td>Coordination and Implementation Group</td>
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<tr>
<td>COPS</td>
<td>Convective and Orographically-induced Precipitation Study</td>
</tr>
<tr>
<td>COST</td>
<td>European COoperation in Science and Technology</td>
</tr>
<tr>
<td>EDW</td>
<td>Elevation Dependent Warming</td>
</tr>
<tr>
<td>EOP</td>
<td>Extended Observation Period</td>
</tr>
<tr>
<td>GABLS</td>
<td>GEWEX Atmospheric Boundary Layer Study</td>
</tr>
<tr>
<td>GEO</td>
<td>Group on Earth Observations</td>
</tr>
<tr>
<td>GEO-GNOME</td>
<td>GEO Global Network for Observations and Information in Mountain Environments</td>
</tr>
<tr>
<td>GEWEX</td>
<td>Global Energy and Water Exchanges</td>
</tr>
<tr>
<td>IOP</td>
<td>Intensive Observation Period</td>
</tr>
<tr>
<td>LAM</td>
<td>Limited-Area Model</td>
</tr>
<tr>
<td>LES</td>
<td>Large-Eddy Simulation</td>
</tr>
<tr>
<td>LPDM</td>
<td>Lagrangian Particle Dispersion Model</td>
</tr>
<tr>
<td>MAP</td>
<td>Mesoscale Alpine Programme</td>
</tr>
<tr>
<td>MoBL</td>
<td>Mountain Boundary Layer</td>
</tr>
<tr>
<td>MoU</td>
<td>Memorandum of Understanding</td>
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<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
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<tr>
<td>P2OA</td>
<td>Plateforme Pyrénéenne d’Observation Atmosphérique</td>
</tr>
<tr>
<td>PyREX</td>
<td>Pyrénées Experiment</td>
</tr>
<tr>
<td>PROBE</td>
<td>PROfiling the atmospheric Boundary layer at European scale</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds-Averaged Navier-Stokes equations</td>
</tr>
<tr>
<td>RPAS</td>
<td>Remotely Piloted Aircraft Systems</td>
</tr>
<tr>
<td>SBL</td>
<td>Stable Boundary Layer</td>
</tr>
<tr>
<td>TEAMx</td>
<td>MulTi-scale transport and Exchange Processes in the Atmosphere over Mountains – programme and eXperiment</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicles</td>
</tr>
<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
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</table>