TEAMx

Numerical Modelling Plan

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Preface

TEAMx is an international research programme that aims at improving the understanding of processes in the atmosphere over mountains at multiple scales and at advancing the representation of these processes in numerical models for weather and climate prediction. Its acronyms stands for *Multi-scale transport and exchange processes in the atmosphere over mountains – Programme and experiment*. TEAMx is a bottom-up initiative, formally established by a Memorandum of Understanding beween a network of universities, research institutions and national weather services. TEAMx is carried out by means of individual and institutional research projects, mostly at national level. International coordination is supported by a Programme Coordination Office at the Department of Atmospheric and Cryospheric Sciences of the University of Innsbruck, Austria. The present document describes all *collaborative* weather and climate modelling activities related to TEAMx.

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1. Introduction

Modellers in the mountain meteorology and climatology community generally agree that the accuracy of numerical weather and climate models over mountainous regions is worse than over adjacent flat and homogeneous terrains (Rotach et al., 2022). The diminished skill in mountainous areas is primarily attributed to the lack of parameterization schemes capable of adequately representing sub-grid-scale processes over complex terrain. Although these two statements enjoy broad consensus, scientific literature provides limited and inconclusive evidence in both cases.

In addition to deficiencies in parameterization schemes, other factors contribute to relatively poor weather forecasts and climate projections over mountains. These include discretization errors in terrain-following coordinate systems, inaccuracies in model terrain representation, and suboptimal data assimilation techniques resulting in less accurate initial conditions. Determining the relative contributions of these factors to overall model skill (or lack thereof) remains an open question. Furthermore, the absence of reliable observations from high-elevation regions makes the verification and evaluation of weather and climate models over such areas particularly challenging.

These considerations have led to the establishment of the TEAMx research programme, which integrates both modelling and observational efforts. A large-scale observational campaign known as the TEAMx Observational Campaign (TOC) is scheduled to occur from autumn 2024 to autumn 2025. The TOC focuses on target areas located along a transect through the Eastern Alps, including the German Alpine Forelands, the Inn Valley, the Alpine Crest and the Adige Valley (Figure 1). Instrumentation operated by numerous research groups will convey detailed information about the dynamic and thermodynamic structure of the atmosphere. Two extended observation periods (EOPs), one during winter and another during summer, will provide valuable additional measurement data, particularly from aircraft operations and radiosoundings.

The main objective of this Numerical Modelling Plan is to provide guidance on conducting modelling research within the TEAMx framework to enhance numerical weather prediction (NWP) and climate model development, and on effectively utilizing the abundant observational data for model verification purposes. The selection of the covered topics follows two major criteria. First: the research must be relevant to the scientific objectives outlined in the TEAMx White Paper. Second: the research must be *collaborative*, that is, it can be carried out in a meaningful way only by multiple principal investigators working in a coordinated manner, exchanging data and expertise with each other. We aim at defining the *potential* scope of collaborative modelling research in TEAMx, so it is not relevant whether the proposed research has already been funded or not.

Chapter 2 lays a foundation for coordinated modelling research within TEAMx, by reviewing some known sources of error for simulations of the atmosphere over mountains. Some of these technical and conceptual challenges have been satisfactorily settled by now, others are still unsolved. The research efforts outlined in the following chapters are directly connected with one or more of the open challenges.

Prior to the TOC, modelling activities will focus on conducting intercomparison studies (Chapter 3) to identify the limitations exhibited by current numerical models when applied to regions with complex terrain. The selection of processes and case studies aligns with the modelling challenges outlined in Chapter 2, and makes reference to the target areas of the TOC.

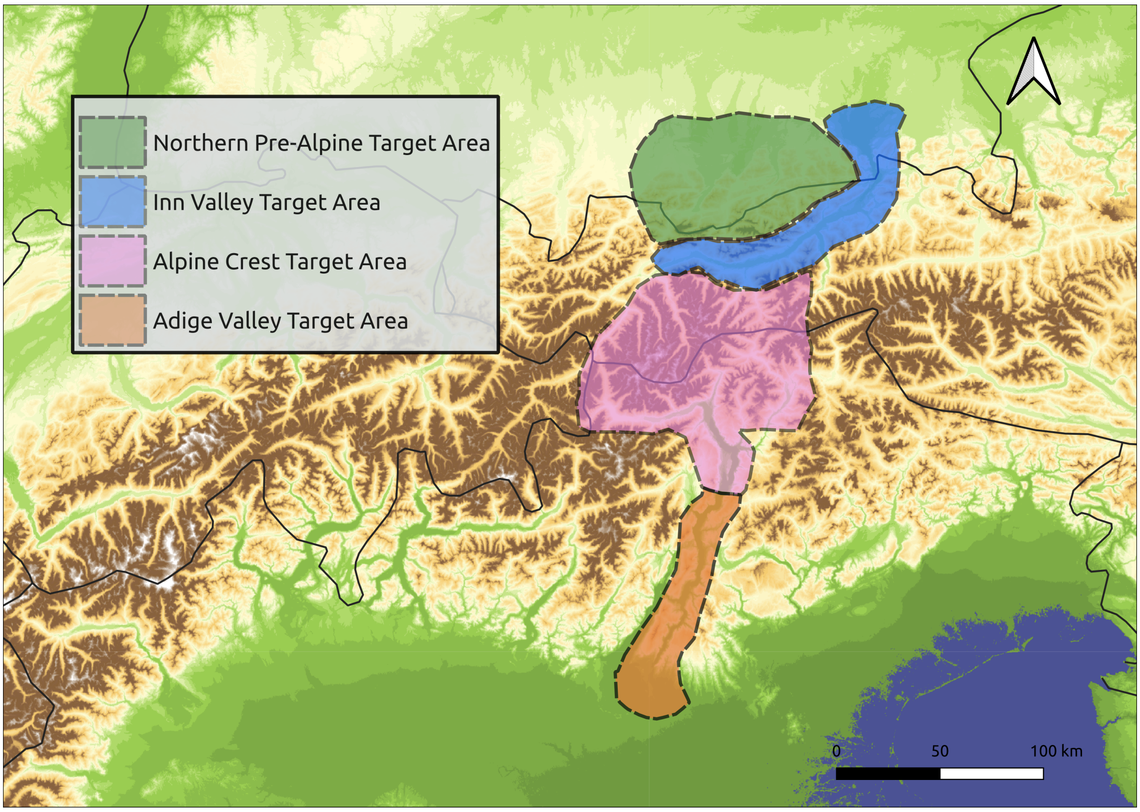
During the TOC, the focus will be on testing next-generation operational NWP systems and experimenting with near-real-time assimilation of campaign observations into operational-scale models (Chapter 4).

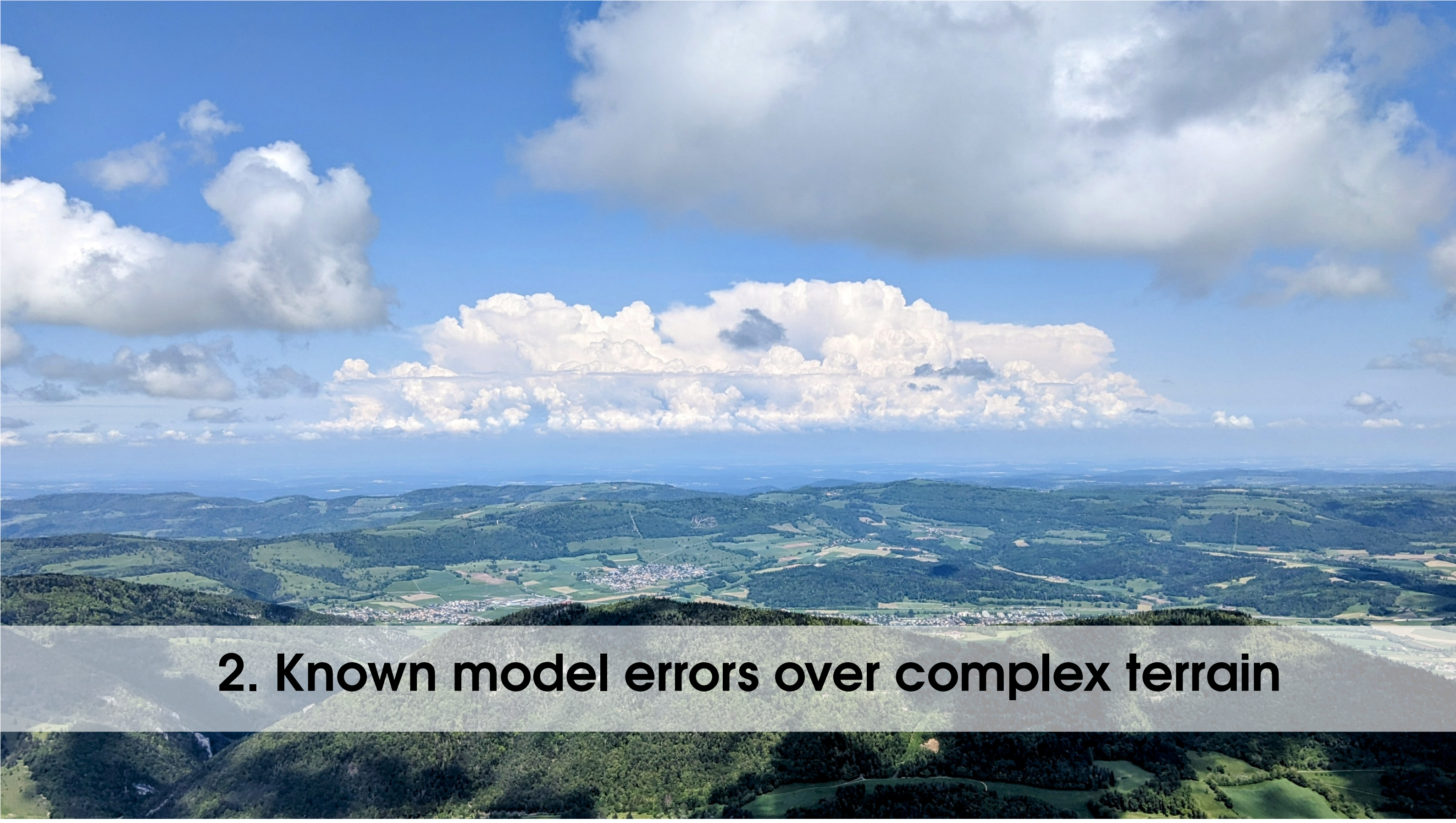
Following the TOC, multiple modelling projects will make use of the atmospheric observations collected during the campaign (Chapter 5). One major objective is to produce an unprecedented very-high resolution analysis of the EOPs, i.e., a projection of the TOC special observations onto a regular grid with mesh size as small as $\Delta x = 100\,\mathrm{m}$ (Chapter 5.1). The TEAMx analysis will make synergistic use of the information content of observations and weather forecasts, and it will enable multiscale simulations of TOC events. Furthermore, observations from the TOC will enable additional in-depth model intercomparison studies, addressing orographic drag (Chapter 5.2.1), dispersion modelling (Chapter 5.2.2) and turbulent exchange in the surface layer.

Overall, the observations gathered during the TOC are expected to initiate a series of process-oriented modelling studies in NWP and climate research. These studies may involve detailed analyses of specific case studies, or idealized simulations designed to clarify the underlying dynamics of particular phenomena. While our current plan does not aim to coordinate these future studies, it aims to establish a common quality standard for all modelling research conducted within TEAMx. To achieve this, we summarize a few well-established best practices (Chapter 6). Our review of best practices concisely summarizes the state of the art on conducting and evaluating numerical simulations of weather and climate processes over mountains. It covers a broad range of themes, some of which may be relevant only for a subset of the TEAMx modelling studies. The best practices are meant to be adopted and promoted on a voluntary basis.

We complete the document with a comprehensive review of published modelling studies that specifically address the TEAMx target areas or nearby regions (Chapter 7).

Figure 1: The TEAMx target areas (shaded regions) cover a transect throught the Alps from North to South: The Northern Pre-Alps, the Inn Valley, an Alpine Crest region around the Sarntal Alps, and the Adige Valley.





2. Known model errors over complex terrain

In recent decades, significant advancements were made in numerical atmospheric modelling and prediction techniques, largely driven by the increasing computational power (Bauer et al., 2015). Operational weather and climate models now employ horizontal grid spacing in the kilometric range, enabling reasonable resolution of a wide range of mesoscale and boundary-layer phenomena specific to mountainous terrain. However, some mountain weather processes remain under-resolved. For instance, while kilometric-scale resolution is generally sufficient for successfully simulating large-scale gravity waves, it is not optimal for capturing interactions between waves and stable boundary layers. High resolution in the numerical grid does not necessarily guarantee more accurate simulations. In fact, NWP and climate models continue to encounter various challenges in simulating atmospheric phenomena over mountainous terrain.

For some well-known problems, satisfactory solutions have already been found:

- **Numerical inaccuracies due to terrain-following grids**. Most models employ a vertical coordinate formulation in which the lowest model level follows the terrain surface, and the influence of the underlying orography diminishes as altitude increases towards a flat model top (Gal-Chen and Somerville, 1975). Consequently, irregularities in the lower boundary, such as orography, are reflected at all grid levels. The irregular geometry of terrain-following grids enhances discretization errors throughout the computational domain. To mitigate these issues, several approaches have been proposed. One method is the use of hybrid coordinate systems, where the coordinate surfaces transition from terrain-following to pressure or geometric height with increasing altitude (Simmons and Burridge, 1981). Another approach involves designing a vertical coordinate that ensures a more rapid decay of small-scale disturbances with altitude, known as the Smooth-LEVEL vertical coordinate (SLEVE, Schär et al., 2002; Leuenberger et al., 2010). Alternatively, the application of a horizontal diffusion filter (Klemp, 2011; Westerhuis and Fuhrer, 2021; Westerhuis et al., 2021) has been considered. Immersed boundary methods (IBMs, Lundquist et al., 2010) and cut cells (Steppeler et al., 2002) have also been proposed as alternatives to represent orography on a three-dimensional Cartesian grid. These methods circumvent some of the challenges associated with terrain-following coordinates but introduce new complexities. For example, the interpolation across solid faces required by IBMs is computationally demanding.

- **Computation of horizontal pressure gradients near sloping surfaces**. Large truncation errors arise when computing the horizontal pressure gradient term in the momentum equations in the presence of steep slopes, especially near the ground. These errors are particularly large when the difference in surface elevation between neighboring grid cells exceeds the vertical grid spacing. Nonlinear amplification of these truncation errors, enhanced by aliasing, may even lead to numerical instability. To mitigate this issue, it is necessary to extrapolate the pressure vertically to a common level before calculating the horizontal gradient (Mahrer, 1984). Zängl (2012) has demonstrated that the implementation of a truly-horizontal pressure gradient discretization facilitates the simulation of flows over very steep slopes.
- **Computation of horizontal diffusion along horizontal surfaces**. The horizontal diffusion of temperature, moisture and hydrometeor variables should be computed on truly horizontal surfaces (Zängl, 2002). If mixing is computed along terrain-following coordinate surfaces over steep slopes, the vertical component of the gradients (which is typically much larger than the horizontal components) is erroneously projected onto the horizontal direction. This can have a systematic detrimental impact on the diffusion of water vapor and hydrometeors, and consequently on precipitation forecasts (Zängl, 2004b).

However, many outstanding issues remain:

- **Badly resolved stable boundary layers**. Simulations of the stable boundary layer over complex terrain are typically inaccurate, partly because of the insufficient vertical resolution of NWP models (currently about 10 m near the ground), partly because of numerical dissipation induced by the dynamical cores. A typical consequence is the overestimation of minimum temperatures at valley floors on clear-sky days. A related problem is that the dissipation of fog is often too rapid in numerical forecasts. This issue can be attributed not only to deficiencies in parameterization schemes but also to the intersecting of physically flat tops of stratus clouds by the sloping vertical coordinate surfaces. This intersection can promote excessive vertical mixing due to numerical diffusion associated with horizontal advection (Westerhuis et al., 2020, 2021). To address this problem, it is desirable to achieve a rapid decay of the orographic signal with altitude. However, in highly complex terrain such as the Alps, currently employed methods like the SLEVE coordinate fail to sufficiently flatten the coordinate surfaces over hilly terrain at the necessary (low) altitudes. A potential solution involves locally smoothing the coordinate surfaces in regions characterized by hilly terrain (Westerhuis and Fuhrer, 2021). Related TEAMx modelling research is outlined in Sec. 3.1.1.
- **Representation of turbulence**. All weather and climate models represent the diffusive effects of atmospheric turbulence with parameterization schemes that were generally developed for flat and homogeneous terrain. Parameterized turbulence is frequently distributed over the orography in a layer of approximately constant depth, but observations suggest that the mountain boundary layer structure can be considerably more complex (Rotach and Zardi, 2007). Additionally, parameterized turbulent kinetic energy is often underestimated in complex-terrain areas (Couvreux et al., 2016). Traditional turbulence parameterizations primarily consider vertical turbulent exchange, neglecting the significant impact of horizontal heterogeneities to the turbulence structure over mountainous terrain (Goger et al., 2018). This discrepancy between parameterizations and reality highlights the need for the development of hybrid or scale-aware turbulence parameterizations (Goger et al., 2019). In TEAMx, several traditional and hybrid turbulence parameterizations are compared in simulations of valley-scale thermally-driven winds (Sec. 3.1.2).
- **Timing of convection initiation.** The accurate simulation of deep moist convection poses a significant challenge for weather and climate models, both over flat terrain and in mountainous regions (Bechtold et al., 2014; Ban et al., 2021). Ongoing TEAMx modeling research using

current km-scale NWP models (see Sections 3.1.3) reveals significant variability in simulated deep moist convection over the Alpine region. This variability encompasses the timing and location of convection initiation, precipitation intensity, and convective development and organization. Despite this variability, a consistent pattern emerges: the models often predict a too early onset of deep convection and convective precipitation, particularly on days with diurnal orographic convection under weak synoptic forcing. This observation aligns with findings from previous studies (Panosetti et al., 2016; Heim et al., 2020). Panosetti et al. (2016) compared a km-scale NWP model simulation over idealized orography with a Large-Eddy Simulation (LES). They linked the too early onset of deep convection in the NWP model to weaker turbulent mixing in the MoBL, resulting in stronger upslope winds and increased horizontal moisture advection towards the mountain ridge. They also showed that the timing and intensity of convective precipitation is sensitive to the choice of turbulence scheme and the activation of a shallow convection scheme. In real-case simulations of diurnal convection over the Alpine region, Heim et al. (2020) found that the onset of deep convection and precipitation is very sensitive to the resolution of the model orography, more so than to the grid spacing. Additionally, they observed that the spatial distribution of nighttime convection south of the Alps is highly sensitive to orographic details, which influence the development of cold-air outflow from the Alpine valleys leading to convective triggering. Despite these uncertainties, orography appears to enhance the predictability of area-averaged bulk quantities related to diurnal convection (Panosetti et al., 2019, 2020). Further insights from related TEAMx modeling research are presented in Sections 3.1.3-3.1.4.

- **Dispersion modelling in complex terrain.** Chemical transport- and dispersion models (CTMs) already have been used operationally for decades to predict air quality, but also for the analysis of historical events, e.g., ozone peaks during heat waves or elevated particulate matter. The resolution of CTMs increased in the last years as computation power increased, and the complexity of physical- and chemical processes have been improved within the numerical models. Several restrictions of CTMs still exist because of the spatial and temporal scale, input data (e.g., emissions) and model physics/chemistry. These are especially a problem in regions with complex terrain and further research and development is needed to further improve the models. An important aspect is the availability of different observational data. TEAMx will provide a comprehensive data source for research applications in the atmospheric chemistry field, and for an intercomparison of dispersion models focusing on ozone and Saharan dust (Sec. 5.2.2).
- **Wind speed overestimation in large-eddy simulations**. Overestimation of near-surface wind speed has been reported in most of the recent large-eddy simulation studies (dx<100 m) over mountainous terrain (Gerber et al., 2018; Goger et al., 2022). This systematic error in wind speed estimation can lead to an inaccurate representation of scale interactions, such as between dynamically-induced gravity waves and the boundary layer within valleys. It may also contribute to the models' inability to maintain realistic vertical gradients in atmospheric variables over time. A major factor contributing to these issues is the smoothing of steep slopes, which can distort the flow patterns. Additionally, unrealistic representation of land-use characteristics could also play a significant role in the inaccuracies observed in wind speed estimation (Quimbayo-Duarte et al., 2022). Planned TEAMx research on LES in the surface layer, making use of eddy-covariance measurements during the campaign, is described in Sec. 5.2.3.
- **Elevation-dependent temperature bias**. Simulations at the kilometer-scale often feature a cold bias on mountain tops/slopes and a warm bias in valleys (e.g., Quéno et al., 2016; Vionnet et al., 2016). Many possible reasons have been identified, including: lack of realism in local breezes (and hence temperature advection) due to coarse model resolution; deficiencies in

physical parameterisations (three-dimensional effects not represented in neither the radiation or turbulence parameterization); inadequate adaptation to complex terrain of the covariance modelling in the assimilation system. Models further struggle to simulate truly calm wind conditions, which are necessary for cold-air pool development resulting from nighttime radiative cooling in valleys and basins.

- **Elevation-dependent precipitation bias**. Observations indicate that the intensity of extreme short-duration precipitation decreases with increasing elevation, a phenomenon known as the "reverse orographic effect." However, current convection-permitting climate models tend to underestimate this effect (Dallan et al., 2023). To ensure accurate projections, it is necessary to develop bias-correction approaches specifically tailored to mountainous terrain (e.g., Velasquez et al., 2020).
- **Precipitation spill-over**. Bias dipoles in precipitation forecasts, characterized by positive and negative biases occurring on opposite sides of a mountain range (windward/leeward), have been observed in several studies (Colle et al., 2005; Serafin and Ferretti, 2007). One potential reason for this phenomenon lies in microphysics parameterizations, which include inaccurate semi-empirical relationships for the fall speed of hydrometeors. Errors in fall speed, coupled with the horizontal advection of hydrometeors across the mountains, result in a horizontal shift of precipitation maxima from their optimal location. Specifically, an upstream shift is observed when the fall speed is overestimated, and a downstream shift occurs when it is underestimated. This issue is particularly relevant for hydrometeors with low fall speeds, such as snow, which can be horizontally advected over long distances.

3. Modelling before the TOC

3.1 Model intercomparison studies

Model intercomparison studies are an important component of the scientific process in NWP and climate modelling. Comparing multiple models against observational data and/or against each other sheds light on their strengths, weaknesses, and uncertainties. One of the best-known idealized model intercomparison studies in ABL research is the GEWEX Atmospheric Boundary Layer Study (GABLS), which consisted of several benchmark cases (GABLS1-4). The first two GABLS studies focused on the intercomparison of single-column models (SCMs) for idealized cases with prescribed surface temperatures and simplified wind profiles. GABLS3 examined the model comparability with observations and the interaction with the underlying surface. GABLS4 dealt with the arctic boundary layer and the performance of snow models. These benchmark cases highlighted inter-model variability in simulations of the same phenomenon and led to improvements of some parameterization schemes.

A single-column model approach such as that used in GABLS is not appropriate to make progress in atmospheric modelling over complex terrain. In fact, the spatial heterogeneity of the lower boundary and the high degree of horizontal variability of the atmospheric state imply that one-dimensional (vertical) parameterizations are rigorously not applicable.

Previous model intercomparison studies in mountain meteorology research dealt with thermally- and dynamically-driven mesoscale processes. Schmidli et al. (2011) compared simulations of the daytime valley-wind system over idealized orography, and noticed that the largest differences between simulations depended on turbulence and surface-layer parameterization schemes. Doyle et al. (2011) compared simulations of mountain waves over both idealized and real orography. They demonstrated that differences in dynamical cores, lower boundary condition formulation, and surface-layer schemes caused marked discrepancies in the simulations by different models.

In the following, four new model intercomparison projects are presented (Table 1), focusing on phenomena commonly observed in mountainous regions. Three of these studies evaluate simulations against observations from campaigns that took place in the Inn Valley during autumn 2017 (Penetration and Interruption of Alpine Foehn project, PIANO Haid et al., 2020) and in summer/autumn 2019 (Cross-valley flow in the Inn Valley project, CROSSINN Adler et al.,

Model	CAP	TDF	CON	LES
ECMWF-IFS (ECMWF, 2023)				
ICON (Zängl et al., 2015)	$*$	$*$	✓	
AROME (Seity et al., 2011; Termonia et al., 2018)		$*$	$*$	
MESO-NH (Lac et al., 2018)	✓		✓	✓
UM (Maher and Earnshaw, 2022)	✓			
WRF (Skamarock et al., 2019)	✓	$*$	$*$	✓
CM1 (Bryan, 2023)				$*$
ARPS (Xue et al., 2000)				✓
GRAMM-SCI (Oettl, 2021)		✓		

Table 1: Models represented in NWP intercomparison studies (as of 7 June 2023). An $*$ means that different model configurations are being tested. The acronyms CAP, TDF and CON refer to the real-case intercomparison studies on cold-air pools, thermally-driven flows, and moist convection, respectively. LES refers to the intercomparison of idealized large-eddy simulations of orographic convection initiation.

2021). Additional intercomparison studies, prospectively making use of TEAMx observations, are described in Chapter 5.2.

3.1.1 Cold-air pools

This study is promoted by the TEAMx Mountain Boundary Layer Working Group. It deals with the evolution of a cold-air pool in the Inn Valley over the city of Innsbruck, covering its entire life cycle from the formation to the breakup.

Cold-air pools are particularly challenging for NWP because of (i) the associated high stability, which means that traditional surface-layer parameterizations based on Monin-Obukhov similarity theory may not provide an adequate description of the turbulent transport and (ii) the oftentimes small scales and local processes, which necessitate very high horizontal and vertical resolution.

A case study was selected from an undisturbed period during the autumn 2017 PIANO field campaign in the Inn Valley, Austria.

The study compares simulations from four different models with a 1-km horizontal grid spacing in a domain covering the entire Alps. All models are run both in a configuration that matches as closely as possible some predetermined settings (vertical model levels, land cover properties, physics parameterizations, initialization time, boundary conditions), and in an optimal configuration determined on the basis of user experience.

The analysis focuses on the model representation of the strength, depth, and spatial extent of the cold-air pool in comparison to observations. The ensemble of simulations can also provide a type of benchmark for future cold-air pool simulations.

3.1.2 Thermally-driven flows

This study is also promoted by the TEAMx Mountain Boundary Layer Working Group. It focuses on the evaluation of model skill in reproducing thermally-driven winds and the associated thermodynamic fields in the Inn Valley, in real-case hindcast simulations. The initiative aims at updating and extending the findings by Schmidli et al. (2011), who considered idealized simulations (and therefore could not evaluate model skill) and focused on the daytime phase only. Here, the simulation of a full diurnal cycle permits evaluating model skill in the different phases of the diurnal evolution of the MoBL: daytime, nighttime, and transitions.

Simulations focus on IOP 8 of the CROSSINN field campaign (13 September 2019), characterized by weak synoptic forcing and a well-developed thermally-driven circulation in the Inn Valley.

Model output is verified mainly in the CROSSINN target area with data from automatic weather stations, i-Box flux stations and CROSSINN observations (soundings, wind lidar profiles, coplanar retrievals).

Simulations are run at 1 km grid spacing, to evaluate model performance at the typical resolution of limited-area operational forecasts. A single computational domain is used, covering the entire Alpine region (Umek et al., 2021) and directly forced by IFS forecasts. Simulations at higher resolution may be performed in a second phase, to evaluate possible improvements at sub-kilometer resolution, which will probably become realistic for operational forecasts in the next few years. Models are configured with similar orography, land-use and vertical resolution. Multiple simulations with the same model in different configurations are also performed, mainly to evaluate the impact of different parameterization schemes.

The analysis considers the strength and timing of the thermally-driven circulation in the valley boundary layer in the Inn Valley, and the associated thermal field and horizontal pressure gradients. At a larger scale, measurements from temperature and humidity profilers and radiosoundings in the whole computational domain are used to evaluate to what extent model deficiencies in the Inn Valley are connected to larger-scale phenomena.

3.1.3 Convection: NWP

This study is promoted by the TEAMx Convection Working Group. It aims at evaluating the ability of current NWP kilometric models with explicit deep convection to forecast summer convection over the Alps in terms of location, timing and intensity. The study focuses on real cases featuring various conditions, from weakly forced summertime diurnal convection to synoptically triggered and organized convection.

The 23-29 July 2019 week has been chosen, as it represents a typical transition from stable conditions to days with localized/stationary convection, and finally to two days with widespread organized convection. The main focus area when choosing this period was the Inn valley, but for most of the days convection occurred and sometimes organized at a larger scale. All simulations cover the area from 43°N to 49 °N and from 5°E to 17°E. Simulation output from all models is remapped to a common grid with horizontal resolution of 0.01°. Model orography follows as closely as possible the operational COSMO model set-up at MeteoSwiss, while the vertical resolution is as close as possible to the 90 vertical levels used in AROME by Météo-France. The location of convective initiation in relation to the orography is examined in detail. Furthermore, the localation, intensity, and chronology of the precipitation events are of key interest.

3.1.4 Convection: LES

This study is also promoted by the TEAMx Convection Working Group. Quasi-idealized LES are used to evaluate inter-model variability in the representation of boundary layer and cumulus development in a realistic but simplified summertime flow. In all simulations, the only parameterized processes are cloud microphysics and subgrid-scale turbulence, which helps to narrow and isolate the potential sources of error. Of particular interest is the determination of whether the different effective resolutions and physics schemes across the models meaningfully impacts the boundary-layer growth and turbulence, the mixing of clouds with their surroundings, and the vertical cloud development.

A section of the Italian Alps is extracted for the terrain, which is modified to isolate the ridge from the surrounding terrain and enforce periodicity along one axis. The initial thermodynamic sounding is a 10-year averaged ERA5 climatology over summer months at 06:00 UTC at the closest grid point to the city of Verona, Italy. The flow is initially quiescent, and sensible and latent heat fluxes are prescribed as diurnally varying sinusoidal functions. Initial experiments at coarse resolution indicate a multi-hour period of ABL deepening driven by surface heating, after which clouds begin to develop over lower ridges along the mountain flanks. These clouds progressively deepen and shift toward the higher terrain, ultimately giving rise to a mesoscale convective systems along the ridge top.

Analyses of the simulations focuses on time-evolving two-dimensional fields like surface precipitation, boundary-layer depth and turbulence, cloud cover, cloud-top altitude, and CAPE/CIN, along with surface fields (winds, water vapour, and potential temperature). Additional scientific insight is gained through analyses of cumulus dilution and detrainment, conditionally averaged buoyancy, cloud water, and updraft profiles, and power spectral densities over different portions of the domain.

3.2 Mountain climate

In parallel to the NWP group, the climate modelling group is working on understanding and modelling processes by which mountains are shaping regional climates and their spatial and temporal variability. Before the TEAMx FOC, the WG Mountain Climate group will exploit available high-resolution (km-scale) simulations available through several ongoing international projects with the main goal of recognizing the processes misrepresented in our current high-resolution models. Some of those data are the following:

- CORDEX FPS on convection over the Alps - This high-resolution multi-model ensemble of climate simulations is becoming available at a horizontal grid spacing of 3 km, integrated over 10-year long periods for present (2000-2009), historical (1991-2000) and future (2090-2099) climate - using RCP8.5 greenhouse gas and aerosol emission scenario (presented in Ban et al., 2021, and Pichelli et al., 2021).
- Austrian climate scenarios ÖKS15 - The ÖKS15 provides a standard ensemble of regional climate projections based on EURO-CORDEX simulations driven by CMIP5 global climate models (Jakob et al. 2014). The standard ensemble is provided with a horizontal grid spacing of 12 km. In addition, ÖKS15 provides (nominal) 1 km scenarios produced by bias-adjusting 12 km EURO-CORDEX simulations (Truhetz et al. 2016). This ensemble data set has served as an Austrian reference for climate change impact research since 2016.
- CH2018 Swiss Climate Scenarios - The CH2018 climate scenarios are based on the EURO-CORDEX RCM ensemble (EUR-11 and EUR-44) and involve comprehensive statistical post-processing and bias adjustment. A range of useful products is provided, including transient scenarios (1981-2099) at daily resolution for individual sites and on a regular 2 km grid. The CH2018 scenarios are planned to be extended/updated in 2025 by means of new approaches and user products. CORDEX simulations at 12 km grid spacing available through ESGF - new simulations are driven by CMIP6 GCMs.

In addition to the existing simulations, the groups will be running additional simulations most likely for shorter time periods and to address a specific research question.

The above-listed data is currently utilized in several ongoing projects:

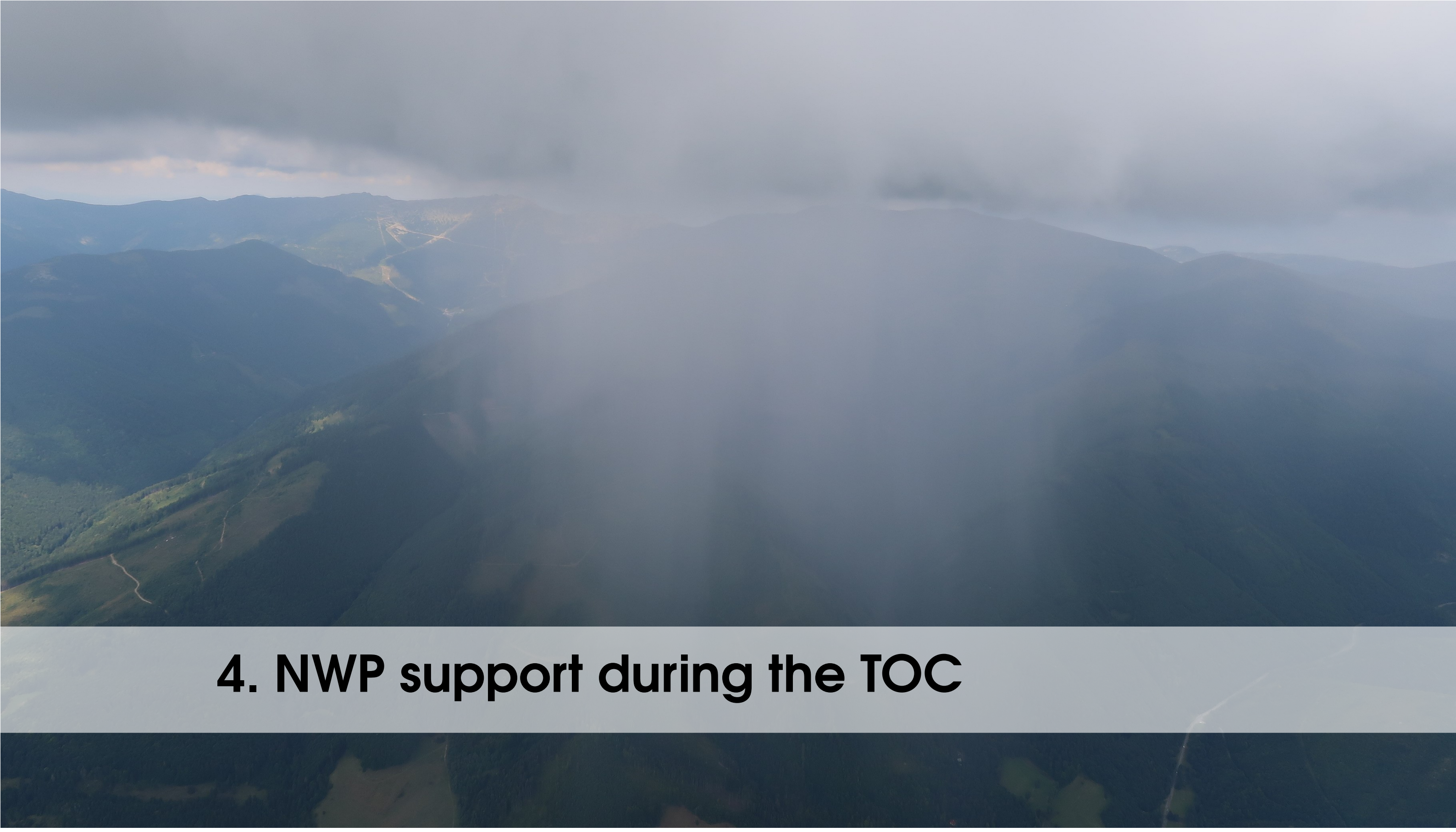
- **HighResMountains - Mountain weather in high-resolution climate data: How will the new generation of ÖKS benefit from new emerging datasets?**
  The main goal of HighResMountains is to gain a deeper understanding of extreme events and their processes and changes with further warming of the atmosphere over the Alps. The specific focus is on precipitation (rain and snow) and mountain wind systems (like foehn) which will be analyzed using different high-resolution datasets - more specifically dynamically downscaled CORDEX FPS Alps dataset and statistically downscaled and bias-adjusted ÖKS15 and CH2018 data. In addition, driving simulations for those data sets conducted with horizontal grid spacing of O(10km) are used to assess the differences between different resolutions and impact of different approaches on the resulting signal. The main

results of the project will provide relevant information and guidelines on methods limitations for the development of new Austrian climate scenarios.

- **Orographic Convective precipitation**
This PostDoc project aims to better understand convective phenomena over the eastern part of the Alps. The main goal of the project is to identify weather and climate conditions that influence most summer storms and their future evolution. In the first phase of the project, the focus is on the analysis of the CORDEX FPS Alps data, while in the second part sensitivity studies will be conducted to better understand the most impacting mechanisms.
- **Austrian Reanalysis - ARA**
The main goal of the ARA project is to create first of its kind high resolution (2.5 km) re-analysis ensemble dataset for Austria by assimilating observations using the 3DVAR of the C-LAEF ensemble system based on the AROME model. This re-analysis will provide detailed spatially, temporally, and physically consistent 3D and 2D information on the state of the atmosphere in Austria from 2010 – 2020, with a potential extension to cover the FOC period. Successful completion of this prototype has the potential to further develop into a viable operational/commercial product. It will provide essential climate variables (ECVs) at spatial and temporal scales relevant for the NWP (numerical weather prediction)/ climate research community and can be further exploited by impact research to improve resilience in the community by strengthening mitigation and adaptation efforts.
- **Do kilometer-scale climate models really perform better over complex orography?**
In this work, regional climate simulation with a grid spacing of 2 km and 12 km conducted with the COSMO model is evaluated against available observations over Europe. In contrast to previous studies which showed a blurred image of the model performance, here high versus low mountains and flatlands are distinguished. The preliminary results show that the increase in the resolution clearly improves the model's performance over flatland but the added value of using higher resolution is often smaller over complex mountainous terrain (i.e., higher mountains) than over flatland, especially for precipitation and clouds. The results suggest that the full potential of the kilometer-scale may not be reached in regions of complex orography and call for future research to improve those models, i.e., calls for the need for TEAMx research on climate scales as well. The work is presented in the manuscript that is currently in preparation (Poujol et al.). The work is however based on one model (COSMO), so there is a potential to extend it to the CORDEX FPS simulations.
- **Snow cover**
A part of the research in WG Mountain Climate assesses the potential and limitations of km-scale climate models to represent past and future changes in snow conditions in the European Alps. In one of the earlier studies, Lüthi et al. (2019) showed how the representation of snow cover is better represented when going to higher resolution with the COSMO model. This work is further extended to simulations within CORDEX FPS with the aim of evaluation and estimation of the added value of high-resolution climate models versus Euro-CORDEX regional climate models, focusing on both past and future conditions over the Alpine region.
- **Urban climate in complex orography**
The main question to be addressed here is how well the simulations perform in cities in mountainous terrain. As mentioned above, we can see a smaller added value in the application of km-scale climate models in complex topography than over flatland. However such analysis still needs to be done more specifically for the cities. In this work, existing CORDEX FPS simulations will be utilized in order to compare the model performance with the current settings, and then later additional sensitivity simulations could be conducted testing different urban parametrizations.

- **Application of machine learning**
  So far, the analysis of existing km-scale simulations has been relying on conventional methods. However, the potential of machine learning has not been fully explored. For example, one could use it to identify the model biases over different weather situations or to assess how much we can learn about the model performance from a very short timescale and how that applies to longer ones.

The above results and findings, together with previously conducted research will potentially be summarized in a Review paper on Mountain Climate (or Complex Orography) modelling which should represent the main results and challenges of modelling climate over complex orography. The current idea is to capture all scales - from global to local and from global climate models down to regional high-resolution (km-scale or even LES scale) models.



4. NWP support during the TOC

The primary aim of running NWP modelling systems during the TEAMx Observational Campaign is to support the planning of the IOPs, especially for running observational platforms that do not operate on a 24/7 basis. This can partly be done with coarse-scale models such as ECMWF's IFS. However, in complex terrain, higher-resolution modelling systems provide more useful local information to guide intensive observations. Five different institutions - the national weather services from Austria (GeoSphere, GS), France (Météo-France, MF), Germany (Deutscher Wetterdienst, DWD), Switzerland (MeteoSwiss, MCH), together with the Italian Institute of Atmospheric Sciences and Climate (ISAC) - run various configurations of three different models (ICON, MOLOCH, AROME). These operational forecasts at high resolutions over the Alps will be available during the TOC for campaign planning. Table 2 summarises some key aspects of each model setup and Figure 2 illustrates the model domains. Except for MOLOCH, these limited-area modelling systems also run a data assimilation system at a high resolution, thereby capturing the state of the atmosphere over the Alps in more detail than global models can do.

Furthermore, some of these institutions will run forecasts dedicated to TEAMx at even higher resolutions; DWD, for example, will provide ICON-simulations at 500 m eight times per day for the following two days. More details about dedicated forecast products will be described in the TOC Implementation Plan.

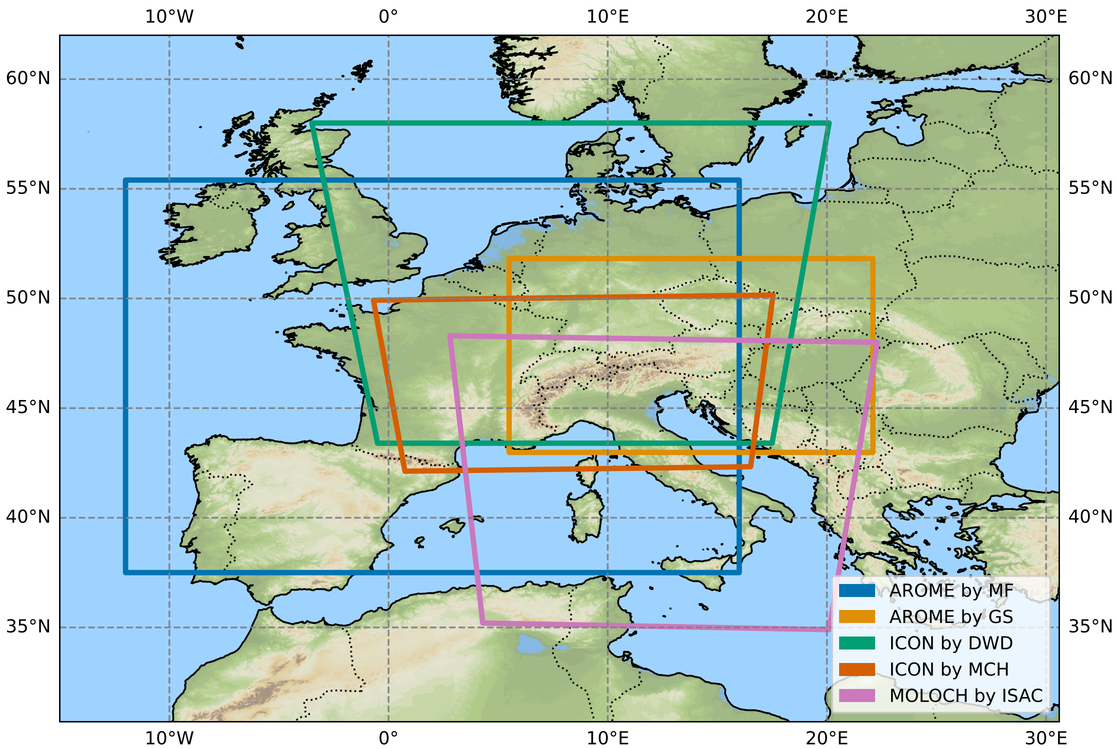
A second motivation to run high resolution modelling systems for the EOPs and IOPs in real time is to get both immediate and retrospective feedback on their performance: scientists will be able to compare different modelling systems with different strengths and weaknesses with a wealth of observations in 4D. The direct intercomparison of different modelling systems with different approaches for data assimilation, discretizations of the dynamics, and physical parametrisations provides an added value for the TEAMx research community.

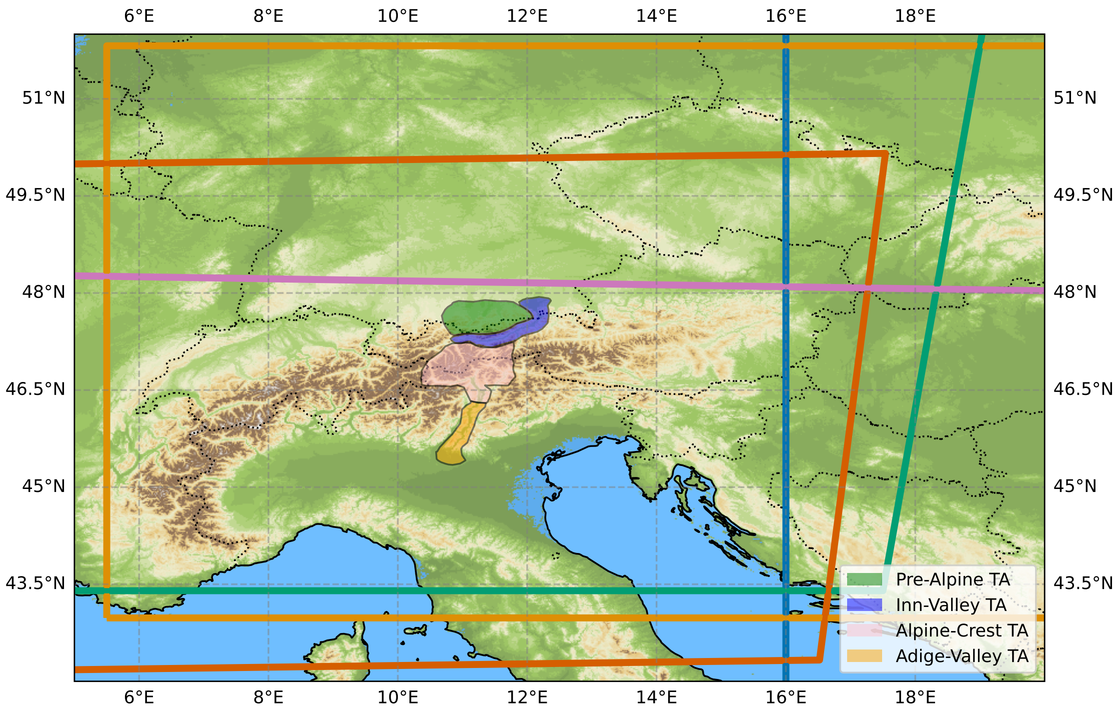
Table 2: Operational NWP models available during the TOC. MF: Météo-France, GS: GeoSphere Austria, DWD: Deutscher Wetterdienst, MCH: MeteoSchweiz, ISAC: Istituto di Scienze dell'Atmosfera e del Clima. Exhaustive information on the model configurations and operational products will be provided in the upcoming TOC Implementation Plan.

Model/ Configuration	Mesh size [km]	Levels	Members	Lead time [h]	Runs [UTC]	Contact
AROME[a] MF	1.3	90	16+1	51	3/9/15/21	Y. Seity
AROME[b] GS C-LAEF(-1k)	2.5 (1)	90	16+1	60	0/12	C. Wittmann
ICON[c] DWD ICON-D2	2.2	65	20	48	0/3/6/.../21	M. Köhler
ICON[c] MCH ICON-CH1-EPS	1.1	80	11	33	0/3/6/.../21	M. Arpagaus
MOLOCH[d] ISAC	1.25	60	1	45	0	O. Drofa

[a] https://doi.org/10.1002/qj.2822
[b] https://doi.org/10.1002/qj.3986
[c] https://doi.org/10.1002/qj.2378
[d] https://link.springer.com/article/10.1007/s42865-020-00015-4

Figure 2: Upper panel: Domains of the operational models which will be available during the TOC. The lower panel shows a zoom of the Alps including the four target areas. Météo-France (MF, blue) and GeoSphere Austria (GS, orange) run AROME, the Deutscher Wetterdienst (DWD, green) and MeteoSwiss (MCH, red) run ICON and ISAC (pink) provides MOLOCH simulations.





5. Modelling after the TOC

5.1 High-resolution analysis of the TOC

Field campaigns such as TEAMx always spawn many modelling studies, where simulations in hindcast mode shed light on the meteorological processes that affect intensive observation periods, thereby aiding the interpretation of measurements. For mesoscale NWP simulations ($\Delta x \sim$1 km), drawing the initial and boundary conditions from global analyses is often an adequate approach. However, tackling the TEAMx scientific objectives requires explicit resolution of advective transport and of coherent turbulent structures in the mountain boundary layer, which is feasible only with microscale simulations ($\Delta x \sim$100 m or smaller for convective boundary layers, $\Delta x \sim$10 m or smaller for stable boundary layers).

Large-eddy simulations of the mountain boundary layer are technically feasible, but their accuracy is severely limited by the lack of microscale detail in their initial and boundary conditions. The highest-resolution analysis products currently available, obtained from convective-scale data assimilation systems, have $\Delta x \sim$1 km. Over mountains, they suffer from non-negligible biases both because of their marginally adequate resolution and because the observations they ingest are too sparse to properly sample the spatial and temporal variability of the mountain boundary layer.

Therefore, we argue that an analysis with native grid resolution of about 100 m is necessary in order to achieve reasonably accurate modelling of the mountain boundary layer (MoBL), and we propose that the computation of such an analysis becomes a cornerstone of the modelling activities foreseen after the TEAMx Field Observation Campaign. In practice, the *TEAMx analysis* should be a four-dimensional gridded dataset, providing a statistically optimal estimate of the atmospheric state over the TEAMx target areas (Inn Valley, Adige Valley, Northern and Southern Alpine Forelands in Bavaria and Po Valley) during the special observation periods of winter 2024-25 and summer 2025, based on all conventional and special atmospheric measurements available during the campaign.

To align with the current state of the art on convective-scale data assimilation, we propose that the TEAMx analysis is produced with ensemble data assimilation (EnDA) methods. Data assimilation combines information from sparse observations and a preexisting simulation (the background) to compute an analysis. In EnDA, the background state and its flow-dependent uncertainty (error covariance) are estimated with an ensemble of numerical simulations. The observation and background error covariances are then used to determine the relative weight of the background and the observations in the final analysis. The process is iterative, meaning that each analysis provides the initial conditions for the subsequent ensemble run.

Because of the high computational requirements, a high-resolution ensemble analysis is only feasible in small nested domains. The TEAMx renalysis shall have a horizontal grid spacing that is similar or slightly smaller than that of operational NWP models (1 km or 500 m) in a broad domain covering the Alps, and of about 100 m in nested domains covering the TEAMx target areas. The parent coarse-resolution analysis provides initial and boundary conditions for the 100 m ones; in turn, synthetic observations from the 100-m model runs can be assimilated in the next cycle of the coarse-resolution one, thus accomplishing two-way feedback. The analyses at different scales may assimilate separate sets of observations (e.g., rain radar only at coarse resolution, doppler wind lidar only at high resolution). In the high-resolution nested domains, as many as possible of the TEAMx special observations shall be assimilated (including Doppler wind lidars; temperature, relative humidity and wind profilers; rain radars; radiosondes and dropsondes; surface and airborne in-situ measurements).

Based on the best of our knowledge, no high-resolution ensemble analysis product has ever been computed so far, although similar undertakings were recently made or are now underway:

- Deployments of the US Department of Energy Atmospheric Radiation Measurement Mobile Facilities are routinely complemented by simulations with the WRF-based LASSO environment (Gustafson et al., 2020). LASSO simulations assimilate boundary-layer observations in mesoscale runs using variational methods, and draw from these runs the boundary forcing for free-running large-eddy simulations. No direct assimilation of observation in LES runs is performed.
- Miyoshi et al. (2016) presented an experimental assimilation of high-frequency (1/30 s^{-1}) volumetric radar measurements in a 100-member ensemble of 100-m simulations. This ‘big data assimilation‘ exercise dealt with a single weather event and a single observation type, and lacks connection with field campaign measurements.
- There are plans to develop hectometric-scale on-demand simulations in the near future, for instance in the Destination Earth On-Demand Extremes Digital Twin DE_330_MF (Randriamampianina, 2023). The prevalent focus of this initiative is on prediction rather than analysis, and plans concerning the assimilation of non-conventional observations are unclear at the moment.

Computing a high-resolution campaign analysis with an ensemble filter poses significant conceptual and technical challenges. Among them:

- Ensemble runs at 100-m resolution are extremely demanding in terms of computational resources.
- The assimilation algorithm must be capable of handling massive amounts of observational data, possibly with correlated observation errors.
- Very dense observations sample scales of atmospheric motion that are smaller than the background model’s effective resolution, so observation thinning or averaging might be needed.
- For some of the special measurement platforms operated during TEAMx, observation operators may not be readily available.
- Background error statistics will likely evolve in a non-Gaussian and nonlinear manner, a challenging scenario for current operational ensemble filters.
- Frequent assimilation increments (still within the model spin-up phase) may introduce dynamical imbalances in the analyses, which need being mitigated.

Designing and testing sensible methods to overcome these challenges will require coordinated research, bringing together expertise in numerical weather prediction, high-resolution modelling and boundary-layer observation with in-situ and remote-sensing platforms. A joint effort to apply for funding is currently being made in a team comprising the Universities of Vienna and Innsbruck, the Karlsruhe Institute of Technology, Meteo Swiss, and the Deutscher Wetterdienst.

The development of a methodology for high-resolution analyses has countless potential applications besides TEAMx (e.g., future field campaigns; parameterization development; energy meteorology).

5.2 Model intercomparison studies

5.2.1 Orographic drag

This study is promoted by the working group on Waves and Dynamics. It aims to examine the interplay between the surface drag, near surface processes and upward propagating gravity wave momentum fluxes and breaking during TEAMx over the Alps in observations and models. It is assumed that the amount of orographic drag at resolutions from 10 km to 100 m should gradually shift from parameterized to resolved. The study aims at deriving constraints and improving orographic drag parameterizations in 1 to 10 km resolution NWP models based on observations and higher resolution simulations produced within this intercomparison.

Suitable observations available within TEAMx that will serve as a reference are the lidar and in-situ observations with the FAAM and Cessna aircrafts, which will provide u and w. Vertical fluxes of horizontal momentum $\overline{u'w'}$ will be derived and compared with the models. The observations will also provide energy spectra. IOPs that feature wave breaking and/or large wind model error will be identified after the TEAMx observational campaign has concluded. Targeted model simulations will then be repeated. Model simulations from ICON at 500m resolution as well as WRF, AROME and IFS will be made from Autumn 2024 to Autumn 2025. 1-hourly model level output will be stored.

The envisaged strategy for the comparisons between model and observations encompasses the following points:

- Curtains of u', w' will be diagnosed from model output along the flight tracks. The challenge of analysis will be the scale definition of large-scale (10-100km) and wave response. Flux spectra comparisons should be sufficient to document model error.
- Downstream tropospheric winds (Föhn during fall or winter storms) will be compared to radiosondes elucidating the skill of the modeled flow-separation. Inter-model and resolution dependence will illustrate the interplay of resolved and parameterized drag.
- Surface drag comparisons are typically tricky, even between models. The hypothesis to be tested will be the invariance of the net (turbulent+resolved) drag with resolution.

5.2.2 Transport modelling: Ozone and Saharan dust

The two main research questions identified by the members of the working group for atmospheric chemistry are: (i) assessment of model ability to reproduce ozone distribution in the Inn-valley; (ii) modelling of Saharan dust events transport over the Alps.

- **Assessment of model ability to reproduce ozone distribution in the Inn-valley.** Different gas-phase chemistry options are implemented in CTMs. The knowledge of precursor emissions and the complex flow around and over terrain must be simulated properly. In complex terrain the model resolution (horizontal and vertical) is an important factor that limits also the performance of the model. What model resolution is needed to reproduce the ozone distribution in the valley? Observations from Sonnblick and at stations in the Inn valley (e.g. at 20 fixed AQ-Stations in Tyrol) permit routine model evaluation and use of Model Output Statistics (MOS) to correct model biases. The following additional observations are foreseen in connection with TEAMx: Ozone flux observations at the FAIR station; Stationary ozone profile measurements along the northern slope of the Inn valley near Innsbruck (city, Sadrach and Seegrube); One mobile ozone station could be installed at a chosen location; Ozone sensors can also be installed on drones. These additional observations will be used to check the skill of ozone forecasts at sites where MOS is not possible, because of the lack of historical observations.

- **Modelling of Saharan dust events transport over the Alps.** Depending on the large-scale weather conditions, Saharan dust can be transported several times per year towards central Europe and over the Alpine region. Special atmospheric conditions can lead to a down-mixing of dust reaching also surface levels and impact human health. The group will use the comprehensive observational data that will be made available during the TOC to investigate if and how state-of-the-art chemical transport models can simulate the large-scale flow over Alps and down-mixing, e.g. during Saharan dust events. The models will be evaluated with respect to the relevant meteorological parameters as well as aerosol observations. Observations available through operational networks (TROPOMI, MODIS, AERONET, and in-situ measurements at Sonnblick and at air quality stations in the Inn Valley) will be complemented with observations during the measurement campaign.

5.2.3 Large-eddy simulations over complex terrain

Currently, no benchmark is available against which to test if LES models produce realistic turbulence properties over complex terrain. In fact, this is not even the case in idealized LES simulations (ideal terrain shape and inflow parameters). In addition, high quality continuous turbulence observations one can compare the LES models against are scarce, and only available for the surface layer (the first few tens of meters above ground, at most). The knowledge of turbulence properties in the upper MoBL is limited to a few observation-based case studies and to idealized numerical modelling.

As a first step towards a systematic understanding of LES skill over complex terrain, we propose investigating the variability of LES results subject to equal initial and boundary conditions in an idealized setting. At the very least, LES models differ by sub-filter-scale model, dynamical core (pseudo-spectral vs finite volumes) and treatment of surface boundary conditions. Even in a simple scenario, these differences will cause some variability in simulations of turbulence properties. We thus propose to conduct a series of experiments that evaluate (i) if inter-model variability is comparable to that over flat and homogeneous terrain; (ii) if any specific weather condition (e.g., stable BL vs. dry-convective BL; decaying free turbulence in the residual layer vs. sustained forced convection) leads to more pronounced inter-model variability.

Proper assessment of model skill requires comparing model error (average deviation from observations) with the estimated model uncertainty. The proposed experiments provide the second ingredient; that is, they quantify structural and parametric LES model uncertainty. Realistic LES simulations and direct comparison with observations will follow at a later stage: for surface-layer observations, relatively soon; for the MoBL core, depending on the outcome of TEAMx turbulence observations (remote sensing, aircraft and UAV observations).

The first benchmark scenario will be the convective MoBL. Inter-model variability between different LES codes will be characterized in 3 different idealized scenarios: flat terrain, moderate orography, steep Alpine orography. Variability in several properties of the MoBL will be considered: bulk properties, e.g. depth; spatial distribution of profiles of turbulent averages and higher-order statistics; spectra, co-spectra and anisotropy invariants; spatial autocorrelations of turbulent fluctuations.

5.3 Climate applications at kilometer-scale grid spacing

Results and datasets obtained during the TEAMx FOC are expected to be of high value for subsequent climate applications. This climatological "digestion" of results will be coordinated by the TEAMx working group on Mountain Climate. A range of possible applications of the FOC results and achievements is envisaged:

- **Climate simulations at km-scale scale**: Most NWP modeling systems applied during the TEAMx FOC can also be run in climate mode without data assimilation and for long-term simulation periods, including future scenario simulations (e.g. Ban et al., 2014). These applications on climate scale will profit from any further insight into model performance and bias structures obtained during the FOC and from any improvements in the representation of land-surface interactions in complex terrain. This includes future applications of limited-area model ensembles at km-scale (such as those planned during the upcoming phase of the CORDEX initiative) as well as kilometer-scale global model applications (such as those envisaged in the nextGEMS project).
- **Climate simulations at O(10km) grid spacing**: Even though there is a clear tendency of climate community to move towards high-resolution km-scale model, the need for coarser resolution regional and global models i.e., models with O(10km) grid spacing, exist. In fact, while RCM models operate at such a resolution for a few decades (for example CORDEX simulations), the GCM community has only started to explore it (see HighResMIP project, `https://highresmip.org`). Such models are and will continue to be used for climate simulations and as driving models for very high resolution km-scale models. Since they as well come with biases, it is important to understand how these models perform and to work on their improvement. Thus whenever possible, the climate simulations will also be performed at O(10km) grid spacing in parallel to km-scale simulations. This will allow us to compare simulations at different resolutions, and to test how improvements in the representation of the exchange between the surface and atmosphere impacts the simulation at coarser resolution.
- **Process-based model analysis**: Past and projected future global warming also strongly affects mountain climates, with the latter partly showing above-average temperature change signals and elevation-dependent patterns (Pepin and Lundquist, 2008; Pepin et al., 2015, 2022). While the short-term TEAMx FOC does not cover the relevant time scales, "twin analogs" evaluated during the FOC could be of value for assessing the robustness of future climate change projections. For instance, quantifying the expected reduction in surface snow cover with climate warming and its possible feedback on near-surface air temperature change relies on the capability of climate models to correctly represent the snow-vs-no snow temperature contrast. Previous work indicates that this representation might be distorted in today's regional climate models i.e., models with 12 and 50 km grid spacing (Winter et al., 2017). The TEAMx FOC offers the possibility to evaluate this relationship by transferring the temporal concept into a spatial one, i.e., by comparing model temperature and flux biases between snow-covered and snow-free sites. In addition to snow coverage, further systematic temporal trends expected as a consequence of global warming could be transferred into a spatial context and evaluated based on the FOC results. For example, those would include land cover change and upward moving tree line, modified aerosol burdens, intense precipitation events, etc.
- **Storylines**: Storyline approaches have emerged as an important pillar of climate change communication and can provide physically-based insights into the nature of future climate extremes and their respective impacts (e.g. Shepherd et al., 2018; Sillmann et al., 2020). An often applied storyline technique consists of transferring a well-understood and well-simulated historical event into a future climate employing surrogate or pseudo-global warming approaches. Depending on the evolvement of weather conditions during the TEAMx FOC and

the ability to represent individual events in the applied modeling systems, a transfer of such events into a future climate along with an assessment of their respective impacts on natural and societal systems could be envisaged.

Note that these applications generally require models to be run in *climate mode*, i.e. in a free-running manner without data assimilation and possibly also without large-scale nudging.

6. Guidelines and best practices

6.1 Lower boundary conditions

Specification of the lower boundary condition for simulations of MoBL processes involves at least two aspects:

- **Orography:** Most idealized modelling studies so far adopt unrealistically smooth terrain profiles. To address research questions focusing on complex terrain, a realistic degree of variability in the properties of the lower boundary should be incorporated in the experiment design. This may be achieved by generating synthetic terrain whose variance follows a predetermined power spectrum, or by drawing information from real high-resolution terrain data (Kirshbaum et al., 2007). Commonly used orography datasets are digital elevation data from the Advanced Spaceborne Thermal Emission and Reflection radiometer(ASTER), the Multi-Error-Removed Improved-Terrain dataset (MERIT), and the Shuttle Radar Topography Mission (SRTM). Model intercomparison studies mimicking real cases require testing of various degrees of orography smoothing to find a setup that allows all models to run stably.
- **Land use and soil type:** The land use and soil type datasets should feature a resolution which is higher than the resolution of the simulations. Furthermore, especially at grid spacings below 200 m, emphasisis should be laid that the used datasets are up to date. Commonly used land use datasets include the COoRdination of INformation on the environment land cover (CORINE), the GLOBal land COVER (GLOBCOVER) map, and ECOlogical and CLImatic MAPping database ECOCLIMAP database. The soil type is often derived from the Harmonized World Soil Database.

6.2 Initial conditions and spin-up time

For (semi-)idealised simulations, ICs should be specified on the basis of available radiosoundings. For real-case simulations, high-resolution data-assimilation cycles can provide accurate analysis fields. However, if a model intercomparison project includes different models and the data-assimilation cycle associated to one of them serves as ICs for all this likely deteriorates comparability, especially in the early hours. As most models have functionalities to be driven by

ECMWF's IFS this is a recommended choice despite the comparably lower resolution. In any case, a spin-up time of at least 6-12 hours should be considered.

6.3 Soil moisture initialization

Soil moisture is an important parameter governing the soil moisture-precipitation feedback (Hohenegger et al., 2009) by influencing the partitioning of the energy fluxes and henceforth the development of thermally-induced circulations over complex terrain (Rihani et al., 2015). Unfortunately, soil moisture initial conditions are often derived from coarse-resolution fields and lack small-scale variability. Chow et al. (2006) tackled this issue by generating realistic soil moisture input with a hydrological model for their LES of thermally-induced flows. In climate simulations, the soil moisture problem can be overcome by extended spin-up times (Ban et al., 2014). This "extended soil spinup dataset" was also used by Schmidli et al. (2018) leading to an improved simulation of daytime valley wind systems over the Swiss Alps.

By way of example, we illustrate how long-term soil spinup can be accomplished with one of the land-surface models available in WRF. The NoahMP model (Niu et al., 2011; Yang et al., 2011; Li et al., 2022) can be run off-line in the High-Resolution Land Data Assimilation System (HRLDAS, Chen et al., 2007). Thus, a long-term run of NoahMP is performed with HRLDAS on the soil grid of the WRF model. The HRLDAS integration uses interpolated ERA5-Land soil reanalyses from ECMWF as initial conditions, and ingests ERA5 reanalyses of atmospheric parameters (air temperature, moisture and precipitation, radiation fluxes) as boundary conditions. Over an integration of at least one year, HRLDAS progressively brings the WRF soil fields in a state compatible both with the WRF orography and soil properties and with the atmospheric initial conditions interpolated from ECMWF reanalyses or operational analyses.

6.4 Grid resolution and turbulence modelling

The properties of many phenomena over complex terrain (e.g. the strength and extent of the valley wind, the formation of gravity waves, or the three-dimensional structure of turbulence) are governed by the underlying orography. Therefore, the right choice of horizontal grid spacing depending on the phenomenon of interest is crucial for a successful weather simulation over mountainous terrain.

Wagner et al. (2014) suggest that at least ten grid points across a valley are necessary to simulate the relevant proceses for the formation of the thermally-induced circulation. The choice of grid spacing is also dependent on the diurnal cycle – during the daytime, coarser grid spacings at the hectometric range might be sufficient for a convective ABL to develop, but during the night-time, when a stable boundary layer persists, horizontal grid spacings well below 100 m are advisable (Cuxart, 2015; Muñoz Esparza et al., 2017). Adjustment of the grid spacing to the simulated phenomena is not feasible for operational NWP models, but it should be considered for tailored high-resolution case studies.

Another relevant decision for numerical modelling below the kilometric range is the choice of turbulence parameterization in the model. At grid spacings around and below 1 km, classic turbulence parameterization schemes, such as the Mellor-Yamada framework, are not entirely appropriate for complex orography, because three-dimensional effects, such as horizontal shear production of turbulence, become relevant (Goger et al., 2018). A solution to overcome this problem is the extension of 1D parameterizations to include a simplified treatment of 3D turbulence dynamics (Zhong and Chow, 2013; Goger et al., 2019; Juliano et al., 2022).

Even with these hybrid turbulence parameterizations, the grey zone of turbulence (Wyngaard, 2004; Honnert et al., 2020) needs special treatment in high-resolution mesoscale simulations. The turbulence grey zone lies at grid spacings between the "mesoscale limit" ($\approx$ 1 km, where turbulence is fully parameterized), and the LES range ($\approx$ 100 m, where the largest eddies are fully resolved).

At grey zone resolution, turbulence is partly parameterized and partly resolved, which often leads to unrealistic flow structures in the simulations (Chow et al., 2019). Scale-aware turbulence schemes might bring a solution to this problem and are necessary for simulations in the hectometric range (e.g. Zhang et al., 2018).

6.5 Online diagnostics and post-processing

When simulations are run in LES mode, it is assumed that the largest eddies in the turbulent flow are resolved. Due to the turbulent nature of the flow, it is unlikely that instantaneous model output (e.g., every 30 minutes) is representative of the mean state of the flow. Therefore, frequent model output is required in order to accurately estimate the mean state of the flow. Then any turbulent model variable $\tilde{a}(\mathbf{x},t)$ can be split into a mean $A(\mathbf{x},t)$ and a fluctuating part $a(\mathbf{x},t)$ (Schmidli, 2013):

$$\tilde{a}(\mathbf{x},t) = A(\mathbf{x},t) + a(\mathbf{x},t).$$

Using such a decomposition, the Reynolds average of a product of two turbulent variables is given by:

$$\overline{\tilde{a}\tilde{b}} = AB + \overline{ab}.$$

If one of the variables is a velocity variable, the covariance $\overline{ab}$ represents a turbulent flux. In LES, a turbulent flux consists of a resolved and a subgrid part. When the turbulent motions are well-resolved in the LES (i.e., $\Delta x \ll l$, where l represents the length scale of the large turbulent eddies), the resolved turbulent flux is larger than the subgrid turbulent flux.

Due to the fact that turbulent motions are explicitly resolved, analysing LES output usually requires post-processing of the high-frequency model output with time- and space averaging (Schmidli, 2013; Göbel et al., 2022). Writing high-frequency output is demanding in terms of model runtime and storage space, so the recommended method to diagnose turbulence statistics is recursive averaging. Following the method of Schmidli (2013), Weinkaemmerer et al. (2022) and Wagner et al. (2014) implemented recursive averaging routines for turbulent flow quantities in idealized simulations for the CM1 model and the WRF model, respectively. The WRF implementation of recursive averaging was further improved by Umek et al. (2021, 2022) and by Göbel et al. (2022). The latter work also introduced a numerically consistent calculation of budget terms in Cartesian coordinates, which is otherwise hard to achieve (given the mass-based curvilinear grid adopted in WRF).

6.6 Model verification

When it comes to evaluating simulations against special observations (e.g., measurements available at a single site and for a short period), visual inspection of plots is the most common approach and it is acceptable in many circumstances. If a quantitative measure of the discrepancy between simulations and observations is desired, many verification scores for both continuous and binary predictands can be considered. See Wilks (2011) for a comprehensive review.

TEAMx modellers will likely consider a variety of forecast variables, and will likely use many different observational data to verify their simulations with. It is thus impossible to formulate exhaustive verification guidelines a-priori. However, some fundamental issues are relevant regardless of the forecasts variables to be verified, the observation types, and the temporal resolution of the data:

- **Error magnitude relative to natural variability**. Comparing forecast error measures between sites with different degrees of natural variability can often be misleading. For instance, a mean absolute error of 2 m s^{-1} in wind speed forecasts may be exceedingly high at sites with near-zero mean wind speeds, but perfectly fine at sites with an aggressive wind climate. It is common practice to normalize error measures (e.g., the root mean square error) with the standard deviation of the verifying observations.

- **Systematic and random errors**. Forecast inaccuracy depends both on systematic deviation from the truth (bias) and on random errors due to forecast uncertainty. Bias is often large over mountainous terrain, but can easily be removed by post-processing. Some verification methods (e.g., Taylor diagrams; Taylor, 2001) are insensitive to mean bias by design, and their use is encouraged because they emphasize forecast errors that are inherently time-dependent or random.
- **Sampling error and small sample size**. Verification scores are always computed from a finite set of forecasts and verifying observations, which implies that they are subject to sampling error. Especially when sample sizes are small, it is important to evaluate the uncertainty margins of verification scores. For instance, when comparing two forecasts, a given difference between verification scores might be too small in relation to the their uncertainty, thus making it impossible to decide if a forecast is better than the other. The recommended approach is to estimate confidence intervals with non-parametric methods such as bootstrapping (resampling with replacement). In general it cannot be assumed that forecast-observation pairs in the verification sample are statistically independent, so their serial or spatial autocorrelation has to be taken into account with block bootstrapping (Wilks, 1997).
- **Testing differences between verification scores**. When comparing different forecasts, statistical hypothesis testing is the recommended method. In general, the null hypothesis to be tested is that the competing forecasts have equal skill. Because forecast errors are often correlated (if forecast A is wrong, most likely even forecast B will be similarly wrong), hypothesis tests should refer to the difference between scores. With this approach, the null hypothesis to be tested is that the score difference is zero.
- **Observation errors**. When verifying forecasts, observations are often taken at face value. Actually, they have their own uncertainty, which is determined both by instrumental error and by representativeness error. The latter component is principally determined by the scale mismatch between the coarse resolution of the model grid and the small footprint of the observations, and is thus model-dependent. Hacker et al. (2011) demonstrated that accounting for observation errors can change the conclusions drawn from verification: for instance, an ensemble forecast that is seemingly severely underdispersive could be judged reasonably reliable if observation errors were simulated in the verification process. Observation errors can be accounted for by randomly perturbing the verifying observations according to a predetermined error variance. Rigorous estimates of observation error variance are hard to obtain, but can be achieved within a data assimilation framework (Desroziers et al., 2005).
- **Double-penalty errors**. Highly resolved forecast fields contain spatial variability at small scales, which inherently enhances model errors. Rainfall forecasts are a typical example: a coarse-resolution model that totally misses a local precipitation maximum is penalized once; a high-resolution model that accurately captures the intensity of the maximum but misrepresents its location is penalized twice (once for missing the event in its right place, once for putting it in the wrong place). Verification scores that are specifically designed to circumvent double-penalty errors should be chosen. One example, in the context of spatial verification of binary events (e.g., accumulated rainfall exceeding a threshold), is the fractions skill score (Roberts and Lean, 2008). Other object-oriented methods such as SAL (Wernli et al., 2008) are also in use.

6.7 Determination of the boundary-layer depth

The boundary-layer depth z_i is hard to evaluate over mountainous terrain, from both measurements and numerical simulations (Seibert et al., 2000; Schmidli, 2013; Lehner and Rotach, 2018). The method followed to determine z_i should always be specified exactly. Comparison of multiple methods is encouraged. Most numerical models can be extended fairly easily to incorporate mass conservation equations for passive tracers emitted at the surface. In addition to common approaches (parcel method, gradient method, bulk Richardson number method), the determination of z_i on the basis of tracer mass fields is recommended.

6.8 Spatial interpolation

We recommend using standard, well-tested, computationally efficient interpolation tools instead of self-coded routines. Some interpolation functions (e.g., those available in `cdo`) require converting model output into CF-compliant format.

In addition, awareness of the exact georeferencing of the model grid (datum, projection) is necessary to correctly evaluate wind forecasts (wind directions on the model grid do not necessarily coincide with geographical wind directions).

6.9 Data availability and research reproducibility

All TEAMx modelling activities are expected to produce output which is reproducible and made openly available. NetCDF output should follow the CF-conventions. Details are described in a separate document, the TEAMx Data Management Plan.

7. Review of previous modelling studies

The following review summarizes published numerical modelling studies that refer to the three TEAMx target areas. Most of them were performed in the Inn Valley and surroundings (Sec. 7.1). Two large sets of simulations are connected with measurement campaigns on foehn winds (MAP, 1999 and PIANO, 2017), where a strong focus was laid on understanding windstorms over the city of Innsbruck. Another set of simulations refers to model evaluation with the i-Box turbulence observations, for purposes of turbulence parameterization evaluation and improvement.

Fewer numerical studies dealt with the other TEAMx target areas (Sec. 7.2-7.4). However, a few modelling studies on convection, gravity-wave breaking, cold-air pool dynamics and glacier-atmosphere interactions were conducted in neighboring regions in the Eastern Alps (Sec. 7.5).

Finally, we give an overview of LES studies of boundary-layer flow over complex orography in Section 7.6. Since studies of high-resolution, real-case LES are still rare, we also introduce studies outside of the TEAMx target areas.

7.1 Inn Valley Target Area

For clarity, we group weather modelling studies in the Inn Valley depending on the studied phenomenon.

- **Foehn winds.** The city of Innsbruck and surroundings are subject to frequent foehn wind episodes throughout the year, with the statistical maxima occurring in spring and autumn. A measurement campaign on the penetration of foehn down to the Inn valley floor was conducted in autumn 2017 (PIANO, Haid et al., 2020). The main focus was laid on foehn-cold air pool interactions. Accompanying simulations in the LES range were performed by Umek et al. (2021, 2022), and the simulations were utilized for process understanding and sensitivity experiments on horizontal grid spacing. A trajectory analysis for an unusual foehn event was performed by Saigger and Gohm (2022). Other relevant foehn research took place in the Alpine Crest Target Area (see below).
- **Thermally-induced circulations.** The valley wind system of the Inn Valley was first investigated numerically by Zängl (2004a) with semi-idealized simulations, while a subsequent work studied the impact of synoptic flow on the valley wind system Zängl (2009). Measurements

at i-Box flux measurement sites (Rotach et al., 2017) were used to evaluate boundary-layer parameterizations (Goger et al., 2016). Simulations of up-valley wind days with the COSMO model showed that 3D effects in the model's TKE progostic equation are essential for the correct simulation of TKE in the Inn Valley (Goger et al., 2018, 2019).

- Other relevant studies investigated wintertime smog episodes in the Inn Valley (Schicker and Seibert, 2009), and the impact of improved land-use datasets on weather forecasts over two Austrian regions, one of them being the Inn Valley (Schicker et al., 2015).

7.2 Adige Valley Target Area

In the Adige Valley, located south of the Alpine main crest, many applied modelling studies were conducted in the recent years. Topics included: the sensitivity of simulated wind speeds to horizontal grid spacings (Giovannini et al., 2014a); process studies on the Vaia storm over Northwestern Italy (Giovannini et al., 2021; Sioni et al., 2023); mountain boundary layer processes (Giovannini et al., 2014b); urban meteorology studies on building energy consumption (Pappaccogli et al., 2021); pollutant dispersion studies in connection with tracer release experiments (Zardi et al., 2021); improvement of turbulence parameterizations for dispersion modelling (Tomasi et al., 2019); evaluation and optimation of snowpack modelling in land-surface models (Tomasi et al., 2017).

7.3 Alpine Crest Target Area

The Alpine Crest Target Area connects the Inn Valley and the Adige Valley. The instrumentation deployed during the TOC in this region focuses on the Sarntal Alps and Vinschgau/Val Venosta. This area is particularly interesting because it represents a climatological maximum of convection initiation events in the interior of the Alps (Manzato et al., 2022).

Located slightly to the north of the Sarntal Alps, the Wipp Valley connects Austria and Italy through the Brenner Pass. It was the main target area for field observations of foehn during the Mesoscale Alpine Programme (MAP). Mayr et al. (2007) and Smith et al. (2007) give broad overviews of the main MAP findings in this respect. Gohm et al. (2004) and Zängl and Gohm (2006) investigated the mechanisms of foehn flow in the Wipp Valley in great detail. An additional set of simulations at the same location was conducted by Zängl et al. (2003); the impact of vertical resolution and the PBL scheme on simulations of foehn was also investigated (Zängl et al., 2008). Gohm and Mayr (2004) discussed the hydraulic aspects of foehn flow as well. (Weissmann et al., 2004) and (Rucker et al., 2008) relevant observations-oriented studies, mostly focusing on doppler wind lidar measurements.

7.4 Northern Pre-Alpine Target Area

The Northern Pre-Alpine Target Area is located in the Bavarian Alpine foreland, directly adjacent to the Alps. Weather in this region is heavily influenced by atmospheric processes related to mountainous terrain, for example Alpine pumping, which was studied in regional climate simulations by Graf et al. (2016). Siedersleben and Gohm (2016) studied the dynamics of potential vorticity banners leading to banded convection over the forelands in a wintertime episode of strong southerly synoptic flow. Hald et al. (2019) instead carried out LES of weather events during the ScaleX campaign and presented a qualitative comparison between simulations and observed turbulence statistics.

7.5 Vicinity of target areas

Zängl (2005a) investigated the interactions between cold-air pools and a valley wind system as well as cold-air pools in the Alpine foreland of Bavaria (Zängl, 2005b). Scheffknecht et al. (2017) investigated a long-lived supercell travelling along the Alpine main crest. Recently, the Hintereisferner glacier in the Ötztal was subject to a detailed study on glacier boundary layer processes (Goger et al., 2022; Voordendag et al., 2024).

7.6 Large-eddy simulations over complex terrain

Real-case large-eddy simulations were for a long time constrained by numerical stability issues and computational resources. One of the first studies was conducted in the Swiss Rivera Valley with the ARPS model by Chow et al. (2006) and Weigel et al. (2006). In the simulations, the valley was resolved well, and the numerical results complemented the observations well and it was possible to fill data and knowledge gaps on heat exchange, turbulence structure, and wind patterns, which would have been impossible with coarser-scale simulations (e.g., kilometric range). The correct transition from meso- to microscale grid spacings was a pressing issue towards real-case LES ($\Delta x < 100$m).

LES usually rely on boundary and initial data from coarser, ie.e, meso-scale domains, which might lead to inconsistencies in turbulence development. Muñoz-Esparza et al. (2014) conducted simulations with the WRF model with a focus on correct turbulence development in the innermost LES domain and found that a cell perturbation method yields improved turbulence generation in the intertial subrange. Multiscale simulations during the CWEX-13 campaign (Muñoz Esparza et al., 2017) tested the cell perturbation approach in a real setting, allowing to omit "intermediate" domains at the hectometric range, where turbulence is likely misrepresented due to the turbulence grey zone.

However, over complex terrain, nested LES also deliver reliable results without the cell perturbation method, likely due to the very inhomogeneous terrain and surface characteristics which allow realistic turbulence generation over the domains. Nowadays, many measurement campaigns are accompanied by high-resolution LES. For example, Gerber et al. (2018) investigated spatial precipitation patterns over a region in the Swiss Alps during the DISCHMEX campaign, and Vionnet et al. (2017) investigated snow accumulation patterns over the French Alps. Furthermore, Umek et al. (2021) conducted LES of foehn-cold air pool interactions during the PIANO campaign, and further extended the study to investigate the impact of horizontal and vertical resolution on the valley boundary layer structure. Conolly et al. (2021) investigated vortex shedding behind Granite Peak in Utah, USA, and found that the LES performed well in representing the vortices during the MATERHORN campaign.

LES studies can also be utilized for studying boundary-layer phenomena like cellular convection during the T-REX campaign (Babić and De Wekker, 2019) or nocturnal low-level jets during the ScaleX campaign (Hald et al., 2019). Another application of high-resolution LES was a study of flow structures for weather forecasting for the Winter Olympic games in China (Liu et al., 2020).

LES can also can help with data gaps in regions, where observations are sparse, like glaciers in high mountain environments, as in Goger et al. (2022) for summer cases and Voordendag et al. (2024) for wind-driven snow redistribution. An overview of boundary-layer flow over the Canadian Rockies shows the complex flow structure and scale interactions with the WRF model (Rohanizadegan et al., 2023).

7.7 Kilometer-scale climate applications

Climate modelling studies so far did not focus on the TEAMx targeted specific sub-regions in the Alps, but were analysing Alps as a whole and surrounding areas. Thus we here provide an overview of existing literature over the entire Alps.

Kilometer-scale applications of climate models over the Alpine domain now have an about 10-year long history. A review of the underlying techniques, assumptions, applications, and challenges is provided by Lucas-Picher et al. (2021) or Schär et al. (2020). The availability of model simulations was boosted by the CORDEX Flagship Pilot Study on Convective Systems in which the Alpine domain was selected as one of the focus areas (Ban et al., 2021; Pichelli et al., 2021; Coppola et al., 2020) as well as by the EUCP project https://www.eucp-project.eu/. Added value analyses indicate a clear benefit of the kilometer-scale resolution in many different aspects. Those are:

- **The diurnal cycle of summer precipitation** (see e.g., Ban et al., 2021; Knist et al., 2020; Lind et al., 2020; Leutwyler et al., 2017; Ban et al., 2015, 2014). In comparison to coarse resolution models which use parametrization of convection, km-scale climate models are able to reproduce the diurnal cycle of summer precipitation. These results are supported by many studies and are more recently confirmed by multi-model ensemble at the km-scale resolution (Ban et al., 2021). The added value of high horizontal resolution is visible in the timing of the diurnal cycle, precipitation intensity, and frequency.
- **Precipitation extremes at daily and sub-daily scale** (see e.g., Ban et al., 2021; Pichelli et al., 2021; Knist et al., 2020; Lind et al., 2020; Ban et al., 2020; Leutwyler et al., 2017; Ban et al., 2015, 2014). Extreme precipitation at short timescales with a potential to trigger flash floods, landslides, and debris flow, was for a long time misrepresented by regional climate models with grid spacing above 10 km. However, km-scale resolution improved the representation of these events, their relation with temperature, and can alter the climate change signal.
- **Snow cover.** A recent study using COSMO simulations at the km-scale resolution showed a much better representation of snow cover over the European Alps when using higher resolution (Lüthi et al., 2019). It was clearly shown that the 2 km model outperforms 12 and 50 km models, despite having a slight overestimation of snow cover in fall and too fast melt of it during springtime. It is also shown that only a high-resolution model can represent elevations higher than 2500 meters, which is important for glaciers and glacier modelling.
- **Temperature** (see e.g., Soares et al., 2022; Ban et al., 2014). Even though most of the km-scale models show warm bias, one can see the improvements in the simulation of diurnal temperature range (Ban et al., 2014).
- **Winds** (see e.g., Belušić Vozila et al., 2023; Belušić et al., 2018). Analysis of wind in high-resolution simulations is still very limited and in addition to the Alps, it includes the surrounding but also very complex areas like Adriatic. The existing literature shows that km-scale climate simulations are better in representing Bora and Sirocco along the Adriatic, as well as land-sea breezes.

In addition to those, future climate model applications in the Alpine domain, including future generations of national or Alpine scale climate scenarios, can be expected to more and more rely on ensembles of kilometer-scale climate model simulations.

Acronyms

AROME	Application of Research to Operations at MEsoscale model
ARPS	Advanced Regional Prediction System model
CM1	Cloud Model 1
CMIP	Coupled Model Intercomparison Project
CORDEX	COordinated Regional Climate Downscaling EXperiment
CORDEX FPS	CORDEX Flagship Pilot Study
COSMO	COnsortium for Small-scale modelling
CROSSINN	CROSS-valley flow in the Inn valley (project)
DWD	Deutscher WetterDienst
ECMWF	European Centre for Medium-range Weather Forecasts
EnDA	Ensemble Data Assimilation
EOP	Extended Observation Period
ERA5	ECMWF Reanalysis version 5
ESGF	Earth System Grid Federation
GABLS	GEWEX Atmospheric Boundary Layer Study
GEWEX	Global Energy and Water Exchanges
GRAMM-SCI	Graz Mesoscale Model–Scientific
HRES	High-RESolution
IBM	Immersed Boundary Method
i-Box	Innsbruck Box
ICON	ICOsahedral Nonhydrostatic weather and climate Model
ICs	Initial Conditions
IFS	Integrated Forecasting System
IOP	Intensive Observation Period
LASSO	LES ARM Symbiotic Simulation and Observation Workflow
LBCs	Lateral Boundary Conditions
LES	Large-Eddy Simulation
LIDAR	Laser Imaging Detection and Ranging

MAP	Mesoscale Alpine Programme
MesoNH	Mesoscale Non-Hydrostatic model
MoBL	Mountain Boundary Layer
MOLOCH	Limited-area model run by the Institute of Atmospheric Sciences and Climate in Bologna
NWP	Numerical Weather Prediction
PIANO	Penetration and Interruption of Alpine Foehn (project)
SCM	Single-Column Model
SLEVE	Smooth-LevEVel VErtical (coordinate)
TEAMx	multi-scale Transport and Exchange processes in the Atmosphere over Mountains – programme and eXperiment
TKE	Turbulent Kinetic Energy
TOC	TEAMx Observational Campaign
UM	Unified Model
WRF	Weather Research and Forecasting model

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