DRAFT

Plan for the TEAMx Observational Campaign

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This is a collaborative working document which will continue to be developed up until the TEAMx Observational Campaign in 2024-5

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DRAFT Plan for the TEAMx Observational Campaign

Contents

1 Introduction

This document outlines the activities proposed for the main TEAMx Observational Campaign (TOC). It has been put together by the TEAMx Programme Coordinator and Field Observations Committee (FOC, Appendix A.1) with input from the TEAMx Working Groups (WGs) and is intended as a working copy which will continue to be further developed in close consultation with the WGs and various members of the TEAMx community. Details will continue to be added and amended as more is known about the outcome of funding decisions and the availability of resources.

The purpose of this document is to provide the TEAMx community with an overview of the planned field activities. It is the intention that the ideas outlined here will facilitate the development of TEAMx research projects, help to foster new collaborations and lead to additional instrumentation being made available for the field campaign.

2 Motivation

TEAMx[1] is an international research programme focused on improving our understanding of exchange processes in the atmosphere over mountains and evaluating how well these are represented in numerical weather prediction and climate models. Research goals and open questions are outlined in the TEAMx White Paper (Serafin et al., 2020), while the motivation for TEAMx is summarised in Rotach et al. (2022).

TEAMx will use state-of-the-art measurement and modelling techniques to study a wide variety of orographically-induced phenomena across a range of scales and the interactions between these scales. The two central pillars of TEAMx are (i) a major observational campaign involving large-scale deployment of in situ micrometeorological instrumentation, ground-based profiling instruments and airborne sensors; and (ii) coordinated model evaluation and development studies combining a hierarchy of tools from large-eddy simulation to global-scale models. Compared to previous research programmes in mountainous terrain TEAMx will investigate smaller-scale processes (in particular, the micro-alpha scale and surface exchange) and how these small-scale processes interact with and are influenced by larger-scale processes.

The main objectives of TEAMx can be summarised as follows:

- **O1.** to improve qualitative and quantitative understanding of transport and exchange processes both between the surface and atmosphere and at multiple scales within the atmosphere,
- **O2.** to provide a unique observational dataset which can be used to investigate the wide range of transport and exchange processes in mountainous terrain and their spatiotemporal variability,
- **O3.** to evaluate and improve the performance of weather and climate models over mountainous terrain, and
- **O4.** to reduce errors in impact models by transferring the knowledge gained to weather and climate service providers.

[1] http://www.teamx-programme.org/

As the first step in addressing these aims, researchers and specialised instrumentation from all over the world will be brought together in a major coordinated field campaign: the TEAMx Observational Campaign (TOC). The TOC will span one complete year and include two Extended Observation Periods (EOPs), one in winter and one in summer. The campaign is planned to take place from Autumn 2024 to Autumn 2025. The focus of the campaign is the European Alps, with five target areas in the Inn Valley (Austria), the Adige Valley (Italy), the alpine foreland north (Germany) and south (Italy) of the Alps and the Alpine Crest area. These target areas have been identified based on the scientific goals of TEAMx (Section 3), the availability of existing long-term measurement infrastructure (Section 4.1) and the extensive knowledge gained through previous research in these areas (Section 6.1).

In order to supplement the existing observations and monitoring networks, a considerable amount of additional instrumentation will be brought in during the campaign (Section 4). In situ and remote sensing measurements (both ground-based and airborne) will provide detailed information about the three-dimensional structure of the mountain boundary layer (MoBL): a dense network of meteorological and air quality monitoring stations will inform about near-surface conditions (in valleys as well as at crest-top); numerous eddy covariance stations over a range of surface types will provide information about near-surface turbulent exchange processes; and atmospheric profilers (including lidars, ceilometers, microwave radiometers and radars), radio-soundings and aircraft measurements will offer insights into the valley atmosphere and conditions aloft. Research topics are organised into six working groups (WGs) on *Atmospheric Chemistry*, *Mountain Boundary Layer*, *Mountain Climate*, *Orographic Convection*, *Surface-atmosphere Exchange* and *Waves and Dynamics*. The specific research goals that have been identified by each of the six working groups are presented in Table 1.

This document is structured as follows. Section 3 outlines the observational strategy, highlighting the main challenges of making measurements in complex terrain and describing the temporal and spatial sampling approaches to address these challenges. The various types of instrumentation required to capture the range of processes of interest are summarised in Section 3.4 and recommendations are made for a minimum base-set of measurements. Section 4 provides an overview of existing measurement infrastructure available during the TOC. First considerations about how the campaign will be carried out are described in Section 5. More details will be developed in a separate Implementation Plan. A summary of relevant previous studies can be found in Section 6.

Overall aims of TEAMx
O1. Improve qualitative and quantitative understanding of transport and exchange processes both between the surface and atmosphere and at multiple scales within the atmosphere. **O2.** Provide a unique observational dataset which can be used to investigate the wide range of transport and exchange processes in mountainous terrain and their spatiotemporal variability. **O3.** Evaluate and improve the performance of weather and climate models over mountainous terrain. **O4.** Reduce errors in impact models by transferring the knowledge gained to weather and climate service providers.
Specific goals identified by the working groups
A. Atmospheric Chemistry **A1.** Improve understanding of the interaction between dynamics and chemistry at relevant scales using chemical composition measurements and high-resolution modelling. **A2.** Improve understanding of sources, transport and chemical processing of trace species and their precursors. **A3.** Develop parameterizations to better represent chemical processes in large-scale models using remote sensing and regional atmospheric models capable of resolving important atmospheric processes in complex topography. **A4.** Investigate the role of gravity waves on the chemical composition of the atmosphere (particularly on stratosphere-troposphere exchange) by developing parameterisations for chemical transport models and comparing with observations of the chemical composition within breaking gravity waves. **A5.** Use long-term chemical atmospheric observations to address the knowledge gaps in the evolution of air pollution sources in the Alps.
B. Mountain Boundary Layer **B1.** Characterise the spatial and temporal structure of the convective and stable MoBL (at sub-hourly to seasonal timescales), particularly the three-dimensional distribution of turbulence. Compare findings to ideal terrain expectations. **B2.** Develop and test objective methods to determine the vertical extent of the MoBL. **B3.** Observe phenomena at the interface between the MoBL and the free atmosphere for a variety of weather conditions, to infer the sources, transport pathways and residence times for atmospheric constituents (e.g. water vapour). **B4.** Relate the intensity of thermally driven orographic flows to the respective forcing factors and quantitative descriptors of orographic variability. **B5.** Improve understanding of interactions between processes, such as how thermally driven orographic flows are affected by other types of baroclinic mesoscale circulations (e.g. lake and sea breezes), how urban areas affect the formation and breakup of cold air pools and how meso- and synoptic scale forcing impact exchange at the top of the MoBL. **B6.** Quantify the contribution of turbulence and organized mesoscale motions to the total MoBL exchange. **B7.** To improve modelling of energy and mass exchange over mountainous terrain, develop better surface-layer schemes for the stable MoBL (in particular concerning the parameterisation of intermittent mixing), more advanced snowpack models and improved parameterisations of entrainment and advective transport at the top of the MoBL, and use large-eddy simulations in conjunction with observations for process studies at the transition between micro- and meso-scales.
C. Mountain Climate **C1.** Improve understanding of the processes affecting mountain climate (e.g. surface-atmosphere interactions, differential warming rates with elevation, extreme events, loss of

ice mass and physical changes in mountain ecosystems, changes in the large-scale circulation).

C2. Improve long-term observational capabilities in mountain regions by evaluating new observational techniques for mountain climate networks, remote sensing products for mountain climate applications, and new strategies for network design and data assimilation in complex terrain.

C3. Quantify and reduce systematic model errors arising from parameterised processes (e.g. the surface energy balance) and their dependence on model resolution.

C4. Implement better parameterizations of mountain-induced exchange into models that work on climatological time scales (e.g. regional/global climate and earth system models) to reduce the uncertainty of mountain climate change projections.

D. Orographic Convection

D1. Conduct observations over a broad range of scales including mountains and the surrounding valleys and plains to identify conditions favourable to convection.

D2. Use high density upper-air observations of wind, temperature and moisture and improve assimilation of high-resolution observations in order to reduce initial-condition errors and improve forecasts.

D3. Improve conceptual understanding of orographic convection using hierarchical numerical experiments that span the gap between real and idealised simulations.

D4. Document the climatology of orographic convection in the pan-Alpine region.

D5. Improve the understanding of the critical features controlling the predictability of convection in complex terrain.

D6. Improve the understanding of the circulation/processes (down to meso-gamma scale) responsible for convective initiation and development, possibly with in situ or remote sensing observations, and define conceptual models in the Alpine area at different scales.

E. Surface-atmosphere Exchange

E1. Improve understanding of the processes involved in transport and exchange of momentum, heat and mass between the Earth's surface and the atmosphere over mountainous terrain.

E2. Improve understanding of the processes responsible for energy balance under-closure and uncertainties in carbon dioxide uptake over mountainous terrain to enable more robust interpretation of eddy covariance fluxes and more accurate quantification of the global carbon budget.

E3. Investigate the lesser-studied conditions (e.g. wintertime, snow cover) and surfaces (e.g. glaciers, urban areas, water bodies) that are important in mountain regions.

E4. Improve understanding and modelling of the effect of surface and sub-surface heterogeneity (e.g. in vegetation or soil characteristics) on surface-atmosphere exchange.

E5. Generalise flux-profile scaling relations to improve surface exchange parameterisations in horizontally heterogeneous and non-flat terrain.

F. Waves and Dynamics

F1. Improve understanding of the generation and propagation of mountain gravity waves over complex, multi-scale mountains in a range of background flow states.

F2. Quantify the transport and turbulent exchange of momentum, energy and mass due to mountain gravity wave dynamics and embedded flows, both in the wake of mountains and in the free atmosphere.

F3. Investigate the interplay between valley conditions and mountain-generated gravity waves (such as the influence of cold air pooling on wave properties) and the role of wave dynamics in valley flushing.

F4. Ultimately, improve weather and climate models through improved understanding and representation of mountain wave and dynamics driven exchange processes, both resolved and parameterized.

Table 1: Overall aims (O) of TEAMx and specific research goals (A-F) of the working groups. More details can be found in the TEAMx White Paper (Serafin et al., 2020).

3 Observational strategy

3.1 General considerations

Acquiring accurate meteorological measurements in complex terrain presents several challenges. Two main issues which set complex terrain apart from other environments are the extremely high spatiotemporal variability of the surface and atmosphere, and the associated range of transport and exchange processes that result from this variability. Spatial variability occurs in three-dimensions and across a wide range of scales, which means that point measurements made at one location will likely not be representative of other locations, even those nearby. Hence multiple repeat measurements are required to firstly observe the spatial differences and secondly inform about the physical processes which result from and contribute to this spatial variability. Since spatial variability in mountainous regions occurs across such a wide range of scales (e.g. between adjacent fields or land cover types, from one side of a valley to the other, at different locations along a valley, at different elevations, between different valleys, between the windward and leeward sides of a mountain range, between the mountains and surrounding plains, etc), high-resolution observations are needed to capture microscale to local-scale variations and repeat observations are needed at several sites across the region to capture mesoscale to regional-scale variations. Such a campaign demands a large amount of instrumentation.

Many measurement techniques and tools to assist interpretation assume horizontal homogeneity of the surface or atmosphere (e.g. retrieving wind and turbulence from a single lidar, retrieving temperature and humidity from microwave profilers, estimating measurement source areas using footprint models). In mountainous terrain the validity of many of the assumptions made for ideal (i.e. flat and horizontally homogenous) landscapes is highly questionable, and processes that are unimportant or usually assumed to have negligible impact may be significant. These processes and phenomena include advection, dispersive fluxes, rotor formation, turbulent wakes, waves, wave breaking, three-dimensional transport of turbulence, local circulations and mesoscale flows, and are mostly very difficult to capture with conventional instrumentation (Emeis et al., 2018; Lehner and Rotach, 2018). Thus, before interpreting measurements in complex landscapes careful assessment of the robustness and representativeness of the techniques is required.

Similarly, thorough consideration must be given to how observations will be compared with model output. In order to capture the spatial variability and scale of relevant processes, extremely high-resolution model runs are required (e.g. large-eddy simulations at ~10 m; climate simulations at ~1 km). For mesoscale model runs (with grid spacing ~1 km) comparison between model output and observations is typically hampered by differences in what each dataset represents (i.e. the instrument source area compared to the closest model grid point). To help minimise incompatibilities, the observational strategy for TEAMx will continue to be developed in close conjunction with the Numerical Modelling Committee. Some observations may be specifically for modelling purposes, for example measurements to capture inflow conditions for model initialisation or stations arranged in a grid-like distribution matched to model grid boxes. However, as mountainous terrain is so spatially heterogeneous, sampling of representative sites rather than across a regular grid, is likely more informative at larger scales (e.g. above about 1 km).

Climate information typically requires observations of some 30-year duration. For mountainous terrain, these data are scarce for meteorological and turbulence measurements, let alone for measurements capturing the three-dimensional structure of the MoBL. Existing long-term observational platforms may help (at least partially) to bridge the gap from field campaigns to climate time scales, but the remaining discrepancies will need to be addressed through modelling and theoretical approaches. However, not all climate-related research requires long-term records. The Mountain Climate WG will also use short-term highly detailed datasets to work towards improving understanding of processes and the representation of these processes in weather and climate models. Additionally, comparisons between types of site can be used to inform long-term projections (e.g. urban/non-urban, snow/no snow, high/low altitude).

Practically speaking, instrumentation will need to withstand the extreme conditions experienced in mountain environments, such as high wind speeds and gustiness, sub-zero temperatures, snowfall and icing, and potentially no direct sunlight during winter. Some sites may be without direct road access or mains power. Costs for installation, maintenance and decommissioning must be budgeted for. It will be necessary to synchronise the clocks of instruments/loggers to ensure that various data sources can be combined. As many groups will be involved it will be necessary to coordinate measurement strategies such as retrieval algorithms, processing options and quality control. Such highly specific topics will be managed and documented by Task Teams (TT), comprising a small group of experts on each topic (Appendix A.2).

Based on these considerations, the following subsections (Section 3.2-3.4) describe and explain the sampling approach for the TEAMx Observational Campaign. All data collected as part of TEAMx will be open access and accessible through a central data portal (although the data itself will be stored across multiple data centres). Guidelines for data format, access and acknowledgement and will be specified in the TEAMx Data Policy (currently in development).

3.2 Temporal sampling approach

The *TEAMx Observational Campaign* (TOC) will span one complete year in order to capture a broadly representative dataset involving a wide range of processes, to allow investigations across different timescales and to observe the full annual cycle. Within this year-long campaign there will be two *Extended Observation Periods* (EOPs). One EOP will take place in summer and another in winter, and each will last at least several weeks. During the EOPs, it should be ensured that all surface-based instrumentation is properly functioning (e.g. with daily checks on data collection and data quality). Individual *Intensive Observation Periods* (IOPs) will take place during the EOPs. The IOPs will last from a few hours to a few days and will be defined based on atmospheric conditions as specified in the Operational Plan (Section 5). Previous studies – at least in and around Innsbruck – suggest clear-cut 'textbook' days or events are extremely rare (e.g. Lehner et al., 2019). Conditions of interest therefore include *thermally dominated dry* (e.g. slope- and valley-winds and mountain-plain circulations but without deep convection), *thermally dominated moist* (e.g. deep convection with precipitation and thunderstorms), *wintertime anticyclonic* (e.g. cold-air pools), *dynamically dominated* (e.g. downslope windstorms, wave events) and *synoptically dominated* (e.g. large-scale systems leading to channelled or cross-valley flow). As well as typical examples of different conditions, extreme events (e.g. windstorms, heavy precipitation, deep propagating wave events) are also of great scientific and societal interest. While some similar types of conditions will be sampled for different seasons, the two EOPs will likely focus on different research questions. Ideally, the campaign would last several years; in practice it cannot reasonably be much longer than one year due to the commitment of instrumentation and personnel. Existing long-term observational platforms within the study region and reanalysis data are therefore critical for assessing the representativeness or generality of the EOPs and IOPs.

During the EOPs and IOPs, additional labour-intensive measurements will be made, including airborne observations, extra ground-based sampling and frequent radio-soundings. This will require a team of operators and an 'operations centre' from where forecasts and measurement details (e.g. flight paths, time and location of radio-soundings, coordination with ground-based instrumentation) for the following day are managed. Subject to resources, some labour-intensive observations may be maintained throughout the EOPs. Details about the EOPs, IOPs and various measurement scenarios will be set out in the Operational Plan (Section 5).

The TOC is planned to take place from Autumn 2025 to Autumn 2025, with the EOPs in January/February 2025 and June/July 2025. This is later than originally planned as result of the knock-on effects of Covid-19 and avoids clashes in the demand for instrumentation reserved for other campaigns.

In a longer-term context, the TOC (and events within the TOC) will be assessed to determine whether this period is exceptional or rather normal in a climatological sense. Long-term monitoring sites within the study region, as well as remote sensing products (e.g. snow cover) and reanalyses will be used for this purpose.

3.3 Spatial sampling approach

The spatial sampling approach comprises several *target areas* (TAs) embedded within regional monitoring networks across the *study region*. Within each target area, one or more *supersites* will contain a multitude of surface-based in situ and remote sensing instrumentation to probe the atmosphere in detail around typical orographic entities such as a valley section, mountain ridge or valley entrance. Each supersite will include a main flux tower with radiation and meteorological measurements and co-located profiling instruments. Since the three-dimensional structure of the atmosphere will be observed, the supersites can be thought of as volumes or boxes spanning several kilometres in the horizontal directions and extending at least through the mountain boundary layer in the vertical direction. In addition, several *Sites of Special Interest* (SSI) can be used to further investigate specific processes.

The TEAMx *study region* refers to the area of the European Alps that is the focus of the TEAMx experimental (observational and modelling) activities. The motivation for basing the observational campaign in the European Alps is the extremely complex orography, variety of land use types, abundant precipitation, high population density, good coverage of existing meteorological observation networks and long-term research infrastructure, and extensive knowledge gained through previous research (Section 6.1). From a practical perspective, the study region is relatively accessible and represents a fairly confined area, with stark contrasts in orography and land cover occurring over short distances.

Within the study region (Figure 1) there are several target areas: these include the Inn Valley Target Area (IVTA), Adige Valley Target Area (AVTA) the Northern Pre-Alpine Target Area (NPATA), the Southern Pre-Alpine Target Area (SPATA) and the Alpine Crest Target Area (ACTA). A high density of instrumentation is or will be operated across these target areas, and particularly at the supersites. Examples of TEAMx supersites that are already largely established include the Innsbruck-Box (i-Box)

(Rotach et al., 2017) and the Innsbruck Atmospheric Observatory (IAO) (Karl et al., 2020), both in the Inn Valley Target Area. In the Pre-Alpine Target Area both the ICOS site at Fendt (Wolf et al., 2017) and the KIT-Campus Alpin in Garmisch-Partenkirchen can serve as TEAMx supersites. Measurements in the Southern Pre-Alpine Target Area (SPATA) to the south of the Alps will be of interest in terms of up/downstream conditions, while additional instrumentation in the Alpine Crest Target Area (ACTA) will help to close the gap between the AVTA and IVTA and provide a cross-alpine transect.

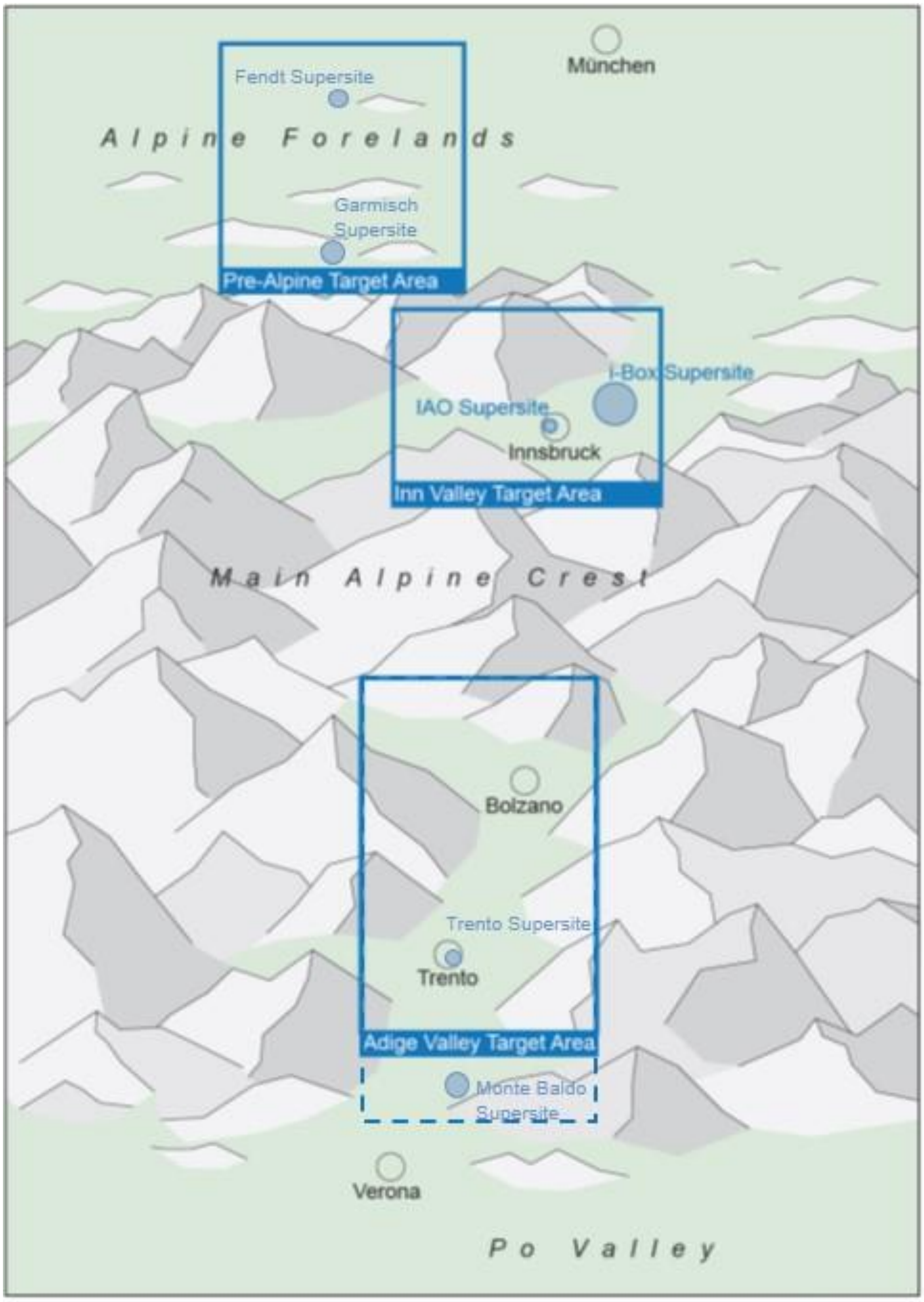

Figure 1: Sketch of the TEAMx study region indicating the approximate locations of the target areas and supersites.

The collection of target areas and supersites is intended to cover complementary aspects (e.g. an east-west orientated valley versus a north-south orientated valley; upstream versus downstream positioning with respect to the main alpine crest and major mesoscale meteorological events; a valley section versus a valley entrance; mountain top versus valley floor). The dense network of instrumentation at the supersites is fundamental to addressing TEAMx objectives. The supersites will be similarly instrumented as far as possible to enable comparison of processes in different settings (see Section 3.4). However, some studies will focus on particular processes that occur more often at some locations than others (e.g. cold pool formation, convection initiation) so may require specialist instrumentation or a differently optimised setup that will not necessarily be repeated everywhere.

By having more than one target area focused on Alpine valleys, the role of synoptic conditions (within broadly the same climate), vegetation type and human factors (such as farming practice or land management) can be investigated. Furthermore, comparisons between TAs and between supersites within the same TA will help to clarify whether particular results are highly local or a more general feature of complex terrain. More generally, comparison of TEAMx results with studies in other mountain ranges will help to assess the representativity and generalisability of results.

Locating the two mountain-valley TAs either side of the main alpine crest enables investigation of large-scale processes and characterisation of upstream and downstream conditions (particularly with respect to summertime convection, foehn events and snow cover). The Adige Valley and the Inn Valley have broadly the same attributes but are located on different sides of the alpine crest. They are both relatively large alpine valleys of similar size with partly urbanised valley floors. The cities of Bolzano/Bozen and Trento/Trient (in the Adige Valley) and Innsbruck (in the Inn Valley) are similar in terms of size (approx. 100,000-125,000 inhabitants) and characteristics (e.g. building materials, layout). Outside the urban areas, the valley floors are used mainly for agriculture (mainly cereal, salad and vegetable crops in the Inn Valley, while orchards and vineyards are common in the Adige Valley). They are also both relatively dry anomalies compared to the surroundings. The approximately north-south orientation of the Adige Valley provides a helpful contrast to the east-west Inn Valley. For example, the spatial patterns in surface heating and associated circulations can be compared and the effect of valley orientation on the interaction between synoptic and local flows can be investigated. Several paired measurement sites can be identified comprising the same type of site (e.g. flat valley floor, slope, crest) or land cover (e.g. agricultural, forest, urban) in each target area. Alternatively, groups of sites with different characteristics (e.g. land cover, slope, elevation) in one target area can be examined together. Sites across the study region will be ranked in terms of their complexity (e.g. slope angle, land cover composition, orographic variability, terrain anisotropy), providing further opportunities to assess the effects of complex terrain.

The Northern Pre-Alpine Target Area in southern Germany includes the Bavarian Alps and foreland and there is a strong south-north gradient in elevation, surface and sub-surface properties (Kiese et al., 2018). This transition from the forelands to the alpine landscape will allow exploration of terrain-induced effects and their relevance in and around mountainous areas. The Southern Pre-Alpine Target Area in northern Italy covers the western Po Valley and flat plains to the south of the Alps. The Monte Baldo supersite lies close to the transition between the alpine foreland and north Italian Alps.

The Alpine Crest Target Area spans the central Alpine region between the southern edge of the IVTA and the northern edge of the AVTA. This TA includes the highest peaks and the least accessible terrain. Therefore, fewer instruments are and will be installed here compared to the other TAs. Ground-based instrumentation will be supplemented by additional in situ and remote sensing observations where needed, but much of the observations made in this target area will be via aircraft transects. From a practical perspective, the relatively compact study region and proximity of the target areas is a major advantage. High-resolution mesoscale model runs (≤ 1 km) can easily incorporate the target areas in one domain and large research aircraft can potentially visit multiple target areas in a single flight.

When characterising the atmosphere over mountainous terrain, having at least one reference dataset for more ideal (i.e. at least flat, preferably also reasonably homogeneous) terrain would allow comparison of results and testing of hypotheses. Although several datasets already exist for ideal-terrain sites, having concurrent measurements collected using comparable techniques that can be post-processed and analysed identically, will be much more valuable than comparing TEAMx findings to the literature (e.g. the Kansas datasets). Therefore, reference sites will be established to the north and south of the Alps in southern Germany and the Po Valley. Ideally, the reference sites would be just far enough away from the Alps to be in flat terrain yet close enough that the regional weather conditions are reasonably similar (or at least relatable through known characteristic differences). As far as possible, land cover at the reference sites should be comparable to sites within the target area. While these reference sites will not be as heavily instrumented as the complex terrain supersites, they should still include basic meteorological observations, multiple level eddy covariance measurements and atmospheric profilers for wind, temperature and humidity. Ideally, the reference sites will have a long term (climatological) record of at least basic meteorological variables. For processes operating at larger scales, reference sites further away may be more relevant. For example, for the Orographic Convection WG, the plain and foothill areas of Veneto and Friuli Venezia Giulia regions would be very useful, since many storms that are triggered near Lake Garda evolve in their mature stage above this area. For the Waves and Dynamics WG, a reference site should be far enough away to be outside the blocking influences (e.g. at least a radius of deformation). Potential reference sites in Europe with an exceptional range of measurements (but all quite far away) include Cabauw, The Netherlands; Lindenberg, Germany; and JOYCE in Jülich, Germany.

In addition to the target areas and supersites, there are several sites across the study region which feature important infrastructure for specific applications and will provide valuable data for TEAMx projects. Some of these sites may not qualify as supersites (as there is not enough instrumentation) but are still of particular interest for various research questions.

As TEAMx brings together a range of disciplines within mountain meteorology, it is likely that the different working groups will have slightly different focus areas and scales of interest, and thus will concentrate on different subsets of the data collected. For the *Surface-atmosphere Exchange* and *Mountain Boundary Layer* WGs the two Alpine valley target areas will be central to investigations of fine-scale boundary-layer structure and exchange processes, whereas the interests of the *Orographic Convection* and *Waves and Dynamics* WGs will likely extend further afield to the surrounding landscape and differences between the north-and-south sides of the Alps. Important locations for the *Atmospheric Chemistry* WG will be the urban areas and crest-top stations, while long-term measurement stations and pan-Alpine networks will be highly relevant for the *Mountain Climate* WG. However, each of the WGs span a wide range of research interests and all are concerned with interactions between processes at different scales, thus there is expected to be considerable cross-over and communication between groups which will add value to individual measurements that can be used for multiple purposes. Through the working groups, all members of the TEAMx community should have the opportunity to contribute to this document – to see the datasets potentially available for their own studies and to see where they may be able to usefully contribute additional instrumentation and/or resources which may also benefit others.

3.4 Instrumental sampling approach

The range of scales involved in transport and exchange over mountainous terrain demands a variety of measurement techniques. Across the study region, meteorological, hydrological and ecological service providers maintain a reasonably dense network of monitoring stations. At coarser resolution there are several remote-sensing networks providing boundary layer information (e.g. from radars, ceilometers and lidars). These existing datasets (Section 4.1) form the backbone instrumentation for the TOC and will also be used to study large-scale processes, to inform about the synoptic and mesoscale conditions, to compile climatologies and to assess the long-term representativeness of particular events during the field campaign. Many of these datasets are freely available, but in some cases data access still needs to be arranged.

During the TOC, the existing networks will be supplemented with additional sites or instrumentation to more fully characterise the MoBL, to establish detailed and extensive enough measurements to capture relevant processes at a wide range of scales, and to address the TEAMx goals (Table 1). Additional weather stations, slope profiles, crest-top stations, flux towers, atmospheric chemistry measurements, radars, lidars and temperature-humidity profilers will be installed across the study region, primarily (but not necessarily exclusively) in the target areas. This core instrumentation should be operational for the whole campaign and will be provided by TEAMx partners and through individual research projects (Section 4.2). Where possible, key observations will be co-located with existing long-term sites that have been operational for several years thereby extending the dataset.

Subject to availability and funding, several major research infrastructure facilities will join the campaign (most likely for one of the EOPs), providing additional measurements at much higher density and a variety of research flights. It is hoped that individual research groups will also supplement this instrumentation with more specialised equipment for specific studies (ideally) during the EOPs, such as tracer experiments to investigate flow and dispersion, distributed temperature sensing using fibre-optic cables to investigate spatial variability in near-surface temperature, additional point measurements to capture spatial variability or study a particular process, or unmanned aerial systems (UASs) to sample the lowest portion of the boundary layer or estimate advection, for example.

The remainder of this section describes the types of measurements that will be involved in the TOC and how they will be used to address the programme goals. Table 2 lists the instrumentation required to achieve these goals, separated into 'minimum requirements' and 'desirable additions'. Most of the instrumentation listed under minimum requirements would ideally be operational over the whole campaign; the desirable additions represent more detailed measurements, some of which will likely be able to operate only during (one or both of) the EOPs. For each set of measurements (Table 2) the most relevant goals (Table 1) are cross-referenced using the codes (A-F).

Minimum requirements	Goals
▪ Good background coverage of meteorological monitoring stations (including precipitation and snow depth measurements) across the study region and within each target area	B4, B5, B7, C1, D1, E1, E3, F1, F2

▪ At least one slope profile (temperature at approx. 2-m height) from valley floor to mountain top at each supersite	B4, B5, B7, C1, D1, E1
▪ At least one multi-level flux tower per supersite with fast-response instrumentation for eddy covariance, a four-component radiometer, basic meteorological equipment and at least one measurement of soil moisture, soil temperature, ground heat flux and snow depth, plus information about site characteristics (land cover, vegetation height, soil properties)	A1, B4, B5, B6, B7, C1, C3, E1, E2, E3, E4, E5, F2, F3
▪ Several flux towers per target area to capture spatial variability: - at least one flux tower (on the valley floor, on grass or agricultural land) with at least three turbulence measurement levels - at least one flux tower (on the valley side, on grass or agricultural land), with at least three turbulence measurement levels - each tower should report momentum and heat fluxes at all levels, and water vapour and carbon dioxide fluxes at least one level	A1, B4, B5, B6, B7, C1, D1, C3, E1, E2, E3, E4, E5, F2, F3
▪ At least one vertical temperature and humidity profile throughout the boundary layer (e.g. via a microwave radiometer or temperature-humidity lidar) per supersite, co-located with the main flux tower	B1, B2, B4, B5, B7, D1, D2, F3
▪ At least one continuous vertical wind profile throughout the boundary layer (e.g. via a vertically pointing Doppler wind lidar) per supersite, co-located with the main flux tower	B1, B2, B4, B5, B7, D1, D2, D5, D6, F1, F2, F3
▪ At least one ceilometer to derive cloud conditions and local boundary layer height at each supersite	B1, B2, B3, B4, B5, B7, D5
▪ Nearby cloud and rain radar to inform about cloud cover and precipitation in each target area, plus a mobile radar to focus on areas of heavy rainfall and a mobile disdrometer	D1, D2, D6, F2
▪ A network of air quality monitoring stations across each target area	A1, A2, A5
▪ Webcams providing images of the local surroundings around the main flux tower at each supersite (both surface cover and cloud cover)	E1, E4, D1, D6
▪ Radio-soundings close to the supersite at 3-hourly intervals during the IOPs and twice daily during the EOPs	B1, B2, B3, B4, B5, B7, D1, D2, D5, D6, F1, F2, F3
▪ The target area should be included in the flight path of the large research aircraft	A4, B3, B5, B7, D6, F1, F2, F3
Desirable additions	
▪ Higher density of meteorological stations (including precipitation and snow depth measurements) around areas of interest in the target area	B4, B5, B7, C1, D1, E1, E3
▪ Multiple slope profiles from valley floor to mountain top at different locations along the valley and on opposite sides of the valley at each supersite; a higher density of stations in the slope profiles	B4, B5, B7, C1, D1, D5, D6, E1
▪ Barographs at several locations to determine pressure variations	B1, B5, B6, E1, F1, F2, F3
▪ Numerous flux towers with multiple levels covering various representative land cover types (e.g. grassland, agriculture, forest, urban, glacier) and locations (e.g. valley floor, mountain top, north/south/west/east-facing slopes) to capture spatial variability across each target area	B4, B5, B6, B7, C1, C3, E1, E2, E3, E4, E5, F3
▪ A network of multi-level flux stations arranged in a grid or adjusted logarithmic pattern	B4, B5, B6, B7, C1, C3, E1, E2, E3, E4, E5, F3
▪ Multiple temperature-humidity profilers co-located with other profiling instrumentation and/or spread out to investigate spatial variability	B1, B2, B4, B5, B7, D2, D6

▪ Multiple Doppler wind lidars performing coplanar scans to provide spatial information about the flow field and/or arranged to give vertical wind profiles at multiple locations using the virtual lidar tower technique at one supersite per target area	B1, B2, B4, B5, B7, D1, D2, D5, D6, F1, F2, F3
▪ Short-range lidars to provide high resolution wind and turbulence measurements close to the surface (e.g. lowest 100-200 m)	B1, B4, B5, B7, D1, D5, D6, E1, E2, E3, F2, F3
▪ A very high frequency radar for continuous tropospheric wind measurements	A1, B3, B7, D2, F1, F2, F3
▪ Multiple Doppler cloud radars, micro rain radars and disdrometers to provide spatial information about clouds and precipitation across the target area	D1, D2
▪ Multiple aerosol lidars to provide spatial information on aerosols across the target area	A1, A2, A3, A4
▪ Flux and concentration measurements of a variety of aerosols and chemical species	A1, A2, A3, A4, A5
▪ Tracer experiment	A1, A3, B1, B4, B5
▪ Thermal cameras to capture surface temperature variability	B1, B4, B5, B6, B7, C1, D5, E1, E2, E3, E4
▪ Distributed temperature sensing to provide detailed vertical temperature profiles and/or information about the horizontal temperature field	B1, B4, B5, B7, D5, D6, E1, E2, E3, E4
▪ Detailed airborne campaigns with smaller aircraft across the target area (involving in situ turbulence probes and lidar measurements)	A1, B1, B2, B4, B5, B6, B7, D6, E1, E2, E3, F1, F2
▪ Measurements of mean and turbulence quantities by unmanned aerial systems (e.g. drones) and/or tethered balloons	A1, B1, B5, B6, B7, E1, E2, E4

Table 2: Recommended instrumentation for the target areas and supersites separated into minimum requirements and desirable additions. The second column indicates which of the TEAMx goals defined in Table 1 (labels A-F) could be addressed using each type of measurements.

3.4.1 Local, synoptic and mesoscale meteorological conditions

A dense network of weather stations both within and surrounding the study region (Section 4.1.1) will enable robust model evaluation and greatly assist data interpretation by informing about spatial variability and near-surface conditions. Meteorological data will be provided by the respective weather services in each country. Monitoring networks of the hydrological and avalanche warning services also provide meteorological variables, as well as other information such as snow depth or run-off. Although most of the stations in today's networks have been established in the last few decades, several long-timeseries historical measurement stations also exist, useful for the *Mountain Climate* WG. Routine radio-soundings, atmospheric profiling instruments and weather stations outside the main study region will provide useful data describing the up- or down-stream conditions and will be helpful for model initialisation. Satellite images and global forecast models (ECMWF, ARPEGE, GFS) will be archived to inform about the large-scale situation.

Within the target areas, higher density clusters of weather stations will be added by TEAMx scientists around features of interest (e.g. along slopes, along cross sections, across transects, on mountain tops, along crests, in a side valley or at a side valley exit) to capture the fine-scale structure of the atmosphere in these regions. Temperature profiles along slopes will inform about the stratification of the valley atmosphere and possible cold-pool depth. A mixture of a few high-quality slope stations supported by a large number of cheaper (e.g. non-ventilated) sensors will offer reasonable quality data with good data coverage over a wide area. Ideally several slope profiles will be installed at each target area to capture spatial variability in stratification and cold-pool depth. Barographs at multiple locations will inform about the diurnal heating of the valley atmosphere, pressure fluctuations during foehn events and form drag.

3.4.2 Surface-atmosphere exchange and near-surface turbulence

Near-surface observations of turbulence will be made using flux towers. Sonic anemometers will be used to derive local-scale momentum and sensible heat fluxes using the eddy covariance technique. If possible, additional levels of turbulence measurements will be added to inform about the near-surface vertical structure of the atmosphere and to capture processes relevant in complex terrain where the presence of a constant flux layer may be questionable. Ideally, fast response measurements of gases will also be made – preferably at least water vapour (for energy balance studies) and carbon dioxide, with other gases measured at a few sites. Basic meteorological data (temperature, humidity and pressure) for the site must also be logged. At least one co-located (ideally four-component) radiometer per tower will provide (incoming and outgoing shortwave and longwave) radiation. Multiple four-component radiometers at different heights could be used to inform about the radiative flux divergence. At least one (ideally more) soil heat flux plate(s) plus soil temperature and soil moisture measurements will provide an estimate of the ground heat flux (needed for energy balance studies). Where resources allow, increased spatial coverage of soil measurements will provide insight into sub-surface variability. Alternatively, cosmic ray neutron sensors can provide area-averaged soil moisture estimates over larger areas. Additional information about soil characteristics will be very useful for model evaluation. The flux towers will also provide important information about the surface heating that drives, and interacts with, summertime Alpine convection.

Several long-term flux towers are currently operational across the study region (Section 4.1.2). Within the target areas, the density of flux measurements will be increased significantly to capture a range of locations (e.g. valley floor, mountain top, north/south/east/west facing slopes, steep/shallow slopes) and surface cover types (e.g. grassland, agriculture, forest, urban, glacier). If possible, there should be at least one 20-30 m tower per target area with five or more turbulence measurement levels and detailed wind and temperature profiles. For detailed process studies (especially katabatic flows) measurements close to the surface will be required, possibly with specialised small anemometers. Multiple multi-level towers in close proximity (forming 3D arrays of turbulence measurements) would provide valuable information on transport and exchange in three dimensions. To capture spatial variability around features of interest, multiple towers should be installed with three or more measurement levels between 2 and 15 m (higher in urban or forest environments). Additional flux towers installed to capture spatial variability (e.g. in land cover or along a transect) will likely only have one measurement level close to the surface (e.g. at 2-5 m). Careful consideration must be given to the layout of the sites. To capture different scales of heterogeneity a logarithmic approach is sometimes used in flat terrain. However, this approach is not immediately transferable to mountainous terrain, where clusters of instrumentation around particular orographic features may be more insightful. An adjusted logarithmic approach, combining logarithmic spacing and clustering, could be an option here.

In practice, achieving a high density of flux measurements depends on successfully acquiring major facilities.

The flux towers across the study region will be ranked according to the complexity of the site (e.g. in terms of slope angle, or heterogeneity of the source area, for example). Several of the flux tower sites have or will have additional instrumentation such as Doppler wind lidars (either vertically pointing or planar scanning), temperature-humidity profilers and ceilometers, and co-located studies using small sensor packages onboard drones or attached to tethered balloons. At some sites, soil chamber measurements will enable ecosystem studies. In winter, detailed snow measurements at some sites will help link snow properties to near-surface exchange processes.

Establishing an appropriate instrumental setup and flux data processing protocol will be an important task. Where possible, eddy covariance data will be processed using the same software and a comparable set of processing options (e.g. double coordinate rotation versus planar fit; quality control measures). A task team will be responsible for providing recommendations. Where this is not possible or desirable (e.g. different established data processing routines at different long-term sites), analyses should consider the potential impact of different processing choices on the findings.

3.4.3 Structure of the mountain boundary layer

Boundary layer profiles of temperature, humidity, wind, aerosols and cloud properties can be obtained at relatively high vertical and temporal resolution from ground-based remote sensing instruments. Several networks of such atmospheric profiling instruments exist across Europe (Cimini et al., 2020), albeit with fewer instruments in mountainous regions. These existing networks will provide valuable data about the structure of the atmosphere in and around the study region (with some gaps). During the TOC a considerable amount of additional atmospheric profiling instrumentation will be added to the target areas and supersites to provide information about the vertical and horizontal structure of the MoBL. As a minimum, vertical profiles of wind speed and direction (up to 1-2 km at least), and temperature and humidity (up to the local boundary layer height) are required at at leat one location at each of the supersites. Ideally, vertical profiles would be measured at multiple locations (e.g. at different points along and across the valley, at the intersection with side-valleys, within a side valley). Turbulence (e.g. horizontal and vertical velocity variances, temperature variance) as well as mean quantities will be measured where possible.

Although labour-intensive and costly, radio-soundings are still the most reliable method of obtaining information about the vertical structure of the atmosphere (temperature, humidity and wind), particularly in complex terrain. This information is also fundamental for the identification of conditions favourable to convection. Therefore, radio-soundings will be conducted at the target areas multiple times per day during the IOPs, and if possible, also during the EOPs (although less frequently). The radio-sounding data will provide a reference for other types of measurements.

For continuous temperature and humidity measurements, passive microwave profilers will be used at several locations. Careful work is needed to refine the calibration and retrieval techniques to account for differences between instruments and ensure reliable data. As the vertical resolution will not always be capable of sufficiently capturing fine-scale features (e.g. sharp elevated inversions), other co-located datasets will be valuable (e.g. from temperature-humidity lidars and/or radio-soundings). The technology is likely not yet advanced enough for lidars capable of providing temperature and humidity profiles to be deployed widely, particularly in such a challenging environment. Such instruments (Raman lidars for temperature, Raman lidars or differential absorption lidars (DIAL) for water vapour) should therefore be deployed in locations where the retrieved data can be at least partially verified by comparison with more conventional techniques such as radio-soundings. Raman lidars also face the issue of substantial noise during daytime. Subject to the availability of instrumentation and personnel, detailed information about the vertical structure of near-surface air temperature could be obtained from sensors mounted on towers, tethered balloons or unmanned aerial systems. Transects of relatively cheap temperature sensors (e.g., HOBOs) could also be used to obtain pseudo-vertical temperature profiles.

Wind profiles can be obtained from radar wind profilers or Doppler wind lidars. While ultra-high frequency (UHF) radar can provide measurements for all weather types, lidars are limited when there is precipitation. Radar can also yield continuous measurements of the wind above the MoBL, whereas lidars have a shorter range (which can be problematic when the aerosol load is low). At least one Doppler wind lidar or radar wind profiler will be used at each supersite to obtain vertical profiles of the three wind components from approx. 50-100 m above the surface to a height of 1-5 km (depending on atmospheric conditions and instrument type). Where possible, turbulence profiles (at least part of the vertical velocity variance) will also be retrieved. Doppler lidar can be helpful to study convective triggering and density currents in the boundary layer, to identify coherent turbulent structures in the MoBL and to observe mesoscale circulations and turbulence intensity in the pre-convective environment. If resources allow, several additional lidars and radars will be deployed. Multiple profiles along a transect would inform about spatial variability and advection processes. Ideally, a combination of instrument types will be used to sample at short-range (e.g. in the lowest 200 m), medium-range and long-range. Multiple lidars combined in advanced scan strategies will be used to reveal cross- and along-valley flow, to investigate the characteristics of particular flow phenomena (e.g. vortices, hydraulic jumps, wave breaking, meandering, exit jets) and to deliver improved accuracy in regions with high spatial inhomogeneity. Lidar scans near the slopes will help to capture the slope-wind layer. Subject to the availability of instrumentation and possibilities for installation, sodars or other wind profilers may also be deployed.

Various methods to determine boundary layer height from ceilometers, lidars, microwave profilers and radio-soundings will be assessed and compared. Ceilometers provide information about the vertical distribution of aerosols and will be used to estimate local boundary layer height and cloud cover characteristics as well as to inform about possible multiple aerosol layers and venting processes. The greater coverage of existing ceilometer networks compared to the other instrumentation offers the chance to obtain a fairly detailed impression of the distribution of local boundary layer height across the study region, but results will have to be systematically evaluated with respect to the definition and typical signatures of the boundary layer over flat terrain compared to what is known about the MoBL over complex terrain. Careful analyses of these different datasets will inform about the structure and variability of the MoBL.

Although the study region is covered by national radar networks, additional radars will be needed to provide higher resolution information in areas of interest. Along with ceilometers, cloud radars and cloud cameras will be used to characterise cloud and fog properties. Micro rain radars will be used for precipitation profiling. Combining multiple lidars with an X-band radar could provide high resolution information about the flow field around storms. The Orographic Convection WG are working with archived radar data to track convective cells over the study region. These preliminary studies will be completed prior to the field campaign in order to characterize convective initiation and dissipation locations via statistical clustering, as well as storm propagation, as a function of the impinging flow stability, speed, direction, humidity and shear profile. This research will help to provide a convective climatology for the Pan-Alpine region which will assist with planning observations during the TOC.

A variety of airborne measurements will be used to observe different portions of the atmosphere and sample across a range of spatial scales. Large research aircraft have a heavy payload and can sample multiple supersites as well as up- and down-stream regions within one flight mission. They can fly into the larger valleys and at higher altitudes but cannot get close to the surface. Cross-alpine transects will be especially useful for studying large-scale processes relevant for gravity wave propagation and breaking. Small aircraft can fly down to about 500 m agl and will sample mean and turbulence quantities in the MoBL, providing information about spatial variability across the target areas. Additional flights with instrumented motor gliders based at local airports could also be considered (e.g. Wildmann et al., 2021). Unmanned aerial systems (e.g. drones) can provide mean and turbulence quantities close to the surface in the region between surface-based measurements and small aircraft measurements (i.e. 10-500 m) and are suitable for use in tributary valleys which are too small for the larger aircraft.

The research aircraft will help to characterise the properties of the mountain atmosphere and its spatiotemporal variability. Aircraft data will include radiation components, surface temperature, cloud cover, turbulence measurements (of heat, moisture, momentum and turbulent kinetic energy) as well as basic meteorological information (temperature, humidity, pressure, wind) and chemical composition. Wind profiles will be obtained from airborne Doppler wind lidars and aerosol profiles from airborne aerosol lidar. Vertical wind profiles along, across, and above the valleys will fill gaps in the ground-based observations, while profiles over a larger area will help to capture large-scale flow structure. Although the aircraft will not be able to fly into thunderstorms, they will be able track the evolution of the flow in the vicinity of mesoscale convective systems (MCS), for example to study flow prior to MCS, hodographs around the MCS as it evolves and the interaction of MCS with orographic circulations. Also of interest are transects through orographic shallow cumuli and congestus for quantifying cloud mixing processes. Subject to permission, dropsondes could be deployed to provide temperature, humidity and wind profiles; GPS dropsondes would be especially useful for detecting shear layers. Data processing of airborne data will need to account for motion of the sensors through the atmosphere and distortion effects from the aircraft. A target team will be established to recommend appropriate and compatible data processing across the programme.

3.4.4 Atmospheric composition

There are several air quality monitoring networks across the study region, mostly located in cities and along roadsides. These networks will be supplemented by more specialised instrumentation measuring additional chemical species and/or fluxes (as well as concentrations) at locations of interest. Aerosol lidars will be used to estimate local aerosol profiles from the ground, while airborne atmospheric composition sensors on tethered balloons, unmanned aerial vehicles and larger aircrafts will provide in situ atmospheric measurements. Several high-altitude observatories across the Alps (Section 4.1.9) provide insight into long-range pollutant transport, mountain venting and the free troposphere.

3.4.5 Surface and sub-surface conditions

Accurate surface cover maps, digital elevation models (DEM) and digital surface models (DSM), information on urban extent and soil properties are needed at high resolution for the supersites and at lower resolution across the study region and surroundings. Temporally varying spatially distributed datasets of vegetation cover, snow cover, soil temperature, soil moisture, surface temperature and cloud cover are also required. These will be helpful when interpreting observed datasets and are critical for model initialisation and evaluation (e.g. Chow et al., 2006; Massey et al., 2014). Depending on the model, the model resolution, and the studied processes, soil measurements at multiple depths down to 1 m and at a spatial resolution of up to 100 m would be desirable. Water table depth would also be useful for climate studies. Many surface datasets already exist (Section 4.1.10) but, for some applications (e.g. very high resolution simulations, source area analyses), higher resolution or more recent information may be necessary.

At the supersites, manual observations of site characteristics will need to be made during the campaign (e.g. crop height, harvesting dates, snow cover) and, if possible, detailed soil sampling should also be carried out. The accuracy of satellite products providing land-surface information will need to be assessed. The multitude of additional instrumentation deployed during the TOC represents the opportunity to calibrate/validate satellite products in mountainous terrain. For long-term studies, satellite remote sensing products will also be used to provide information about changes in surface conditions that have occurred over several years.

4 Observational resources available to TEAMx

This section summarises the observational resources available to TEAMx, focusing on existing sites that will continue operating during the TEAMx Observational Campaign (Section 4.1). Details about instrumentation that is planned to be deployed during the campaign will follow in Section 4.2.

4.1 Existing infrastructure and available datasets

Available datasets for existing sites that are expected to continue during the TEAMx Observational Campaign are briefly described here. For many of these sites, use of the datasets within TEAMx has been discussed with the person responsible; for others contact points are still needed. Information about these existing sites is being collated in a database and used to generate the maps below. There is also an interactive map available. Figure 2 and Figure 3 provide an overview of the locations of the sites separated by instrument type and coloured according to the availability of the data (depending on whether the site is already operational or not or whether data access still needs to be checked).

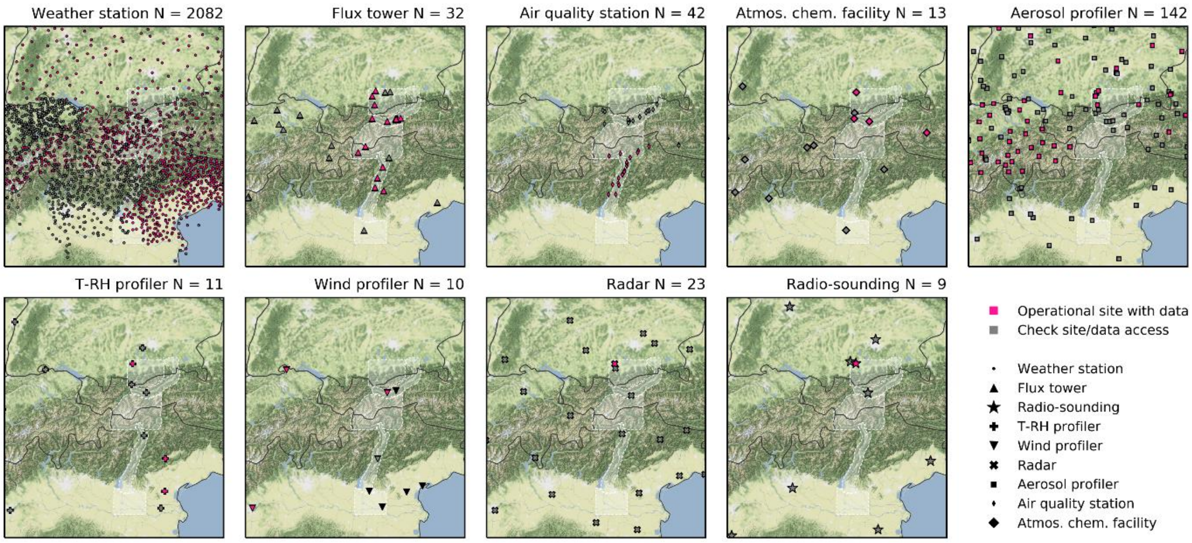

Figure 2: Instrumentation in and around the study region separated by type and coloured according to the availability of data. The number of stations (N) within the area shown is indicated at the top right. The target areas are indicated by the dashed lines and shading. Map tiles (and for all similar figures in this document) are by Stamen Design under CC BY 3.0 with data by OpenStreetMap © OpenStreetMap contributors.

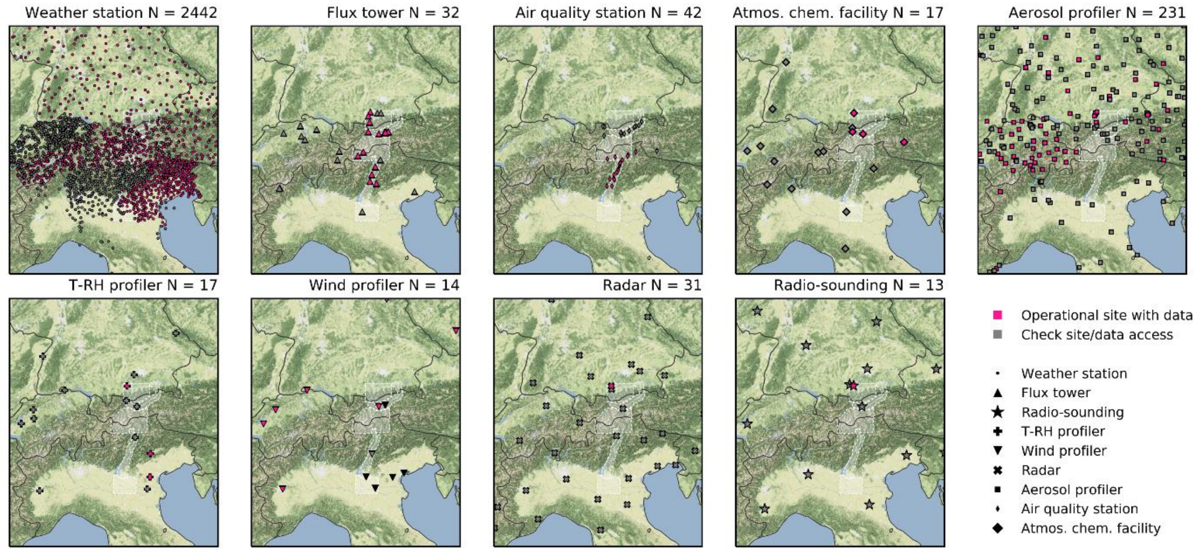

Figure 3: As Figure 2 except for a larger region.

4.1.1 Automatic weather stations

The national and regional weather services maintain a reasonably dense network of mostly automated meteorological stations across the study region and the surroundings. While the majority of weather stations have been installed in the last 30 years (Figure 4), there are some stations with long timeseries available for climate studies (e.g. the HISTALP[2] network). Data access for research purposes should not usually be a problem (but still needs to be confirmed in many cases). Across the alpine region, most stations are located on or close to the valley floor with few mountain-top sites. However, the weather and snow stations of the avalanche warning services are mainly located at higher altitudes and therefore particularly useful for filling the gaps missed by the weather services (Figure 5). Data from citizen weather stations may also be useful to provide fine-scale information, but careful quality control is required – this is likely to be especially challenging in complex terrain where spatial variability is anyway very high.

- Austria's national weather service (GeoSphere) operates around 260 weather stations across Austria (the TAWES network[3]).
- Germany's national weather service (Deutscher Wetterdienst, DWD) operates about 450 weather stations across Germany[4].
- MeteoSwiss operates about 160 automatic weather stations across Switzerland (SwissMetNet[5]) and additionally about 130 precipitation stations.
- In Italy the weather networks are manged regionally. In northern Italy, the Province of Bolzano/Bozen operates 119 stations across South Tyrol[6] and MeteoTrentino operates 124

[2] http://www.zamg.ac.at/histalp/
[3] https://www.zamg.ac.at/cms/de/klima/messnetze/wetterstationen
[4] https://www.dwd.de/EN/climate_environment/cdc/cdc_node.html
[5] https://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/land-based-stations/automatisches-messnetz.html
[6] http://weather.provinz.bz.it/download-data.asp

weather stations across the Province of Trento/Trient[7]. The Edmund Mach Foundation (FEM) operates an additional 50+ weather stations around the Trento/Trient area[8]. ARPA Friuli Venezia Giulia-OSMER[9] will provide data from about 40 stations of the Friuli Venezia Giulia regional network[10]. About ten stations (in the south-eastern Alps) also have an automatic measurement of snow height. ARPA Lombardia[11] operate over 200 weather stations and several hydrological stations across Lombardy.

- The Intercantonal Measurement and Information System (IMIS) network[12] maintained by WSL Institute for Snow and Avalanche Research SLF consists of about 180 automated weather stations across the Swiss Alps and Jura Mountains (many manual snow measurements are also made). Many of these stations have been operational for over 20 years and will be useful data for the Mountain Climate WG in particular.
- The avalanche warning service (Lawinenwarndienste Tirol, LWD Tirol) and the hydrological service (Hydrographischer Dienst Tirol, HD Tirol) operates automatic weather stations across Tyrol[13] with over 130 LWD Tirol stations and over 40 HD Tirol stations in North and East Tyrol. There are also weather stations used by the avalanche warning and hydrological services for other regions (e.g. LWD Vorarlberg, LWD Salzburg, HD Bozen), but these have not been collated in the database so far. In addition to the meteorological data, various types of hydrological data (e.g. precipitation, snow depth, ground water, run-off) are also collected by these networks[14].
- Several long-term Ecosystem Research (LTER) sites exist across Europe[15] (data for Austria, Germany, Italy and Switzerland have been added here). These sites provide meteorological data co-located with ecological information, and some have multiple sites concentrated in particular areas, for example, the Val Mazia/Matsch[16] research area (managed by EURAC) in South Tyrol and the extremely high density WegenerNet[17] (managed by The Wegener Center/University of Graz) in east Austria.
- There are multiple weather stations operated by universities or research institutes spread across the area of interest. The University of Innsbruck operates several weather stations in Tyrol (Sattelberg, Ellbögen, Vent, Tisenjoch, Hintereis, im Hinteren Eis). The University of Trento operates the weather station at Molino Vittoria[18] in downtown Trento. The Edmund Mach Foundation operates a weather station at Cembra beech forest alongside ecological measurements.

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[7] https://www.meteotrentino.it/#!/content?menuItemDesktop=143
[8] https://meteo.fmach.it/meteo/mappa.php
[9] https://www.meteo.fvg.it/home.php
[10] https://www.meteo.fvg.it/anagrafe.php?ln=-en
[11] https://www.dati.lombardia.it/Ambiente/Mappa-Stazioni-Meteorologiche/8ux9-ue3c
[12] https://www.slf.ch/en/avalanche-bulletin-and-snow-situation/measured-values/description-of-automated-stations.html
[13] https://www.data.gv.at/katalog/dataset/land-tirol_wetterstationsdatentirol
[14] https://ehyd.gv.at/
[15] https://deims.org/search/sites
[16] https://browser.lter.eurac.edu/api
[17] https://wegcenter.uni-graz.at/en/wegenernet/wegenernet-home/
[18] http://www.ing.unitn.it/~prometeo/home.htm

- Around the Adige Valley, the MTAA amateur weather society operate around 40-50 weather stations[19], including a slope profile with a station on Monte Bondone[20]. It is also possible they may be able to install additional stations for the campaign. Note these stations have not yet been added to the database/maps.
- Most eddy covariance stations (Section 4.1.2) and atmospheric observatories (Section 4.1.9) also provide basic meteorological information.
- There are other potential sources of weather data from various corporations, companies and industry (e.g. transport, energy) but these have not been exhaustively collected here (and sites may not always be appropriate for meteorological research purposes).
- Citizen weather stations (e.g. Netatmo[21], the Met Office Weather Observations Website[22], Weather Underground[23]) provide some additional information although the coverage is better in cities than across the Alps. Since we cannot rely on these data being available and they would require extensive quality control, these stations have not been added to the database.

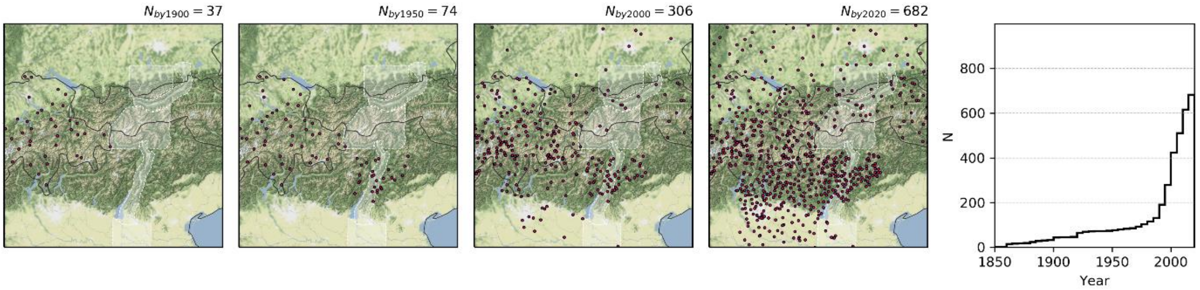

Figure 4: Weather stations across the alpine region and surroundings separated according to the measurement starting date (before 1900, 1950, 2000 and 2020). The number of sites (N) within the area shown is indicated at the top right of each map. The histogram displays the number of sites as a function of time. Note that the points and totals only include stations where the measurement starting date is provided in the metadata and this information is currently not available for all stations.

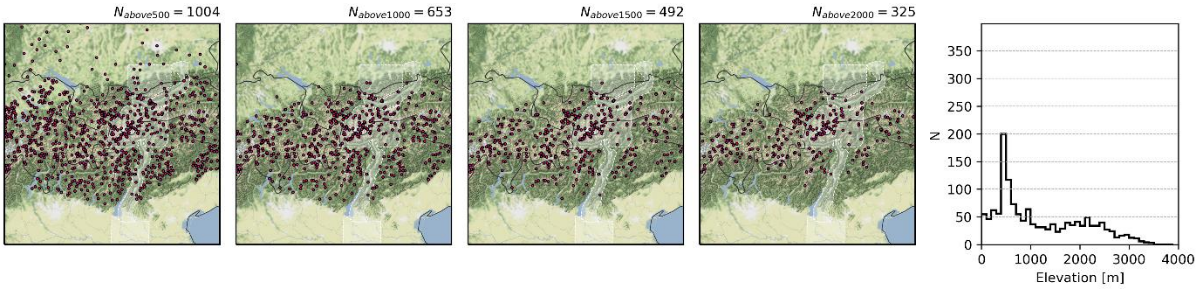

Figure 5: Weather stations across the alpine region and surroundings separated according to site elevation (above 500, 1000, 1500 and 2000 m a.s.l). The number of sites (N) within the area shown is indicated at the top right of each map. The histogram displays the number of sites at each elevation

[19] https://www.meteotrentinoaltoadige.it/stazioni-meteo/mappa-stazioni-meteo
[20] https://www.meteogardolo.it/
[21] https://weathermap.netatmo.com/
[22] https://wow.metoffice.gov.uk/
[23] https://www.wunderground.com/wundermap

(100-m bins). Note that the points and totals only include stations where the site elevation is provided in the metadata and this information is currently not available for all stations.

4.1.2 Eddy covariance stations

Several long-term eddy covariance (EC) stations are operational across the study region, many of which are part of the ICOS-Ecosystem[24] and FLUXNET[25] networks. Most sites provide eddy covariance fluxes of momentum, heat, water vapour and carbon dioxide at a single level (Figure 6), along with either four-component or net radiation, soil heat flux measurements and basic meteorological data. A few sites provide multiple-level turbulence measurements and/or additional gas fluxes (e.g. CH_4, N_2O, O_3). While many of the flux stations are within the target areas and some constitute key infrastructure for the supersites, others will inform about spatial variability and different land cover types across the study region. Most of the sites represent grassland or forests but there are also glacier, urban and peat bog sites (Figure 7). High-altitude/crest-top EC stations include Arbeser and Hintereisferner (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

- There are three ICOS ecosystem stations with long-term EC measurements in the Adige Valley region: Renon forest (operated by the Free University of Bozen-Bolzano), and Lavarone forest and Monte Bondone grassland (operated by FEM). FEM also maintains a peatland site at Monte Bondone. A new long-term flux station at a vineyard site at Caldaro Hill has also recently been installed as part of the TEAMx project ASTER[26]. A further multi-level flux tower at Mezzolombardo in the Adige Valley will be installed as part of the TEAMx project INTERFACE[27]. If funded, a PRIN proposal would allow a multi-level flux tower to be installed on a sloped site close to Monte Baldo, east of Lake Garda.
- ICOS stations at Bosco Fontana Forest (operated by Università Cattolica del Sacro Cuore) or Lison vineyard (operated by University of Padova) could potentially serve as reference sites in the Po Valley.
- The University of Innsbruck operates numerous long-term flux sites in and around the Innsbruck area, many of which form part of the supersites of the Inn Valley target area. There are currently six flux stations as part of the i-Box supersite (mostly with multiple measurement levels), situated about 20 km east of Innsbruck. These stations are mainly installed above grassland at different characteristic locations: flat valley floor (Kolsass), north-facing slopes (Weerberg, Hochhäuser), south-facing slopes (Terfens, Eggen) and mountain top (Arbeser). Funding for a seventh i-Box site (on the south facing slope) has been obtained and a mobile energy balance station will also be available during the campaign. In central Innsbruck, the Innsbruck Atmospheric Observatory (IAO) urban flux site is currently being extended with a vertical profile of turbulence measurements into the street canyon. The Forest-Atmosphere Interactions Research (FAIR) site in a Scots pine forest west of Innsbruck features a 30-m flux tower with five levels of turbulence measurements, measurements of gas exchange (H_2O, CO_2), four-component radiation as well as photosynthetically active radiation (PAR) fluxes above the canopy and in the understorey, three sets of soil temperature, moisture and heat flux sensors,

[24] http://www.icos-etc.eu/icos/
[25] http://www.europe-fluxdata.eu/home/sites-list
[26] http://www.teamx-programme.org/projects/ASTER/
[27] http://www.teamx-programme.org/projects/INTERFACE/

as well as various eco-physiological observations (tree stem sap flow, dendrometry, active and passive chlorophyll fluorescence). Advanced measurements of a wide variety of chemical species are made at IAO and FAIR stations (Section 4.1.8).

- The University of Innsbruck also operates a glacier site at Hintereisferner in the Rofen Valley and maintains the flux tower at the LTER Matsch/Mazia Valley study area (Muntatschinig). Unfortunately, the Neustift FLUXNET grassland site in the nearby Stubai Valley has been decommissioned due to a lack of funding.
- The Northern Pre-Alpine Target Area contains three long-term flux stations of the TERENO Observatory[28] (Fendt, Rottenbuch and Graswang) located on grassland and maintained by KIT, plus the ICOS stations at Mooseurach (forest) and Schechenfilz (peat bog). Note, the Schechenfilz site may not remain operational for the TOC.
- There are other flux stations located further away from the target areas, including SwissFluxNet[29] stations (Alp Weissenstein, Chamau, Frueebueel, Laegeren, Oensingen) and other ICOS stations.

[28] https://www.tereno.net/joomla/index.php/observatories/pre-alpine-observatory
[29] https://gl.ethz.ch/infrastructure/sites.html

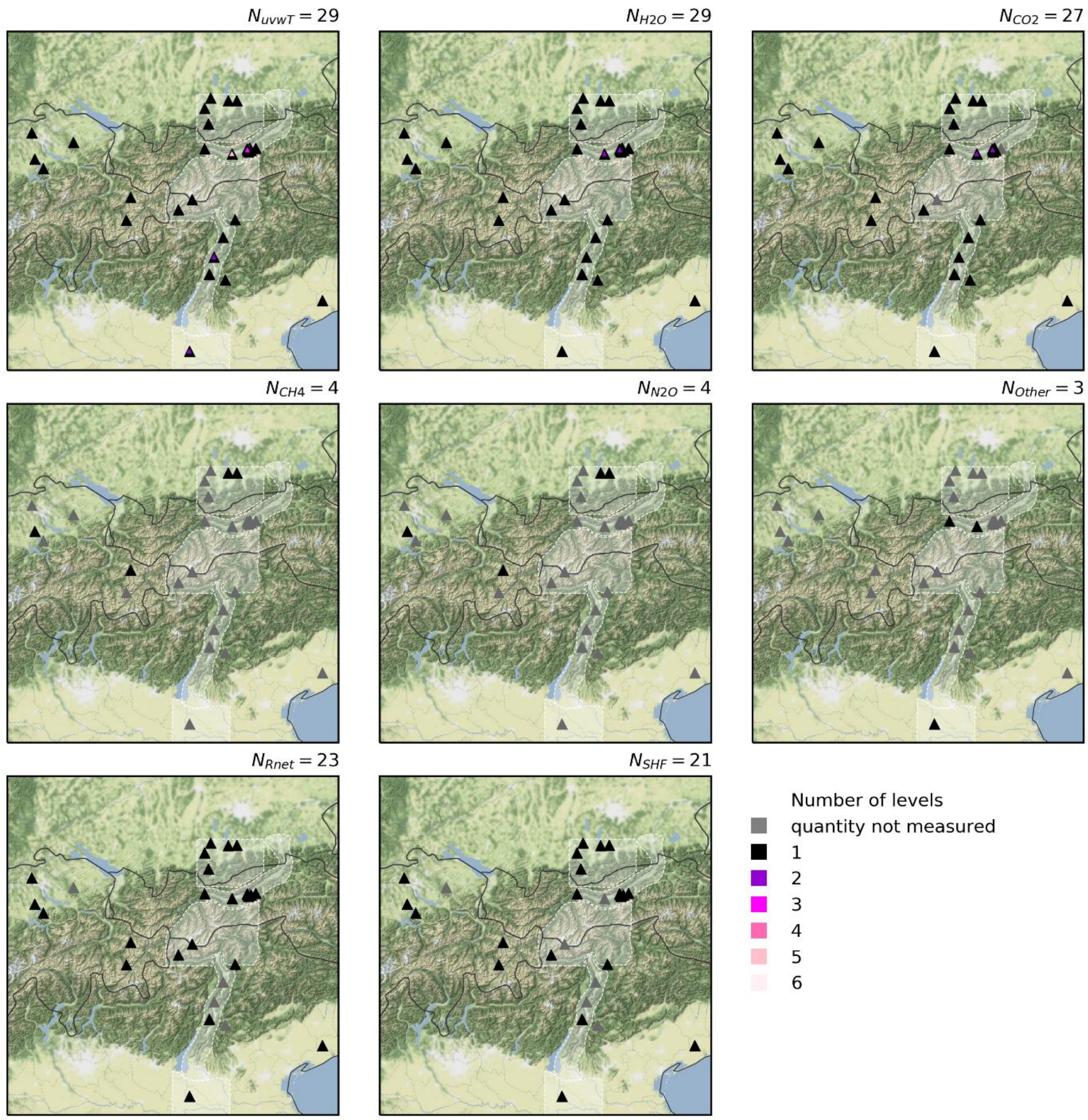

Figure 6: Flux sites across the study region separated according to the quantity measured with fast-response instrumentation: *u*, *v, w* and *T* (the three wind components and temperature); H_2O; CO_2; CH_4; N_2O; and additional gases (e.g. O_3, CO) grouped into the 'Other' category. For energy balance studies, sites measuring net radiation (R_{net}) and soil heat flux (*SHF*) are also shown. The colour of the points indicates the number of levels of eddy covariance measurements of that quantity at each site. The number of sites (N) measuring each quantity within the area shown is indicated at the top right.

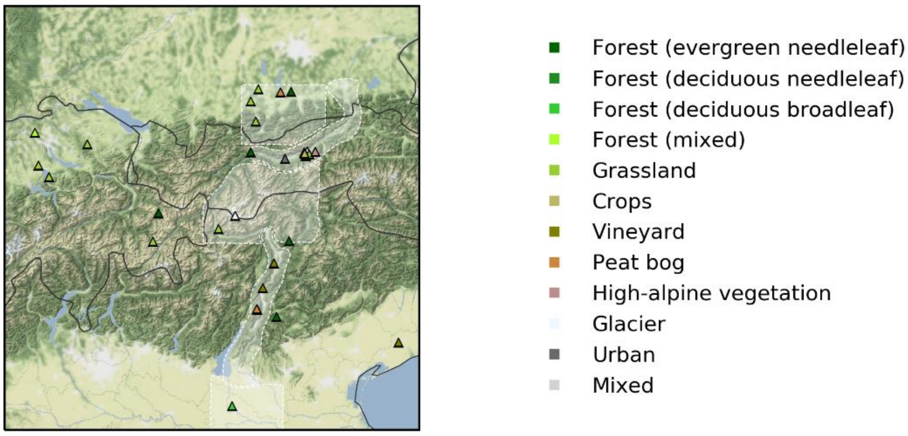

Figure 7: Flux sites across the study region coloured according to land cover.

4.1.3 Ceilometers

The Aerosol and Cloud Profiler Network co-ordinated by E-PROFILE[30] includes ceilometers (mostly CL31, CL51 and CHM15k models) from across Europe. DWD[31] also provides a detailed list of ceilometers, including many that are not in E-PROFILE. These are largely based on national networks maintained by the weather or aviation services. There are also a few research instruments in operation.

- Austro Control operates a national network of 66 ceilometers (CL31) across Austria, with a higher density around airports. GeoSphere Austria operates an additional seven research ceilometers (CL51), one of which is located at the valley cable car station of the Sonnblick Observatory. An eighth ceilometer has recently been installed at Kufstein in the Inn Valley.
- Switzerland has over 60 ceilometers. The MeteoSwiss network is mainly made up of CL31 instruments with four CHM15k instruments.
- DWD maintains a network of over 120 ceilometers (CHM15K) across Germany for detection of clouds and aerosol layers.
- There are 37 ceilometers across Italy. These are mainly CT25Ks but there are also some CHM15ks (the CHM15ks are part of the Alice-net[32] network). However, there is no ceilometer coverage in the AVTA.
- In the Northern Pre-Alpine Target Area, KIT/IMK-IFU operates three ceilometers (at each of the TERENO flux sites) and could deploy an additional ceilometer (e.g. at Garmisch) for the TOC.

4.1.4 Temperature-humidity profilers (microwave radiometers and lidars)

E-PROFILE[33] is planning to establish a remote-sensing network for temperature-humidity profilers[34] in time for the TEAMx field campaign. Most instruments in the currently fairly sparse network are

[30] https://e-profile.eu
[31] https://www.dwd.de/EN/research/projects/ceilomap/ceilomap_node.html
[32] http://www.alice-net.eu/
[33] https://e-profile.eu
[34] http://mtp-5.ru/

microwave radiometers, but there are also a few highly specialised lidars in operation capable of retrieving profiles of temperature, water vapour and other species.

- There are three operational RPG microwave profilers in Switzerland, at Payerne, Schaffhausen, and Grenchen (HATPRO-G5). Two research instruments from the University of Bern are operated at Payerne: a microwave radiometer (TEMPERA) and a Raman lidar (RALMO). There is also a microwave radiometer (TROWARA) at Bern.
- DWD operates microwave profilers at Schneefernerhaus (Zugspitze) and Oberpfaffenhofen in southern Germany. The DWD Hohenpeissenberg Observatory also has a Raman lidar (the Raman Aerosol Lidar PollyXT at Hohenpeissenberg, RALPH).
- The University of Innsbruck has a temperature-humidity profiler (HATPRO G3, RPG Radiometer Physics) which is usually operated continuously at the IAO site, but it is currently under repair.
- ARPAV operate several microwave profilers (MTP-5) in northern Italy, including one in Bolzano and two in the Po Valley region (the MTP-5 at Rovigo is currently broken and awaiting repair). An additional HATPRO at Legnago is broken but cannot be repaired.

4.1.5 Doppler-wind lidars and radar wind profilers

E-PROFILE coordinates a European network of radar wind profilers and is aiming to add Doppler wind lidars by the time of the TEAMx field campaign. A detailed list of wind profilers (Doppler wind lidars and radar wind profilers) in Europe is also provided by DWD[35].

- MeteoSwiss operates radar wind profilers (Degreane, PCL1300) associated with Doppler lidars (Leosphere, WLS-200s) at Grenchen, Payerne and Schaffhausen.
- Austro Control operates a LAP3000 radar wind profiler at Vienna Airport.
- DWD operates four LAP-16000 radar wind profilers and four Doppler lidars in north Germany.
- ARPA Piemonte operates a wind profiler at Turin.
- ARPAV are in the process of installing sodars at Venice and Verona airports.
- There a radar wind profiler (DEGREWIND PCL1300) at Trento-Mattarello Airport operated by MeteoTrentino.
- The University of Innsbruck has two pulsed Doppler wind lidars (Streamline, Halo Photonics) and a short-range continuous wave Doppler-wind lidar (WindRanger, METEK) which will likely be deployed at the valley floor i-Box site to provide detailed wind and turbulence information for the lowest 100-200 m. For most of the TOC the pulsed lidars will be used to provide vertical profiles at the IAO and i-Box supersites, however they may be deployed differently (e.g. for coplanar scans) for a specific purpose during the Summer EOP.
- The University of Trento have a Doppler wind lidar (Leosphere Windcube WLS100S) which is currently at Trento Airport but will also be deployed elsewhere, e.g.at the Monte Baldo supersite.

[35] https://www.dwd.de/EN/research/projects/ceilomap/ceilomap_node.html

4.1.6 Weather radars

The weather radar network within EUMETNET, the Operational Program for Exchange of Weather Radar Information (OPERA)[36] consists of mostly Doppler C-band radars (Huuskonen et al., 2014). OPERA provides composite surface rain rate and maximum reflectivity products from raw single site radar data at 15-minute resolution for the whole of Europe. Most radars are part of national networks, but there are also a few research instruments. Weather radars can also be used to derive vertical wind profiles if raw Doppler volume data are available.

Detailed radar mosaics for the study region (particularly the AVTA) will be very helpful for the Orographic Convection WG for tracking convective cells. In most cases, existing radar products can be made available for research purposes but may require an individual agreement. For example, members of the Orographic Convection WG have been working with a ten-year archive of TAASRAD19, a high-resolution gridded radar reflectivity dataset covering northern Italy, and a one-year archive of Monte Macaion radar data, courtesy of the Italian Institute of Atmospheric Sciences and Climate (ISAC-CNR). Both of these datasets provide coverage over the AVTA and portions of the Trentino region of Italy.

- The Austrian national radar network consists of four dual-polarisation Doppler C-band radars operated by Austro Control (at Patscherkofel, Salzburg/Feldkirchen, Vienna/Schwechat and Zirbitzkogel; Valuga is no longer active). AustroControl has a long-term (> 10 years) archive of radar data in 2D (maximum reflectivity) and 3D (1-16 km height) on at 1-km grid at 5-min intervals.
- The Swiss national radar network consists of five dual-polarisation Doppler C-band radars operated by MeteoSwiss (at Albis, La Dôle, Monte Lema, Pointe de la Plaine Morte and Weissfluhgipfel).
- There are nineteen radars across Italy, eleven of which are in the north of the country: three single-polarisation Doppler C-band radars (at Concordia Sagittaria, Monte Macaion/Gantkofel and Teolo) and eight dual-polarisation Doppler C-band radars (at Bric della Croce, Fossalon di Grado, Gattatico, Milano-Linate, Monte Crocione-Lucca, Monte Zoufplan – Udine, San Pietro Capofiume and Settepani). ARPA Friuli Venezia Giulia (FVG)-OSMER may be able to provide radar volume data from the Fossalon radar in FVG. ARPAV will provide data from their two C-band radars (Teolo and Concordia Sagittaria).
- ARPAV is planning to operate a mobile weather radar near Monte Rite (in summer) and a nearby valley (in winter).
- Slovenia operates two Doppler C-band radars, one single-polarisation (at Lisca), one dual-polarisation (at Pasja Ravan).
- DWD operates seventeen dual-polarisation Doppler C-Band radars across Germany, six of which are in the south of the country (at Eisberg, Feldberg, Isen/Munich, Memmingen, Offenthal and Türkheim), plus an identical research radar and a micro-rain radar at Hohenpeissenberg. There are also dual-polarisation Doppler X-band radars at Frankfurt and Munich.

[36] https://www.eumetnet.eu/wp-content/themes/aeron-child/observations-programme/current-activities/opera/database/OPERA_Database/index.html

- As part of the TERENO Pre-Alpine Observatory, a single-polarisation X-band radar[37] is operated by KIT/IMK-IFU at Geigersau (but data quality can be variable).

4.1.7 Radio-soundings

- Innsbruck Airport is the only site in the Alps where radiosondes are launched routinely (once every 24 h, at 02:15 or 03:15 UTC). It may be possible to arrange more frequent radiosoundings during IOPs.
- Payerne is the only site in Switzerland where radiosondes are launched routinely (twice every 24 h, at 23:00 and 11:00 UTC).
- There exist additional radiosonde launch sites in southern Germany (Hohenpeissenberg, Altenstadt, Munich), the Po Valley (Milan Airport, Udine Airport, San Pietro Capofiume in Bologna), and eastern Austria (Linz Airport, Graz Airport, Hohe Warte in Vienna).

4.1.8 Atmospheric chemistry measurements

There are a variety of atmospheric chemistry measurements across and around the study region, including regional air quality networks, ground-based remote sensing sites (which provide total column amounts and vertical profiles), and tall-tower and high-altitude stations (which monitor atmospheric composition, Section 4.1.9). Research institutions also operate highly specialised equipment at sites of interest, either continuously or for short campaigns, to determine concentrations or fluxes of different species. Information about aerosol layers in the atmosphere can also be obtained from ceilometers (Section 4.1.3), Several of the eddy covariance sites listed above provide fluxes of other species (in addition to CO_2) – typically CH_4 and N_2O (Figure 6).

- Many of the regional air quality monitoring sites are situated along major roads. The Amt der Tiroler Landesregierung, Waldschutz – Luftgüte operate a network of air quality monitoring stations along the Inn Valley[38]. Concentrations of NO_2 and NO are typically measured, often with PM10 and O_3, while SO_2 and CO measurements are less common. Data is also collected across Austria[39].
- The Environmental Protection Agencies of the Province of Bolzano[40] and Trento[41] operate networks of air quality monitoring stations located mostly along the Adige Valley (urban and rural background, urban and rural traffic stations). Two high-altitude stations are located at Renon-Ritten (approx. 1800 m a.s.l.), north of Bolzano, and at Mt. Gaza (approx. 1600 m a.s.l.), west of Trento.
- In Switzerland, the National Air Pollution Monitoring Network (NABEL) measures air pollution at 16 sites. A large amount of data is available via the ACTRiS Data Centre[42].
- A multitude of atmospheric chemistry measurements are made by the University of Innsbruck at the FAIR (forest) and IAO (urban) sites in the Inn Valley. Besides CO_2 and H_2O, turbulent flux measurements of ozone at the FAIR site are in the planning. A fast-sampling manifold will

[37] https://www.tereno.net/joomla/index.php/observatories/pre-alpine-observatory
[38] https://www.tirol.gv.at/umwelt/luftqualitaet/messnetz-galerie-webcams/
[39] http://luft.umweltbundesamt.at/pub/gmap/start.html
[40] https://umwelt.provinz.bz.it/luft.asp
[41] http://www.appa.provincia.tn.it/aria/
[42] https://actris.nilu.no/

transfer air samples from above the canopy to the air-conditioned lab container for the flux measurement of various other trace gases (e.g. carbonyl sulfide, terpenoids and other VOCs). At IAO, multi-year data series of fluxes of CO_2, NO and NOx have been measured and these are intended to continue beyond the TOC. Ozone deposition velocities are measured by means of chemiluminescence of cumarin. The IAO turbulence setup will be extended down into the street canyon with three additional turbulence levels, one of which features a fast closed-path sensor for CO_2 and H_2O (matching the one above the urban canopy). Two Pandora UV-visible spectrometers provide total column O_3 and total column, tropospheric column and surface concentrations of NO_2. One Pandora instrument might be operated at Seegrube (1905 m.a.s.l.) allowing for more spatially detailed observations of the valley atmosphere (depending on funding and site permission). Pandora instruments at IAO are part of the Pandonia Global Network[43] (PGN) comprising over 60 locations globally.

- Davos (Switzerland) is another PGN site in the Alps.
- The Sonnblick Observatory, in cooperation with its partners (TU Wien, Umweltbundesamt), has a key focus on atmospheric chemistry measurements. Most of these measurements are run under the umbrella of the WMO programme Global Atmosphere Watch (GAW), and includes aerosols, greenhouse gases and atmospheric deposition measurements, among others.

4.1.9 Atmospheric observatories (tall-tower and high-altitude stations)

There are several mountain-top observatories[44] in and around the Alps which continuously monitor atmospheric composition (as well as meteorological variables) using in situ measurements. These include Sonnblick Observatory[45], Schneefernerhaus (Zugspitze)[46], Jungfraujoch[47] and Plateau Rosa in the Alps, and Monte Cimone[48] and Schauinsland further away. There are also a number of sites at lower elevations where atmospheric composition is measured at multiple levels on tall towers (e.g. Hohenpeissenberg, Karlsruhe, Ispra and Křešín u Pacova). The locations of these sites are shown in Figure 8. At most of these sites at least CO_2, CH_4, CO and N_2O are measured; many sites also monitor a range of other gases. Most of the high-altitude/tall-tower sites are part of regional or global networks, such as the WMO Global Atmosphere Watch[49] (GAW) network, ICOS-Atmosphere and the Network for the Detection of Atmospheric Composition Change[50] (NDACC).

- The NDACC sites provide atmospheric composition measurements from ground-based remote sensing instruments for a range of species (including ozone, aerosols and greenhouse gases) as well as temperature, water vapour, wind and UV radiation. Several NDACC sites are within or close to the European Alps. These include Gross-Enzersdorf and Sonnblick in Austria; Hohenpeissenberg and Zugspitze in Germany; Arosa, Bern, Jungfraujoch and Payerne in Switzerland; and the Observatoire de Haute Provence in France.

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[43] https://www.pandonia-global-network.org/
[44] https://www.vao.bayern.de/observatories.htm
[45] https://www.sonnblick.net/en/
[46] https://schneefernerhaus.de/en/
[47] http://www.hfsjg.ch/en/home/
[48] http://cimone.isac.cnr.it/
[49] https://public.wmo.int/en/programmes/global-atmosphere-watch-programme
[50] https://www.ndaccdemo.org/

- The high-altitude research station Sonnblick Observatory (SBO) is located at 3106 m asl. at Mount Hoher Sonnblick in Austria, at the border of the provinces of Salzburg and Carinthia. The SBO provides climatological data since 1886 and environmental data since the late 1980s. The SBO is part of various international monitoring programmes including atmospheric, cryospheric and biological parameters such as aerosols, greenhouse gases, radiation, chemical analysis of snow and precipitation, permafrost, glacier mass balance and biodiversity.
- The Schneefernerhaus[51] high-altitude research station is located 300 m below the summit of Zugspitze (2960 m asl). The Federal Environment Agency measures greenhouse gases, aerosols and reactive trace gases at Schneefernerhaus. At Schneefernerhaus and at the Zugspitze summit DWD measures synoptic data, radiation and radioactivity. An FTIR spectrometer provides vertical column densities and vertical profiles of various trace gases. Aerosol backscatter is measured up to 45 km. *Contact: Till Rehm [t.rehm@schneefernerhaus.de]*
- Continuous meteorological measurements have been made at Hohenpeissenberg since 1781. Continuous ozone measurements are obtained from Brewer and Dobson spectrometers, lidar (at 15-50 km) and radio-soundings (up to 30-35 km, several times per week). Various trace gases and aerosols are also measured and an aerosol mass spectrometer is operated continuously. The chemical composition of precipitation is also analysed and there is a research radar. *Contact: Christian Plaß-Dülmer [christian.plass-duelmer@dwd.de]*
- The Jungfraujoch[52] high-altitude research station is situated at the top of the Aletsch glacier between two peaks (Jungfrau and Mönch). The observatory is at an elevation of 3580 m asl. Meteorological variables, radiation, atmospheric composition and vertical profiles are measured using FTIR and UV-visible spectrometry. Jungfraujoch is part of GAW and NDACC and is an ICOS-Atmosphere station.
- At Arosa, several spectrometers are used to measure total column ozone. The first ozone measurements began here with a Dobson spectrometer in 1926 making this the longest ozone record in the world. Ozone profiles are determined from spectrometer measurements at sunrise and sunset.
- At Bern, atmospheric profiles of ozone and water vapour are determined from microwave radiometers.
- At Payerne, atmospheric profiles of ozone are determined several times a week from radio-soundings (up to about 30-35 km) and continuously from the Stratospheric Ozone Monitoring Radiometer (SOMORA) (up to 65 km)[53]. A Raman lidar (RALMO, Raman Lidar for Meteorological Observations) provides vertical profiles of temperature, water vapour and aerosols (Brocard et al., 2013; Dinoev et al., 2013).
- The Col Margherita Atmospheric Observatory[54] (operated by the University of Venice and the Institute for Polar Sciences of the Italian National Research Council (CNR)) is located on a rocky grassed peak in the central eastern Italian Alps (2543 m asl) and has very few orographic obstructions making this a good site for investigating atmospheric circulation on a regional scale. *Contact: Carlo Barbante [barbante@unive.it]*

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[51] https://schneefernerhaus.de/en/
[52] https://www.hfsjg.ch/en/home/
[53] https://www.meteoswiss.admin.ch/home/measurement-and-forecasting-systems/atmosphere/ozonmessungen.html
[54] http://colmargherita.dsa.unive.it/

- At the Observatoire de Haute Provence (OHP), ozone is measured using a Dobson spectrometer, differential absorption lidar and radio-soundings. Lidars are also used to measure temperature and water vapour. UV-visible spectrometers provide column measurements of various species.
- The Pic du Midi Observatory in the Pyrenees[55] and the Puy de Dome Observatory in Massif Central[56] may also be useful for long range transport studies.

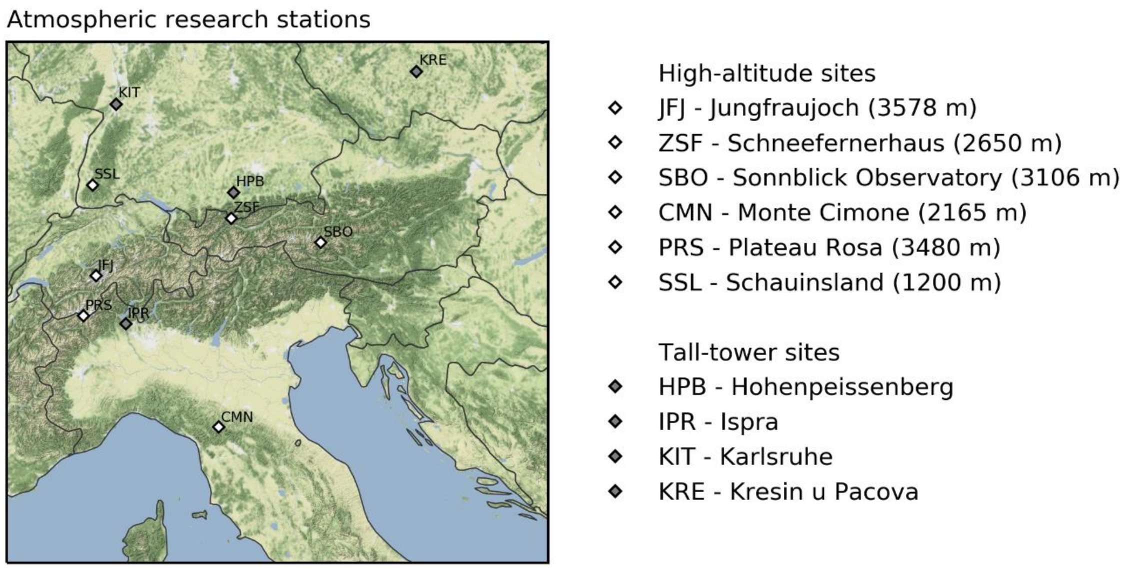

Figure 8: High-altitude and tall tower sites in and around the study region.

4.1.10 Spatial datasets, satellite products and visual information

A number of spatial datasets exist which describe subsurface, surface and atmospheric information across the study region at relatively high resolution. For some of the older datasets it may be necessary to check the information is still accurate, particularly in terms of land cover, for example.

- For Tirol, Austria, a digital surface model and digital elevation model (at 1-m, 5-m and 10-m horizontal resolution) are freely available from Land Tirol[57], as well as land use[58] and building model[59] shape files. Aerial imagery (RGB at 1 m horizontal resolution) also exists.
- For northern Italy a digital surface model and digital elevation model are freely available for the Province of Trento[60] (at 1-m and 2-m horizontal resolution) and the Province of Bolzano[61] (at 2.5-m horizontal resolution).

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[55] http://p2oa.aero.obs-mip.fr/spip.php?rubrique126&lang=en
[56] http://wwwobs.univ-bpclermont.fr/SO/mesures/gaw.php
[57] https://www.data.gv.at/katalog/dataset/0454f5f3-1d8c-464e-847d-541901eb021a
[58] https://www.data.gv.at/katalog/dataset/0eaa80ce-5156-4043-aeab-77f2b24b76b5
[59] https://www.data.gv.at/katalog/dataset/ac74b38e-57cd-4c8c-8fea-c397da185fcf
[60] https://siat.provincia.tn.it/stem/
[61] http://dati.retecivica.bz.it/it/dataset?res_format=WCS&tags=LiDAR

- Bergfex[62] provides numerous webcams all over Europe which offer continuous visual information. There is good coverage across the alpine region. There are also several webcams in Friuli Venezia Giulia[63].

To provide real-time information about changing surface conditions over a larger area, satellite data products will be archived for the duration of the campaign, including surface temperature, soil moisture, albedo, snow cover and vegetation characteristics (e.g. NDVI, LAI), as well as aerosol optical depth (e.g. from i-AERUS-GEO) and wind profiles (note the Aeolus satellite may no longer be operational by the time of the TOC). Brightness temperature perturbations from the Atmospheric Infrared Sounder (AIRS) are useful for gravity waves[64]. Soil moisture maps at 1-km resolution from SMOS[65] L4 will be useful for model initialisation and validation. Satellite data in the visible channel will also be very useful. The Meteosat Third Generation[66] (MTG) will likely be operational by the time of the TOC. Its visible channel will offer a spatial resolution of up to 500 m and a temporal resolution of 2.5 min and is expected to be especially useful for the Orographic Convection WG.

4.1.11 Other data products

Mode-S temperature and wind data from commercial aircraft is archived by Austro Control for Austria and by KNMI for Europe as part of the European Meteorological Aircraft Derived Data Centre (EMADDC). Most data are from cruising height (9-12 km) with lower-level data concentrated around airports and their approach corridors. Mode-S provides more data than from AMDAR as not all airlines participate in the AMDAR program whereas all must have a Mode-S capable transponder. Mode-S data are likely to be available for TEAMx on request.

Some aircraft of the Swiss Airlines fleet (Boeing 777 and some Airbus A320/330) are able to report turbulence in real-time and derive eddy dissipation rate using an NCAR algorithm. These data are likely to be available for TEAMx and will be very useful for the Waves and Dynamics WG.

Lightning data across Europe is provided by EUCLID[67] (European Cooperation for Lightning Detection). These data will be useful for the Orographic Convection WG and have already been used to produce a convection initiation climatology based on flash density for the TEAMx study region (Manzato et al., 2022).

[62] https://www.bergfex.com/sommer/oesterreich/webcams/
[63] https://fornidisopra.panomax.com/
[64] https://datapub.fz-juelich.de/slcs/airs/gravity_waves/html/view_2021_094.html
[65] https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/smos
[66] https://www.eumetsat.int/meteosat-third-generation
[67] https://www.euclid.org/

4.2 Additional instrumentation during the TOC

The instrumentation which will be installed by various groups during the TOC is going to be published step by step on the homepage. The final details will be added to this document at a later stage.

5 Implementation of the TOC

The details of how the observational campaign will be carried out are described in a separate document, the Implementation Plan. The first draft of the Implementation Plan has been discussed at the 3rd TEAMx Workshop in June 2023 and the inputs from the community are now being addressed. The following chapters describe general considerations about an operational strategy for the TOC which had been made at an earlier stage.

5.1 Operations Centre

A TEAMx Operations Centres will be tasked with making decisions about the day-to-day organisation of the TOC. When weather conditions could be favourable for IOPs, the Operations Centre will coordinate decisions on which instruments are deployed and whether an IOP will take place or not. Likely several groups will join these discussions remotely so that the discussion can include all involved teams and/or PIs. The team manning the Operations Centre will need to change throughout the TOC depending on when each group is participating (e.g. Summer vs Winter EOP).

5.2 Timeframe for the EOPs

The two EOPs will last a couple of weeks each. The winter EOP is currently (September 2023) scheduled from 20 January to 28 February, 2025, and the summer EOP is planned to take place from 16 June to 25 July, 2025.

5.3 Defining conditions and observations for the IOPs

As clear-cut ‘textbook’ days or events are extremely rare, IOPs will be focus on three types of situations: *thermally dominated (dry and moist), dynamically modified* and *synoptically dominated*. During the EOPs, daily meetings will be held at an operations centre to update the forecasts for that day and decide on the actions for the following days based on the forecast, instrument status and what has already been conducted/what is still required. Operational forecasts will be provided by GeoSphere Austria, MeteoSwiss, DWD, MeteoFrance, and ISAC. A task team will be needed to provide forecasting support to assist decision-making and one leading scientist from a team will be responsible each day. It is not yet decided whether there will be one overall meeting, or individual meetings for each target area with communication between.

Some of the research questions may be addressed in individual target areas or at individual supersites. Thus, not all types of IOPs will necessarily involve intensive measurements in all target areas or at all supersites.

The following subsections describe the ideal conditions for the various IOPs and specify which observations will be made.

5.3.1 Thermally-dominated IOPs (dry and moist)

For thermally-dominated IOPs there should be only weak synoptic forcing. A clear valley-wind circulation can be expected in the Inn Valley in summer, although the period of up-valley flow may be very short or even non-existent in winter. There will be two types of thermally dominated IOPs: dry (i.e., only shallow cumuli without precipitation) and moist (i.e., deep convection with precipitation and thunderstorms). However, note that late afternoon thunderstorms are common in summer (at least in Innsbruck) and often preclude complete ‘golden’ valley-wind days. Katabatic flows at multiple scales (downslope, down-valley, and mountain-to-plain) are of interest to many groups.

5.3.2 Dynamically-dominated IOPs

With weak or absent thermal forcing, impinging flow responds mainly to mesoscale terrain by ascending (‘flow over’) or detouring around it (‘flow around’ or ‘blocking’). Dynamically-dominated IOPs will include downslope windstorms (e.g. foehn events) and trapped and propagating wave events.

Trapped lee waves are generated by a number of mechanisms, which might be more prevalent in some seasons or under some meteorological conditions. For example, they may propagate in a surface stable layer, which might be more typical of winter or night-time, they may propagate at an inversion, which may be the capping inversion of a well-mixed boundary layer (probably more frequent in summer) or the inversion associated with fronts, or they may be trapped by a substantial increase of the wind speed with height.

Foehn (at least in Innsbruck) is most common in spring and autumn (i.e. outside the EOPs), but does not occur very often in summer due to the large-scale flow. In winter foehn penetration to the surface is less common although foehn aloft or in the Wipp Valley is quite common. Such wintertime conditions would be very relevant for testing and developing weather and climate models (Vosper et al., 2018), particularly low-level drag parameterizations.

As vertically propagating or trapped waves are of particular interest for large-scale dynamics, forecasts of vertical velocities will be used to determine the potential for large or interesting wave events to develop.

5.3.3 Synoptically-dominated IOPs

Synoptically-dominated IOPs will focus on case studies where atmospheric conditions are dominated by large-scale systems that affect all Target Areas. These are more common in autumn and winter.

5.3.4 Extreme events

Due to their scientific and societal importance, extreme events (should any occur during the TOC) are also of interest. These include extreme downslope windstorms, heavy precipitation, high-drag states, deep propagating wave events, persistent cold pools, prolonged hot and/or dry weather.

5.4 Details of process studies

5.4.1 Orographic Convection

The Orographic Convection WG will likely focus on orographic triggering at small scales (mainly investigating the thermally forced/dynamically modified circulation in valleys). There is also interest in orographic convection triggering in the pre-Alpine area and evolution of convective cells into larger scale convective systems. Considering the difficulty in predicting convection, especially during summertime, and the need to forecast high-impact convective systems, these topics are very relevant for their operational impact. Specific research questions related to orographic triggering at small scales include:

- **Cooperative convective initiation processes –** To what extent are strongly organized convective cells the result of 'seeding' by smaller cumuli along the valley sidewalls and canyons, and how does this process evolve? Is this process essential to prevent the entrainment of dry air into convective cells at various stages of their development, particularly initiation, thus preventing convective cell deterioration?
- **Up-slope/up-valley wind focusing of CAPE in canyons during the afternoon** – Do sub-meso-gamma scale canyons vent heat resulting in the elevating and repositioning of CAPE maxima on the southern and western sides of Alpine valleys above or within the strongest anabatic convergence zones? How does this control convective initiation?
- **Up-slope/up-valley wind focusing of recirculated moisture that subsided in the head of valleys during the afternoon –** Do sub-meso-gamma scale canyons along the southwest-facing valley sidewalls recirculate moist air that subsided during the early afternoon into the upper parts of a broad alpine valley also modifying CAPE above or within the strongest anabatic convergence zones? How does this control convective initiation?
- **Dry and moist heat plumes rising along the valley/side walls and mesoscale mid-upper tropospheric divergence aloft –** Do heat plumes in canyons along the valley sidewalls modify the mass field aloft thus accentuating mid-upper tropospheric divergence and altering the sense of the upscale ageostrophic circulation aloft affecting downstream convective initiation? Does this enhance environmental ascent and expand its influence, subsequently modifying the downstream convective environment?
- **Residual moisture from upstream convection –** Does the abovementioned outflow aloft vent moisture as well that, in turn, modifies the downstream convective environment affecting convective initiation?
- **Residual vertical shear effects from upstream convection –** Does this outflow restructure the mid-tropospheric momentum fields sufficiently to modify the characteristics of newly initiated convective cells (i.e. from air mass to multicellular or super-cellular) that in turn modifies the downstream convective evolution?
- **The sensitivity of LES numerical formulations to convective initiation –** To what extent are LES formulated numerical models required for simulating convective initiation at the meso-gamma and canyon scales and why? Do LES models improve the simulation of the aforementioned physical processes over non-LES models and why? What strategies can be employed to improve the assimilation of meso-γ and finer scale data into LES numerical models to improve the simulation of the physical processes described above and why?

Critical measurements for convection initiation include frequent (ideally 3-hourly) soundings in the pre-Alpine region both north and south of the Alps, as well as some sites directly over the high terrain. Soundings in the pre-Alpine region should be launched to better characterize the mesoscale environment in preferred areas of convection initiation: for southern Alps, probably the sounding of Milan (followed by Udine) is the most relevant with respect to the AVTA, otherwise a dedicated launch site could be established.

The operational radar network will be valuable for observing and tracking thunderstorms over the Alps. The incipient cloud development can be observed with scanning or profiling K-band cloud radars. Precipitation radars (e.g., C-band) are also needed to provide clear-air Doppler winds in the sub-cloud layer and to track the evolution of Alpine thunderstorms. The existing radar networks should be able to capture pre-Alpine orographic triggering well but may not offer good coverage in the target areas (particularly if blocked by topography). Locating mobile radar systems within the target areas would ensure detailed coverage in the region of interest and help to better understand the mesoscale dynamics associated with precipitation. To investigate the triggering of convection, observations related to horizontal convergence and vertical motion in the boundary layer and immediately above are needed. Observations of turbulence in convective clouds (e.g. dissipation rates and spectral width derived from radar observations or in-situ data observed by aircraft) would be helpful to improve turbulence parameterization schemes.

Thus, additional instruments including Doppler lidars, Raman lidars, cloud radars, precipitation radars, disdrometers and flux towers are needed to provide detailed information on specific storms. Such observations are critical to facilitate novel insights into convection initiation and evolution. Flux towers and satellite information will provide important information about how near-surface turbulence contributes to and interacts with summertime Alpine convection. Along with soundings, high-resolution thermodynamic information can be obtained from one or more profiling Raman lidars at strategic locations upstream of convection-initiation hotpots. The boundary-layer inflow into convective clouds will also be sampled by multiple Doppler lidars, allowing for a detailed 3D observation of wind and temperature in the inflow region. Ceilometers will be helpful to monitor the CBL height, which can be affected by (horizontal) convergence lines.

It would be also interesting to sample the conditions over a large area upstream of the orography, relevant for convective initiation, the climatology of which is found in Manzato et al. (2022). Northeast Italy, particularly the Veneto and Friuli Venezia Giulia plain and foothills, is well-known maximum of lightning activity (Feudale and Manzato, 2014) and would benefit from additional instrumentation during the Summer EOP, particularly profiles of wind and temperature.

Both the IVTA and AVTA have pretty dry anomalies, especially in winter, but also in summer. Also, the convective initiation flash density and convective initiation (2005-2019 EUCLID data provided by ALDIS) show that these target areas are probably not the best choice for convection/precipitation studies. While the AVTA sees a rather high frequency of initiations on the southern side, the IVTA does not; the NPATA has an intermediate number of convective initiations. An isolated maximum of convective initiation is found between Innsbruck and Trento, just north of Bolzano in the Sarntaler Alps. Although this region is a relatively large orographic feature and would be difficult to sample, it could be an interesting site to examine why the lightning peak is there and which processes favour deep convection. The Monte Baldo supersite has some advantages for convection initiation studies (although not for evolution into large scale systems). It has a reasonable location for initiation at the foothills of the Alps and a simple shape, but asymmetric surroundings with the Po valley to the east and Lake Garda to the west. An area south-east of Monte Baldo would be helpful for identification of upstream conditions and would be more relevant for convection (initiation and organization). Verona Airport could be one option but the administrative problems that would need to be overcome to transfer the equipment to the airport may not be trivial. Other nearby sites appropriate not only for convective initiation but also for the evolution into larger scale systems are Monte Grappa and Asiago. Both are easy to access and close to the foothills and plains.

5.4.2 Surface-atmosphere Exchange

The Surface-atmosphere Exchange WG will mainly focus on surface and near-surface observations but these will be linked to the MoBL structure and local- and meso-scale flows. Particular topics of interest include surface energy balance and closure (including quantifying advection, dispersive fluxes and storage terms), reducing uncertainties in the CO_2 budget, the effect of various types of heterogeneity (e.g. surface cover, terrain, sub-surface properties) on surface-atmosphere exchange, process understanding with the aim of improving climate models, slope- and valley- winds, very near surface katabatic flows and low-level jets, surface-atmosphere exchange over snow-covered surfaces, improving similarity scaling relations and fundamental turbulence properties (e.g. anisotropy). Multiple surface types are of interest, including projects dedicated to glaciers and urban areas.

Detailed studies of turbulent exchange at individual sites, as well as comparisons across multiple sites with different characteristics will improve understanding of factors affecting surface-atmosphere exchange. Concurrent measurements at nearby sites will help to quantify spatial variability. Multi-level flux towers will allow flux divergence and gradients to be analysed, while dense arrays of flux towers will enable estimation of 3D transport and exchange. Tethered balloon measurements, distributed temperature sensing, drone measurements and thermal imagery will help to capture small scale spatial variability and fill in the gaps between observations. There is interest in various quantities, including fluxes of radiation, momentum, turbulent heat, carbon dioxide, methane, and other trace gases.

5.4.3 Waves and Dynamics

Topics of interest to the Waves and Dynamics WG include:

- **Low-level redistributions of momentum, heat and moisture due to mountain gravity waves and embedded flows**: upwind profiles from radiosondes, dropsondes and aircraft would be compared with leeside 4D observations of bulk fields from weather stations and aircraft (profiles, sawtooth legs), turbulence from flux stations and aircraft (straight and level flux legs), remote sensing of winds from radar and lidar. Microbarograph measurements to estimate surface pressure and drag on mountains would be very useful. The focus would be on foehn conditions during the Winter EOP in the IVTA, AVTA and an alpine crest site. Comparisons with flows in Dubrovnik (during bora) and Iceland are also of interest.
- **Multi-scale mountain waves in directionally sheared flow**: in-situ measurements of u, v, w and T on aircraft, downward pointing lidars on aircraft and coplanar retrievals from ground-based Doppler wind lidars would be used to study mountain waves in the troposphere and lower stratosphere during the Winter EOP.
- **Mountain waves in the Eastern Alpine region:** mountain waves in the troposphere and lower stratosphere during westerly/north-westerly flow conditions will be studied during the Winter EOP using DLR Falcon airborne observations (downward looking wind lidar, in-situ measurements of u, v, w, T and trace gases). In the CH4@Alps project methane transport is of particular interest. Additional measurements of temperature in the middle atmosphere with a ground-based Rayleigh lidar for deep wave propagation studies are under consideration by DLR. Turbulence observations from commercial aircraft would also be useful. These observations would be combined with global/mesoscale model data

- **Transition between turbulence and orographic gravity waves in very stable boundary layers:** ground-based measurements of bulk and turbulent properties plus radiosonde data would be used to observe gravity waves in very stable boundary layers during the Winter EOP.
- **Vertical structure of gravity waves and wave-breaking in deep precipitating systems over complex terrain:** remote sensing equipment onboard the UWKA (dual-Doppler cloud radar, Doppler lidar) will be used to study propagating gravity waves interacting with passing deep precipitating systems. The UWKA will probably only fly during the Summer EOP.
- **Comparison between valley and mountain crest conditions:** using available observations from a range of valley and mountain top stations.
- **Foehn flows:** observations of turbulence within, at the upper boundary and just above foehn flows, to sample shear-generated turbulence and turbulence associated with convective overturning due to waves, jumps and rotors.
- **Long-term study of mountain waves:** several years of Mode-S data from commercial aircraft and Austro Control would be used to study mountain waves over the Eastern Alps.
- **Investigation of different types of orography:** for example, comparison of isolated peaks (isotropic) with the 2D ridge-structure of elongated valleys (anisotropic).

The Waves and Dynamics WG would want at least one mountain crest site. This site should include a flux tower to provide in situ measurements of bulk quantities and turbulence (wind components, temperature and humidity), at least one T/RH profiler to provide vertical profiles of temperature and humidity throughout the boundary layer and at least one vertically pointing Doppler wind lidar to provide a vertical wind profile throughout the boundary layer, nearby radio-soundings at 3-hourly intervals during the IOPs. The site should be included in the flight path of research aircraft, particularly DLR-Falcon during the Winter EOP. Desirable additions include twice daily radiosoundings during the EOPs, a VHF radar to provide continuous tropospheric wind measurements and GPS dropsondes from research aircraft. If resources allow, additional mountain crest sites would be of interest.

Existing sites that would be suitable candidates for such a mountain crest site include Schneefernerhaus, Hintereisferner and Arbeserkogel. The Sarntaler Alps area would also be suitable but there are few existing measurements here. The site needs to be accessible throughout the winter and ideally would provide a broad-sky view for remote sensing (Schneefernerhaus and Hintereisferner are located on steep slopes beneath mountain crest height).

5.4.4 Atmospheric Chemistry

Details will follow.

5.4.5 Mountain Boundary Layer

Details will follow.

5.4.6 Mountain Climate

Details will follow.

6 Overview of previous research projects

This section provides an overview of relevant previous research that has been conducted in and around the target areas (Section 6.1) and lists topics that would be useful preliminary studies to help with the planning and design of the TOC (Section 6.2).

6.1 Summary of previous research in and around the target areas

A brief summary of relevant research in and around the target areas is presented here. There are numerous Master theses covering a range of topics which are not listed here; they can be accessed via University of Innsbruck (https://www.uibk.ac.at/acinn/theses/master-theses.html.en) and University of Trento (https://webapps.unitn.it/Biblioteca/en/Web/Tesi).

6.1.1 Previous research on the Inn Valley and surroundings

Atmospheric research in the Inn Valley started at the beginning of the 20th century, with early studies targeting foehn (von Ficker, 1910) and thermally driven winds (Wagner, 1938). Similarly, the first major field campaigns (HAWEI in 1978 and MERKUR, which took place in connection with ALPEX, in 1982) focused on thermally driven circulations, including the morning transition from down- to up-valley winds (Freytag, 1980; Brehm and Freytag, 1982; Freytag, 1987), the valley mass budget (Freytag, 1987), and valley-exit jets (Pamperin and Stilke, 1985). Outside of these field campaigns, several studies have documented the diurnal cycle of the valley-wind circulation (Defant, 1907; Dreiseitl et al., 1980; Lehner et al., 2019) and described its forcing mechanisms, that is, the along-valley temperature and pressure gradients (Nickus and Vergeiner, 1984; Vergeiner and Dreiseitl, 1987). Recent field observations during CROSSINN in 2019 studied the fine-scale, three-dimensional structure of thermally driven circulations using state-of-the-art lidar technology (Adler et al., 2021).

Two dedicated field campaigns, a sub-project of MAP in 1999 (Mayr et al., 2004; Mayr et al., 2007), and PIANO in 2017 (Haid et al., 2020; Muschinski et al., 2021; Umek et al., 2021) targeted foehn. Research during MAP focused strongly on the distinction between shallow and deep foehn (Mayr and Armi, 2008) and on foehn formation mechanisms at the Brenner Pass, which were studied using hydraulic theory (Flamant et al., 2002; Gohm and Mayr, 2004), which was also extended to continuously stratified flow (Armi and Mayr, 2007). Results from MAP concerning mountain wave generation and breaking are summarised in a review paper (Smith et al., 2007). To identify foehn conditions, objective identification methods were developed (Vergeiner, 2004; Plavcan et al., 2014) and compared with human identification (Mayr et al., 2018). The interaction of foehn with cold-air pools over Innsbruck was studied during PIANO (Haid et al., 2020; Muschinski et al., 2021; Umek et al., 2021). While the focus has been mainly on south foehn, some studies have also looked at north foehn.

The vertical structure of the boundary layer has been analysed using various types of instrumentation, including surface temperature measurements along the north valley sidewall (Dreiseitl, 1988), ceilometers (Emeis et al., 2007), tethered-balloon soundings, interpolated aircraft measurements, and a microwave radiometer, revealing multi-layered daytime temperature profiles (Emeis et al., 2007; Wagner et al., 2014; Wagner et al., 2015b). Nocturnal inversions received some attention as well (Vergeiner et al., 1978), including their formation (Schätzle, 1978) and erosion (Brehm, 1982; Brehm and Freytag, 1982). Turbulent exchange is monitored by long-term infrastructure: the i-Box in the lower Inn Valley (Rotach et al., 2017) and the Innsbruck Atmospheric Observatory (IAO) in the city of Innsbruck (Karl et al., 2020). Analyses includes assessment of measurement strategies and post-processing options (Stiperski and Rotach, 2016), similarity scaling (Sfyri et al., 2018), anisotropy (Stiperski et al., 2019) and the performance of a microwave radiometer (Massaro et al., 2015).

The Neustift FLUXNET site (AT-Neu) is situated on grassland close to the village of Neustift in the nearby Stubai Valley (doi: 10.18140/FLX/1669365, Pastorello et al. (2020)). The Neustift site has been operational since 2001 and has been the focus of numerous studies over the last 20 years, involving studies of momentum (Wohlfahrt and Cernusca, 2002), sensible and latent heat (Hammerle et al., 2008; Wieser et al., 2008) and CO_2 (Wohlfahrt et al., 2005a; Wohlfahrt et al., 2005b; Wohlfahrt et al., 2008b; a) fluxes; the advection of CO_2 (Zhao et al., in preparation); and validation of satellite remote sensing products (Pasolli et al., 2015). Several modelling studies have been conducted using the data from the site (Wohlfahrt, 2004; Tenhunen et al., 2009). Several short-term campaigns have also taken place to quantify fluxes of methane (Knox et al., 2020), nitrous oxide (Hörtnagl and Wohlfahrt, 2014), ozone (Wohlfahrt et al., 2009), gaseous elemental mercury (Fritsche et al., 2008), carbon monoxide (Hammerle et al., in preparation), carbonyl sulfide (Gerdel et al., 2017; Spielmann et al., 2019; Spielmann et al., 2020) and various volatile organic compounds (Bamberger et al., 2010; Müller et al., 2010; Bamberger et al., 2011; Hörtnagl et al., 2011; Ruuskanen et al., 2011; Brilli et al., 2012; Bamberger et al., 2014).

Air pollution measurements have been taken in the lower Inn Valley during ALPNAP in winter 2005-06 (Heimann et al., 2007) and during a follow-up experiment in winter 2007-08, along the highway (Beauchamp et al., 2004; Schnitzhofer et al., 2008) and in Innsbruck (Karl et al., 2020). Analysis has focused on the impact of meteorological conditions on air pollution (Schäfer et al., 2008), including the impact of slope- and valley-wind circulations on the spatial distribution of aerosol concentrations (Gohm et al., 2009; Harnisch et al., 2009; Schnitzhofer et al., 2009), the impact of inversions on SO_2 (Vergeiner et al., 1978), and the impact of foehn on ozone (Seibert et al., 2000). Various atmospheric constituents and their related processes have been studied using measurements and simulations, including NO_x (Karl et al., 2017), non-methane volatile organic compounds, NO_x/CO_2 enhancement ratios, ion concentration in precipitation, and aerosol optical depth.

In addition to observations, numerical simulations have been used extensively to study foehn (e.g. Zängl et al., 2004; Zängl and Gohm, 2006) and the valley-wind circulation (Zängl, 2004; 2009), including idealized simulations of gap flows (Zängl, 2002; 2003), air pollution transport (Lehner and Gohm, 2010; Lang et al., 2015), and heat and mass exchange between the valley and the atmosphere aloft (Wagner et al., 2014; Leukauf et al., 2015; Wagner et al., 2015a; Wagner et al., 2015b; Leukauf et al., 2016; Leukauf et al., 2017). Simulations have also been used to evaluate model performance over complex terrain for different conditions, including the impact of PBL schemes and vertical grid spacing on foehn (Zängl et al., 2008), 1.5 order turbulence closure (Goger et al., 2018; Goger et al., 2019), and land-use datasets (Schicker et al., 2016).

6.1.2 Previous research on the Adige Valley and surroundings

Analysis of meteorological processes in the valleys connecting the Brenner Pass with the Po plain was pioneered by (Defant, 1909) with a study of periodic winds in South Tyrol. Between the 1920s and 1930s the local dominant circulation patterns in the vicinity of Trento were documented, including the daily periodic winds in the Adige Valley and the Ora del Garda wind system, a lake- and valley-breeze occurring in the Valle dei Laghi, which connects the northern tip of Lake Garda with Trento (Pollak, 1924; Wiener, 1929; Jelinek, 1934). These studies are summarised in a later review by Wagner (1938).

These same wind systems continue to attract considerable interest. Climatological aspects of the Ora del Garda breeze, including diurnal periodicity and seasonality, were studied by Giovannini et al. (2015), who also described the response of the local wind system to different synoptic flow scenarios. The impact of the Ora del Garda on the convective boundary layer in the Valle dei Laghi was documented by (Laiti et al., 2013a; Laiti et al., 2014b). They used airborne measurements to study the cooling and stabilising effect of the lake breeze on the valley atmosphere and, for this purpose, established a novel method of interpolating three-dimensionally distributed aircraft measurements on a regular grid (Laiti et al., 2013b). Data from the same research flights (de Franceschi et al., 2003) were used to develop a methodology to determine the depth of the convective boundary layer from high-resolution pseudo-soundings (Rampanelli and Zardi, 2004).

For the Adige Valley itself, Giovannini et al. (2017) documented the impact of local land-use inhomogeneities on the breeze system and described the dynamical links between the surface wind field and spatially varying temperature and pressure perturbations along the valley. These observational studies laid the foundation for a sequence of idealized modelling investigations exploring the mechanisms of thermally-driven circulations, highlighting in particular how the heat budget of valleys depends on the interplay between convectively-driven turbulent mixing and heat advection by along- and cross-valley circulations (Rampanelli et al., 2004; Serafin and Zardi, 2010b; a; 2011).

Micrometeorological research in the Adige Valley is partially connected with FLUXNET, a global network initiative monitoring ecosystem exchange through continuous eddy covariance measurements of carbon dioxide, water and energy fluxes. Three long-term high-altitude FLUXNET sites are active in the valley, namely IT-Ren (Renon, evergreen forest), IT-Lav (Lavarone, evergreen forest) and IT-MBo (Monte Bondone, alpine grassland). Along with Bosco Fontana, Renon and Monte Bondone are now ICOS ecosystem sites. Previous research includes turbulence characteristics in and just above forest canopies (Marcolla et al., 2003; Cescatti and Marcolla, 2004; Cava et al., 2006; Cava et al., 2008; Cava and Katul, 2012) and exploration of the drivers of the interannual variability of net ecosystem exchange (Marcolla et al., 2011). The role of non-turbulent (advective) fluxes in local carbon exchange has been investigated at the Renon site (e.g. Marcolla et al., 2005). Satellite-derived vegetation data (e.g. Gianelle et al., 2009) and latent heat fluxes (Yao et al., 2015) have been compared with eddy covariance measurements. Studies have also looked at the carbon balance of alpine peatlands (Pullens et al., 2016).

In the early 2000s, another stream of micrometeorological research was initiated, partly in connection with environmental impact assessment studies for prospected waste incinerator plants in Trento and Bolzano/Bozen (Ragazzi et al., 2013). Sonic anemometer data were used to investigate surface-layer similarity scaling over the valley floor (de Franceschi et al., 2009), to explore how the time scales separating large-scale anisotropic from small-scale isotropic turbulent fluctuations depends on atmospheric stability and wind intensity (Falocchi et al., 2019), and to improve recursive filters for the separation of turbulent signals from the mean flow (de Franceschi and Zardi, 2003; Falocchi et al., 2018).

The Adige Valley has also been the focus of a large number of applied meteorology studies concerning atmospheric dispersion and air quality (de Franceschi and Zardi, 2009; Tomasi et al., 2015; Falocchi et al., 2020), harvesting of renewable energy (Laiti et al., 2014a; Laiti et al., 2018) and the energy efficiency of buildings (Pappaccogli et al., 2018). The urban heat island of the city of Trento has been thoroughly investigated (Giovannini et al., 2011; Giovannini et al., 2014b), including an evaluation of the temperature variability in the street canyon (Giovannini et al., 2013) and an analysis of the implications of urban expansion for long-term temperature timeseries (Giovannini et al., 2014a).

The synoptic climatology of the Trentino region and the pathways of moisture transport towards the area, which encompasses a long stretch of the Adige Valley, have been described respectively by Panziera et al. (2015; 2016) and by Bertò et al. (2004). Northeast Italy, particularly the Friuli-Venezia Giulia region is a known hotspot for severe weather events (Bechini et al., 2001; Bertato et al., 2003; Manzato, 2012) and lightning activity (Feudale and Manzato, 2014).

To the east of the Adige Valley into northeast Italy, the Friuli Venezia Giulia region is a known hotspot for severe weather events (Bechini et al., 2001; Bertato et al., 2003; Manzato, 2012; Miglietta et al. 2016) and lightning activity (Feudale and Manzato, 2014; Manzato et al. 2022).

6.1.3 Previous research at and around the TERENO Pre-Alpine Observatory

The set-up of the TERENO Pre-Alpine Observatory was motivated by the fact that mountain areas such as the (pre-)alpine region in southern Germany have been exposed to more intense warming compared to the global average trend and to higher frequencies of extreme hydrological events such as droughts and intensive rainfall (Böhm et al., 2001; Calanca, 2007). Analysis of the temperature time series for the Mount Hohenpeissenberg DWD station reveal a mean annual temperature increase of 1.5°C for the years 1880-2012 which is almost double the globally averaged combined land and ocean surface temperature increase of 0.85 (0.65 to 1.06) °C reported for the same time period (IPCC, 2014).

Several highly specialised short-term campaigns have taken place at the TERENO Observatory, for example incorporating lidars, chamber measurements and distributed temperature sensing. Flux footprints of all three measurements sites have been studied in detail to assess the surface heterogeneity: footprint climatologies were determined for all three EC sites (Soltani et al., 2018) and the performance of different footprint models was evaluated using artificial tracer release experiments (Heidbach et al., 2017). The ScaleX[68] experiments are cooperative, intensive research campaigns that aim to assess spatially distributed patterns and gradients in land surface–atmosphere exchange processes within the TERENO Pre-Alpine Observatory and specifically near the Fendt site (Wolf et al., 2017). Special to ScaleX was the focus on processes in complex terrain and interdisciplinary links that emerge at the sub-mesoscales when bridging observations and models.

The lysimeter facilities installed at DE-Gwg, DE-RbW and DE-Fen are part of the SOILCan lysimeter network that was established between March and December 2010 as joint initiative of German TERENO partner institutions (Pütz et al., 2016). Within SOILCan, lysimeters were translocated along climate gradients within and across observatories. The underlying idea is based on the “space for time” concept that anticipates climatic change over time by a translocation e.g. intact soil-plant mesocosms, in space. The main research focus of the lysimeter study is the impact of climate and management changes on the components of grassland water, carbon and nitrogen cycling and budgets, on biosphere-atmosphere-hydrosphere matter exchange (i.e. greenhouse gas emissions and leaching), on yields and on biodiversity.

[68] https://scalex.imk-ifu.kit.edu/

Due to the high spatiotemporal variability of precipitation, its accurate estimation is a challenging task. In particular in mountainous terrain, both rain gauges and weather radars are limited in providing reliable observations. A promising new technique that helps improving rainfall estimation is the usage of attenuation data from commercial microwave link (CML) networks, which are used to provide a large part of the backhaul of the cell-phone network (Messer et al., 2006). Within the DFG-funded project *Integrating Microwave Link Data For Analysis of Precipitation in Complex Terrain: Theoretical Aspects and Hydrometeorological Applications (IMAP)* in cooperation with Ericsson as CML network operator KIT IMK-IFU currently acquires data of more than 4000 CMLs in Germany. Of these, 12 CMLs are located within the TERENO Pre-Alpine Observatory. Data is delivered in real-time to a KIT server and further processed to derive rain rates from the partly noisy raw data (Chwala et al., 2016). This is done via own developed (Chwala et al., 2012) and other published methods (e.g. Schleiss et al., 2013), integrated and available via an open-source processing toolbox: pycomlink[69].

6.2 Preliminary studies

Several smaller measurement campaigns are planned by individual research groups in the run-up to the TOC to test equipment and measurement strategies. These are summarised here.

- A preliminary campaign in the Inn Valley took place in summer 2022 and with involvement from KIT, GeoSphere, DWD and IFU. Activities focused on the i-Box region and the lower Inn Valley.
- A climatology of convective initiation in the Alpine region has been completed to help identify where the Orographic Convection WG should focus their activities (Manzato et al., 2022).
- A climatology of cold-air pools is being compiled for Innsbruck, Bolzano and Trento.

Suggestions for other preliminary studies:

- A preliminary study of the region around the Adige Valley exit and the Po Valley would be useful for better understanding this highly complex region, especially for informing decisions about where and what to measure during the TOC.
- Before data from atmospheric profiling instrumentation can be used, the performance of retrieval algorithms for boundary layer height in mountainous terrain must be investigated.
- Assessment of radiometer accuracy and magnitude of radiative flux divergence close to the surface would assist with planning the instrumental setup.
- Preliminary studies into advection would help with the design of advection measurements (e.g. location and spacing of instrumentation, need for measurements at more than one level) during the TOC.

[69] https://github.com/pycomlink/pycomlink

Appendix A Relevant organisational structures

A.1 Field Observations Committee

The TEAMx Field Observations Committee (FOC) is responsible for the initial design and planning of the TEAMx Observational Campaign.

A.2 Task Teams

The TEAMx Task Teams (TT) comprise small groups of experts on particular topics who will manage the detailed planning of important aspects of the campaign which require coordination. Task Teams will be established as needed. So far, task teams have been established for the following topics:

- Data management and data policy
- Coordinating aircraft measurements
- Coordinating non-piloted airborne observations (including obtaining the necessary permissions), including drones, fixed-wing unmanned aerial systems and tethered balloons).

The need for TTs on the following topics has been identified:

- Making forecasts during the campaign
- Planning flight paths for research aircraft
- Designing coordinated lidar scanning strategies for the target areas (*Mountain Boundary Layer* WG)
- Coordinating atmospheric profiling systems (scanning strategies, retrieval algorithms, quality assessment)
- Specifying the layout and instrumental setup of surface flux stations for the target areas (*Surface-atmosphere Exchange* WG)
- Deciding on the protocol for eddy covariance data processing (*Surface-atmosphere Exchange* WG)
- Deciding on the protocol for data processing of airborne measurements
- Coordinating data treatment and quality assessment

Appendix B Definitions

General acronyms

CIG	Coordination and Implementation Group
CML	Commercial Microwave Link
DIAL	Differential Absorption Lidar
DTS	Distributed Temperature Sensing
EOP	Extended Observation Period
FOC	Field Observations Committee
IOP	Intensive Observation Period
MoBL	Mountain Boundary Layer
NMC	Numerical Modelling Committee
PCO	Project Coordination Office
SSI	Site of Special Interest
TA	Target Area
TOC	TEAMx Observational Campaign
TT	Task Teams
UAS	Unmanned aerial systems
UHF	Ultra-High Frequency
VHF	Very High Frequency
WG	Working Group

Target areas

ACTA	Alpine Crest Target Area
AVTA	Adige Valley Target Area
IVTA	Inn Valley Target Area
NPATA	Northern Pre-Alpine Target Area
SPATA	Southern Pre-Alpine Target Area

Supersites and Sites of Special Interest

FAIR	Forest-Atmosphere Interactions Research
i-Box	Innsbruck-Box
IAO	Innsbruck Atmospheric Observatory
SBO	Sonnblick Observatory

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