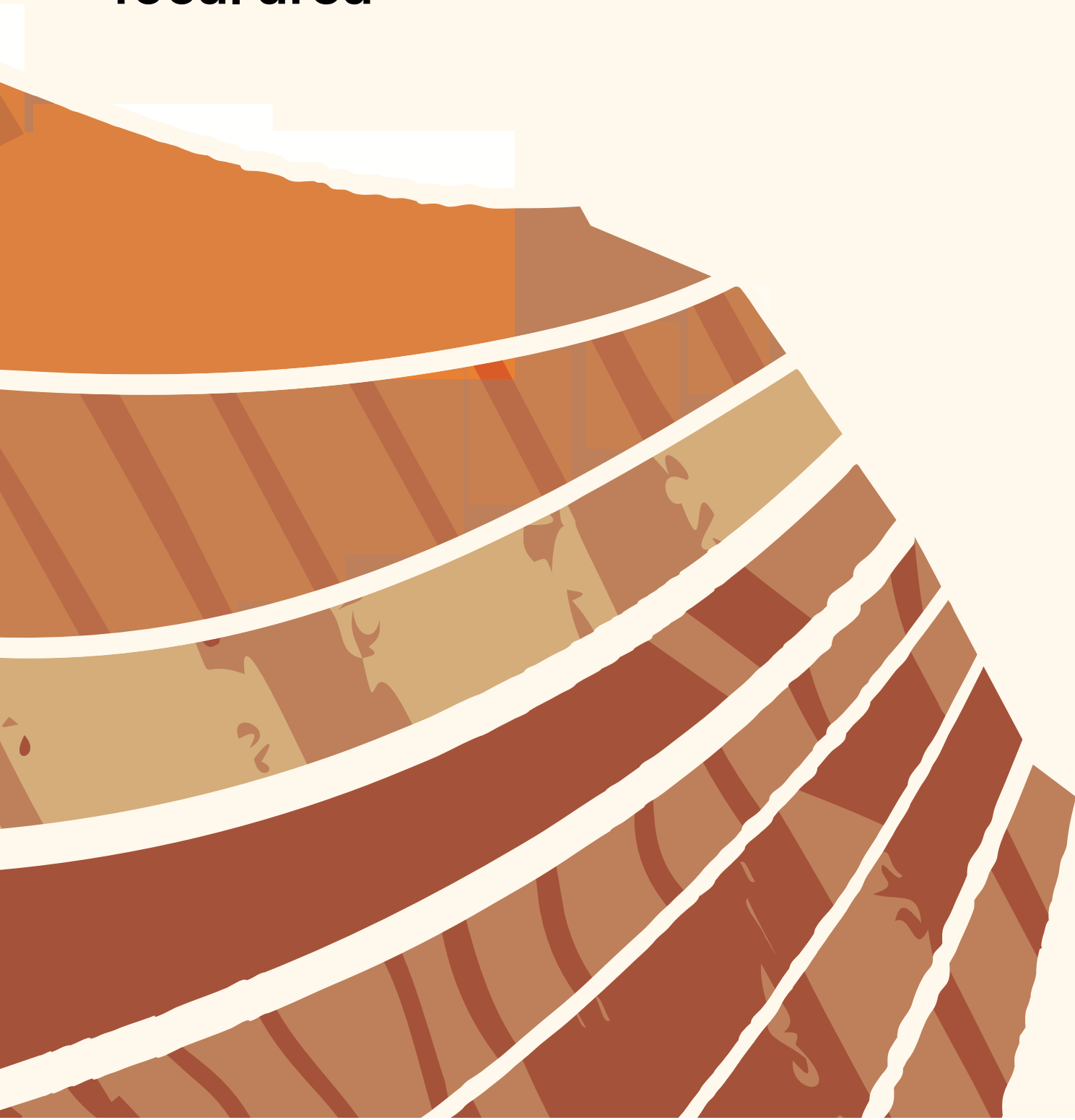


Chapter 7

The Austrian Alps as multi-dimensional focal area



Second Austrian Assessment Report on Climate Change | AAR2

Chapter 7 The Austrian Alps as multi-dimensional focal area

This publication was subject to an anonymous international peer review process guided by several review editors, the AAR2 co-chairs and the APCC Steering Committee.

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Recommended citation

S. Fuchs, W. Schöner, R. Steiger, et al. (2025): The Austrian Alps as multi-dimensional focal area. In "Second Austrian Assessment Report on Climate Change (AAR2) of the Austrian Panel on Climate Change (APCC)". [D. Huppmann, M. Keiler, K. Riahi, H. Rieder (eds.)]. Austrian Academy of Sciences Press, Vienna, Austria | doi: doi.org/10.1553/aar2-ch7

You can download the recommended citation in the formats Endnote (.ris) and BibTex (.bib) at aar2.ccca.ac.at/citation.

Vienna, June 2025

ISBN: 978-3-7001-5110-4 | austriaca.at/5110-4 (full report)

Production

Publisher: Austrian Academy of Sciences Press, Vienna
Typesetting: Crossdesign Werbeagentur GmbH, Graz
Cover: paulaidaanton | Agentur für digiloges Design
Graphic design Figure 7.3: paulaidaanton | Agentur für digiloges Design
AI-based tools such as DeepL were used to support the linguistic revision.

Contact address for product safety:
Austrian Academy of Sciences Press
Dr. Ignaz Seipel-Platz 2
A-1010 Wien
Tel.: +43-1-51581-3420
E-Mail: verlag@oeaw.ac.at

Funding acknowledgement

The AAR2 was funded by the Climate and Energy Fund under the 14th Austrian Climate Research Program (ACRP).

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The AAR2 is a report by the Austrian Panel on Climate Change (APCC).
<https://aar2.ccca.ac.at/en>

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EXECUTIVE SUMMARY

By 2024, the temperature in the Austrian Alps had increased by 3.1°C compared to pre-industrial times (*high confidence*). It is projected to keep increasing in the future, conditional on future emissions (*high confidence*). While past and future temperature increases within the Austrian Alps are spatially relatively homogeneous, changes in precipitation vary from region to region (strongest increase of 10 % for median precipitation in the north in winter and almost no change in summer for GWL 4.0°C) (*medium confidence*). {7.3.1, 7.3.2}

In the past (instrumental period), warming in the Austrian Alps was almost identical to the rest of Austria (*high confidence*); for the future, model simulations show a slight elevation dependent warming (*medium confidence*). In an Austria-wide comparison, the role of the Alps as sentinels of climate change is thus hardly evident in their specific warming trend, but rather in the change in specific impacts such as the strong decline of the cryosphere in response to warming. The following changes in the cryosphere characteristics of the Alpine landscape are directly related to climate change: (i) Decreasing snowfall and snow on the ground (about 3 cm/decade decrease in mean snow depth); (ii) About 7 days/decade decrease in snow-cover days since 1961 and further decline by 10–15 snow-cover days under GWL 2.0°C/60–80 snow-cover days under GWL 4.0°C (*robust evidence, medium agreement*); (iii) Glacier retreat (40 % of glacier area in Austria were lost between 1969 and 2015 and glaciers will completely disappear under GWL 4.0°C) (*high confidence*); (iv) Increase in permafrost temperature (e.g., +0.1°C/year at 3 m depth since 2016) and widespread permafrost degradation (*low confidence*). These changes will further exacerbate alpine and downstream droughts, challenge tourism and alter the ecosystem services of the Alps. {7.3.1, 7.3.2, 7.4.1, 7.4.2}

The role of the Alps as a water tower for Austria and even more for Central Europe is evident from the climatic water balance (which is positive by average of 466 mm for the period 1981–2010) (*high confidence*) and from the comparison of the runoff contribution to the area-related mountain share of individual river catchment areas. Such a comparison shows that the runoff contribution clearly exceeds the area share (33 % to 17 % for the entire Danube catchment, 38 % to 21 % for the entire Rhine catchment) (*high confidence*). As a result of future climate change, a positive shift in the cli-

matic water balance in Austria is anticipated (+107±56 mm) under GWL 2.0°C. The role as a water tower will increase on average, but the increasing risk of droughts will lead to a stronger negative climatic water balance for subperiods within a year (*medium confidence*). {7.4.1}

In recent decades and in the future, the hydrological cycle in the Austrian Alps has been and will be characterized by changes in snow depth, earlier and increased snowmelt (*high confidence*) and an increase in extreme precipitation events on the time scale of hours (thunderstorms) in summer (*robust evidence, medium agreement*). As a result, summer floods in small catchments in the Alps have increased and will continue to do so in the future, while floods caused by heavy spring snowmelt are increasingly shifting to winter (*high confidence*). Increasing glacier loss exacerbates low flow conditions in glacierized catchment areas in the Alps in summer, however, with a decreasing contribution in the future due to the disappearing glaciers (*high confidence*). {7.4.1}

There is evidence that some natural hazards in the Alpine region will become more frequent and more intense in the future, such as wildfire and fluvial flooding (*high confidence*), torrential flooding (*medium confidence*) and pluvial flooding (*low confidence*). For fluvial floods, the trend is more pronounced in smaller catchments than in larger ones. A clear seasonal shift from winter and spring fluvial floods to summer floods is detectable (*high confidence*). Expected changes in the components of the hydrological cycle as the main driver of slope failure will facilitate the occurrence of landslides. This will affect alpine communities by causing major economic losses, specifically as the built environment and land use expand. Furthermore, it will affect the transport infrastructure and services, and thus the mobility of the population and the accessibility of mountain communities, and it may interrupt pan-European transport routes. {7.4.1, 7.4.3}

There is evidence of an upward shift of plant and animal species due to warmer conditions (*high confidence*). Therefore, cold environments above the tree line will shrink, leading to a loss of biodiversity. Large-ranged, warm-demanding species will replace short-ranged, cold-adapted species, some of which are endemic and restricted to the Austrian Alps (*medium evidence, high agreement*). There is an in-

creasing risk of mismatching of interactions between groups of organisms, e.g., plants and pollinators, and of physiological stress of high-elevation species due to warming (*medium confidence*). {7.4.1}

Climate change has a negative impact on the condition and availability of transportation infrastructure in Alpine regions (*high confidence*). An increasing frequency of high temperatures can cause physical deterioration of traffic infrastructure, including railway tracks and road tarmac. This phenomenon is particularly prevalent in mountainous regions especially in tight bends, leading to (thermal) overload of the infrastructure. This is exacerbated by the increase in heavy goods traffic, growth of tourism and local travel. Congestion increases due to the limited availability of alternative routes in mountainous areas and emissions increase significantly as a result. Adaptation can be achieved by shifting transit and holiday traffic to rail by, e.g., robust accompanying planning and policy measures for the Brenner Base Tunnel, making public transport more attractive, improving services for carless travel, and reducing traffic-related pollutant emissions through alternative drive systems. {7.4.3}

Winter tourism based on snow and ice sports will be severely affected by shortened ski-seasons and deteriorating snow-making conditions (*high confidence*). Without adaptation and transition to snow-independent tourism, this could lead to significant economic losses and unemployment in regions with high climate-related risks (*medium evidence, high agreement*). Job losses in regions dependent on winter tourism could increase commuting and out-migration. {7.4.2}

Summer tourism may benefit from more pleasant temperatures compared to the lowlands and urban areas, but risks and costs from natural hazards for hikers and the hiking infrastructure are likely to increase (*medium evidence, high agreement*). The maintenance of hiking and climbing infrastructure is currently mainly provided by alpine NGOs. If increasing costs for maintenance cannot be handled by NGOs anymore, other stakeholders such as destination management organizations or regional governments are required to step in to prevent a decline of summer tourism's high quality and reliability. {7.4.2}

Rising air temperatures and more frequent and severe drought periods will lead to shifts in tree species distribution and forest composition, which may have negative consequences for the protective function of forests at elevations <1,000 m a.s.l. This will happen in parallel with other natural forest disturbances caused by wind, fire, pests and insects (e.g., bark beetle) leading to a decrease in the protective function of forests at higher elevations (*high confidence*). Tangible and intangible losses to infrastructure, buildings and human lives may result because of increasing hazard potential downslope of a degenerated protection forest. Furthermore, secondary hazards may develop in affected areas (such as snow avalanches and debris flows), and soil loss and increasing surface runoff may be observed. Post-disturbance management decisions can have an important impact on the protective effect of forests. If left in the stand, deadwood could maintain the protective function of forests after windthrow and bark beetle disturbances, especially during the first 15 years. To better adapt to these threats, uneven and multi-layered stands with trees of all sizes and age classes, and a minimum canopy cover of about 40 %, only small openings and a sufficient presence of natural regeneration should be considered. {7.4.2}

7.1. Chapter introduction

The European Alps are the largest mountain range in Europe, covering more than 190,000 km² and are home to 14 million people, more than 30,000 animal species and 13,000 plant species (Permanent Secretariat of the Alpine Convention, 2019). Eight countries share the Alpine area and according to the Alpine Convention, Austria is the country with the largest share of the Alpine area (28.7 %) (Salto, 2024). The European Alps are often referred to as the ‘water towers’ of Europe as they supply four large European river basins (Danube, Rhine, Rhone and Po) with water (Permanent Secretariat of the Alpine Convention, 2009). Consequently, the European water balance is dependent on the Alpine water storage volume. Moreover, the European Alps contain unique landscapes, diverse cultural heritage, ecosystem services, they are an important tourist destination, and a source of livelihoods. Since a significant number of studies suggest that the European Alps are disproportionately affected by climate change, the challenge is to strike a balance between promoting economic development and, at the same time, preserving environmental quality (Alpine Convention, 2015).

Chapter 7 focuses on the Austrian Alps (hereafter ‘the Alps’) and the impacts of climate change on them, as this region not only offers special lifestyle opportunities for its

inhabitants but is also of great importance for Austria as a whole. Thus, the Alps are examined on three levels: As a natural or near-natural environment, as a provider of services, goods and livelihoods, and as a home to communities. The following two hypotheses form the backbone of the assessment in Chapter 7 and are explored throughout.

- Climate change in the Alps shows a different intensity compared to the foreland, as suggested by various processes (e.g., albedo feedback, water vapor effect, cloud formation). These processes will continue to have an impact in the future, making the Alps particularly sensitive to climate change.
- Due to their special socioeconomic features, their dependence on certain sectors, and the national and European significance of the region, the Alps have special vulnerabilities but also capacities to adapt to and mitigate these changes compared to the rest of the country.

This chapter aims to describe the manifestations of climate change in the Alps and its impacts on natural hazards, biodiversity, demography, settlements, mobility, and ecosystem services, and services and goods (forestry, agriculture, tourism, energy). Existing mitigation and adaptation options are presented and the needs for further adaptation and mitigation are outlined. First, the area of interest of Chapter 7

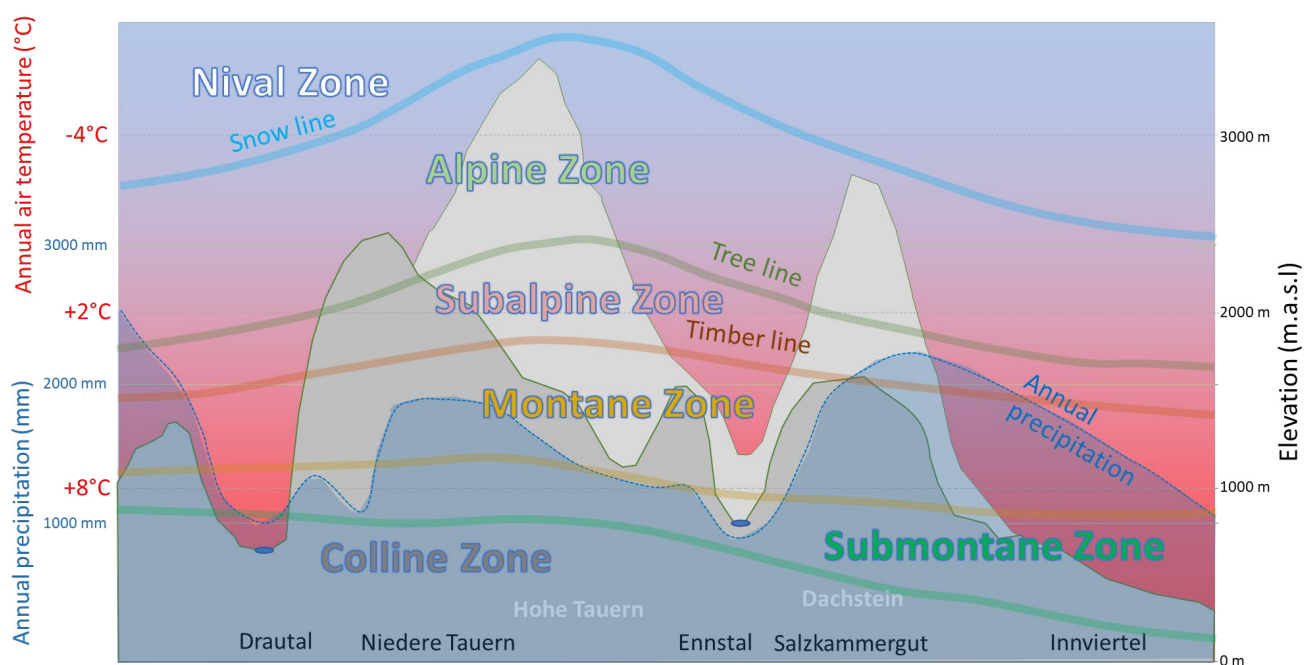


Figure 7.1 Schematic and simplified North-South cross-section through the Austrian Alps at approximately Salzburg with information on altitudinal vegetation belts, annual mean air temperature and mean annual precipitation. The climatic snowline and tree line are higher in the Inner Alps, because of lower precipitation and higher solar insolation.

(7.2.1) together with the demographic and spatial setting (7.2.2) are presented. The manifestation of climate change in the Alps is then shown (7.3). The Alps are then addressed as a natural environment (7.4.1), as a provider of services and goods (7.4.2), and as a home to communities (7.4.3). Based on these insights, adaptation and mitigation needs are identified and discussed in Section 7.5.

7.2. Delineation and differentiation of the Austrian Alps

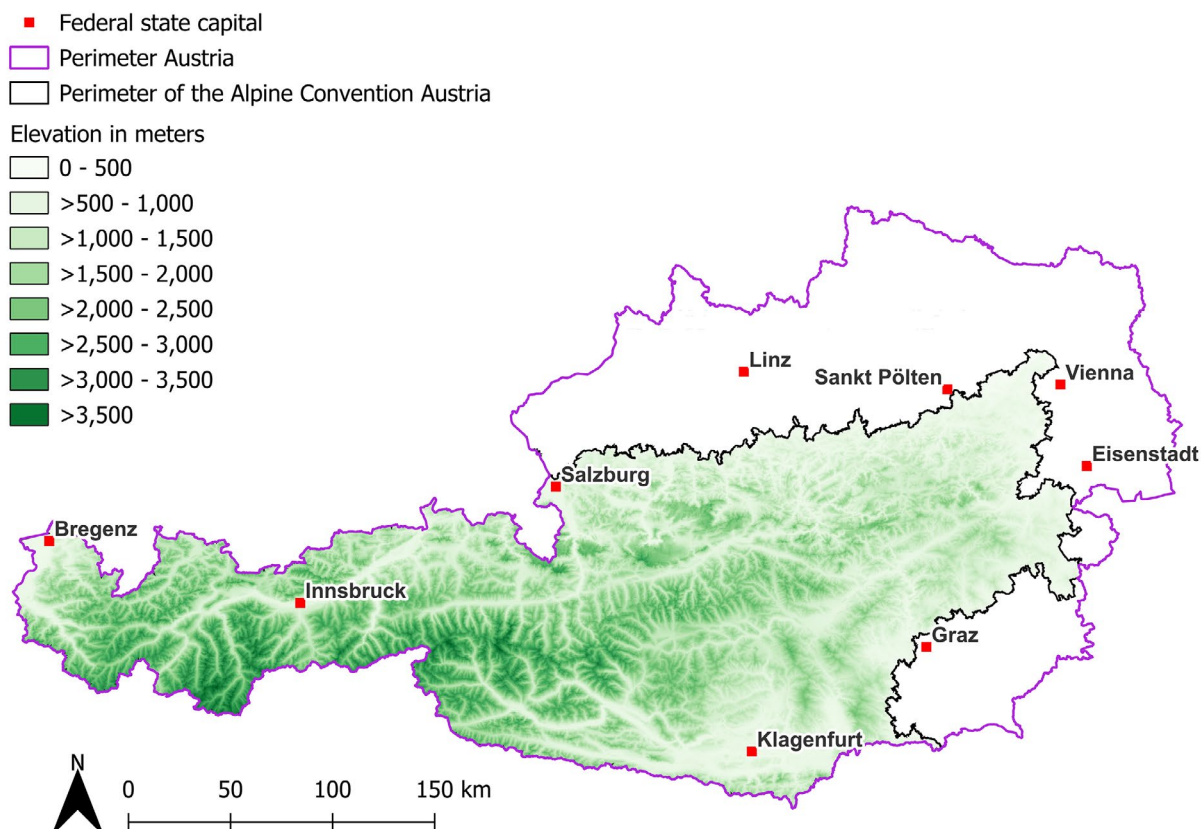
This subchapter defines the area of interest (presents the criteria for such a definition) and describes its special characteristics in the context of climate change.

7.2.1. Natural boundaries

Austria has the largest share of the European Alps, as defined by the Alpine Convention, covering more than 65 % of the country. Regional subdivisions of the Austrian Alps,

such as North, Central and South Alps further subdivide the Alps, but more important in the context of climate change is the vertical vegetation zonation such as the montane, alpine, subnival and nival zones as well as the tree line ecotone, and the expected changes due to the effects of climate change (Figure 7.1).

Natural boundaries can be used to delineate the Austrian Alps from the rest of the country. Delineation can be done using natural boundaries such as vegetation or climate boundaries, gradient thresholds, features, characteristics, topography, etc., but none of these seem to be universally applicable (and climate alone will not be sufficient to delineate the Austrian Alps). For an in-depth discussion see, for example, studies by Kapos et al. (2000), Elsen and Tingley (2015), Körner et al. (2021) and Price et al. (2022). Mountain topography has a high degree of complexity that affects climatic conditions. This includes elevation, slope steepness and slope direction, resulting in (steep) gradients of climate variables in both vertical and horizontal directions. Gradients can be observed in terms of, e.g., temperature, precipitation and solar radiation. Additional effects of mountain



Sources: data.gv.at, data-synergis.opendata.arcgis.com, www.atlas.alpconv.org (11.11.2024)

Figure 7.2 Delineation of the Austrian Alps according to usage in Chapter 7.

topography such as shading, clouds, surface material (bedrock, bare rock, vegetation of various types), local wind, and snow drift add to the observed variability. The lower human influence, compared to the Central European lowlands, together with the compression of thermal life zones along the elevation gradient, the diversity of microclimates and geology make the Alps an outstanding biodiversity hotspot (Smyčka et al., 2017). With about 4,500 species of vascular plants, they host about 40 % of the continent's native flora, 750–800 of which are alpine, including 270 endemic species (Ozenda and Borel, 2003).

In this chapter, the widely used delimitation according to the Alpine Convention is used (Figure 7.2).

7.2.2. Socioeconomic settings

Although the Alps cover 65 % of the country, only 39 % of the population lives in the region. However, it needs to be considered that in most Alpine municipalities the potentially suitable area for settlements, traffic infrastructure and agriculture is less than 25 % of the total area (Permanent Settlement Area, DSR – *Dauersiedlungsraum*) (Wonka, 2008). This limitation has a significant impact on the development of settlements in Alpine areas. The DSR is significantly lower in Alpine federal provinces and municipalities than in non-alpine areas. In Tyrol, the DSR amounts to 12 % of the total state area of the federal province resulting in a concentration of settlement activities, major transportation routes and agriculture in a very limited space (Österreichische Raumordnungskonferenz, 2023a). Related to the DSR, population density in many municipalities in the main valley areas exceeds 250 inhabitants/km² (Österreichische Raumordnungskonferenz, 2020). According to the urban-rural typology of the European Union, a population density of more than 300 inhabitants/km² is considered urban (European Union, 2010). Thus, agglomeration effects are not limited to alpine cities but also occur in ribbon-like settlements in the main valley areas. Given the significant demand for housing and commercial space, the limited amount of land available for development also affects housing density, the proportion of building land and subsequently the amount of land take and soil sealing (Österreichische Raumordnungskonferenz, 2023b). However, both the amount of building land per capita and the amount of sealed area per capita, are significantly lower in Alpine federal provinces and districts (Österreichische Raumordnungskonferenz, 2016; Umweltbundesamt, 2023a), indicating a more efficient use of building land there (Österreichische Raumordnungskonferenz, 2021). This is

attributed to the comparably higher building land prices in many Alpine regions, which show significant peaks in urban centers and distinct tourist areas (Statistik Austria, 2023a). In addition to the influence of limited development space, high land prices in Alpine valleys can also be regarded as the result of increasing land competition there.

The Austrian Alps are characterized by different settlement structures. While most of them can also be found outside the Alps, ribbon-like settlement structures with high population densities in the main valley areas (e.g., Rhine valley, Innsbruck urban region) (Schindelegger et al., 2022), scattered settlements on slopes and hillsides (permanent and recreational) as well as tourist resorts with urban characteristics, can be regarded specific to Alpine regions. Major differences compared to settlement development outside the Alps are caused by specific framework conditions including the limited area suitable for development, topographic barriers to infrastructure provision, the potential exposure to various natural hazards (Fuchs et al., 2015b; Meyer and Job, 2022) and of local significance high development pressure from tourism. These conditions also have a significant impact on the transport systems and, thus, the mobility patterns in the Alpine areas compared to the rest of Austria (Tomschy et al., 2016).

Demographic changes, including changes in population and households, reflect existing structural and economic disparities among Alpine regions. Furthermore, demographic changes are a major driver of settlement and infrastructure development. Available data on population development for the period 2011–2021 (Österreichische Raumordnungskonferenz, 2023c), indicate a divide in the Austrian Alps with a population increase in the western part (i.e., Vorarlberg, Tyrol except for East Tyrol, Salzburg except for Lungau) and population decline in the eastern and southern part. Population data at the municipal level for 2011–2021 indicate population growth in all urban regions and, for the western part of the Austrian Alps, also in the main valleys. In the western part of the Austrian Alps, municipalities in side valleys and peripheral locations show a smaller increase and in some cases a decrease in population. In the eastern part of the Austrian Alps, population growth is mainly limited to urban and regional centers. These regional migration trends from side valleys to main valleys and from rural regions to urban and regional centers have also been observed in previous decades (Österreichische Raumordnungskonferenz, 2023c).

Population growth in Alpine regions affects the growth in all settlement types, with a greater impact on the expan-

sion of building land in ribbon-like structures. A decrease in population results in vacant buildings rather than a reduction in built-up areas.

Urban influences outside of cities and ribbon-like settlement structures can be found in distinct tourism locations where urbanization processes occur selectively, on a small scale and far from existing urban areas (e.g., Sölden, St. Anton am Arlberg), a phenomenon referred to as micro-urbanization (Chai and Seto, 2019).

These demographic and spatial characteristics of alpine areas together with natural features suggest that climate change may have different impacts that require alpine-specific adaptation and that the potential for mitigation may also differ from non-mountainous areas in Austria. These aspects are analyzed and discussed in the following sections.

An economic activity of above-average importance in the Austrian Alps compared to the rest of Austria is tourism. As landscape attractiveness and perceived naturalness are important resources for tourism (Romeo et al., 2021), the Austrian Alps offer good natural conditions for this economic activity. Abundant natural resources combined with limited economic alternatives in rural areas have led to the importance of tourism in the Austrian Alps. In Tyrol, the most tourism-intensive federal province of Austria, the contribution of tourism to the gross regional domestic product is 14.9 % if only direct effects are considered, or 19.7 % if indirect effects are also included (Fritz et al., 2021). Due to the importance of climate-sensitive natural resources, climate change is considered a major challenge for mountain tourism (Steiger et al., 2022) (*high confidence*).

The labor market in the Alps differs when it comes to employment opportunities in tourism. The alpine tourism labor market is characterized by high seasonality and many part-time jobs. Therefore, finding and keeping qualified workers is an evident problem in the hospitality industry in the Alpine region (Heimerl et al., 2020). While the demand is increasing, the seasonal labor force, which is needed for winter tourism, is decreasing (Humer and Spiegelheld, 2020). Unattractive working conditions, difficulty in finding housing in ski resorts, labor law issues and climate change, leading to uncertainty and a possible shorter season are mentioned as the main reason for this development (ORF, 2023). Furthermore, the dismissal of seasonal workers at the beginning of the pandemic may have damaged the image of workplaces in tourism (Mayer et al., 2021). To counteract the shortage of staff, improving the working atmosphere, the attractiveness of the job and the payment were found to in-

crease occupational commitment in response to staff shortages (Schwaiger and Zehrer, 2022).

7.3. Manifestation of climate change in the Austrian Alps

The manifestation of climate change in the Austrian Alps is presented in the following sections starting with a description of past climate change, followed by a subchapter focusing on the future climate change in the area.

7.3.1. Past climate change in the Austrian Alps

Past climate in the Austrian Alps has been described by observations since about 1770 (see [Section 1.2.1](#)), but observation networks at higher alpine sites are less dense and have been established more recently (e.g., Hochobir, 2,140 m a.s.l., in 1851). As a result of the ZAMG HISTALP-initiative (GeoSphere Austria, 2017) and later projects, the description of past climate in the Austrian Alps is based on an outstanding database and related analyses.

The **air temperature** in the Alpine region has increased relatively homogeneously in space by 2°C since pre-industrial times (3.1°C for year 2024, see [Section 1.2.1](#)), which is about twice as much as on the global scale (Auer et al., 2014; Olefs et al., 2021). Individual months have shown weak signals of an altitude dependence of the warming in the Alps, which, however, averaged out when analyzed on an annual basis (Auer et al., 2014; Tudoroiu et al., 2016).

In contrast to temperature change, **precipitation** change varied both seasonally and spatially in the Alpine region (also within Austria) (Auer et al., 2014; Olefs et al., 2021). A dichotomy (e.g., increase of precipitation in the north, decrease in the south in winter) (Auer et al., 2007) reflects the effect of the Alps as a barrier on atmospheric circulation and thus on precipitation. The accuracy of precipitation measurements decreases significantly with increasing altitude. A high-resolution climate model experiment (Ménégoz et al., 2020) forced by ERA-20C for the period 1903–2010, confirmed the precipitation increase in the northern Alps in winter and suggested accelerated increase at higher elevations, whereas drying in summer was decreased or even not significant at higher elevations. Overall precipitation trends in Austria vary seasonally and spatially, with a general wetting trend in the north in winter and only a weak trend or a general decreasing trend in the north and south in summer (*robust evidence*). Moreover, the wetting intensity increases

with altitude in the north in winter and decreases with altitude in summer (*low confidence*). Generally, the confidence in spatio-temporal trends of precipitation decreases significantly with altitude.

The increase in **air temperature** has led to a vertical shift of the **zero degree line** (temporal trends transferred from Switzerland, north: 133 ± 40 m/decade, south: 118 ± 37 m/decade, for the period 1984–2018) (Scherrer et al., 2021), as well as the **snow line** by 42 ± 26 m/decade in the north and 88 ± 44 m/decade in the south (Hu et al., 2020). In an earlier work, Hantel et al. (2012) estimated a temperature sensitivity of the median snowline of 166 m/°C for 1961–2010. This has significantly reduced the proportion of snow precipitation at high elevations in the Alps, especially in the summer. The associated effects on the energy balance at the Earth's surface (**albedo** lowering) have led to a significant increase in the snow and ice melt (snow cover, glaciers, permafrost) in the Austrian Alps (Olefs et al., 2021; Schöner et al., 2019) (for glaciers and permafrost, see also Section 7.4.1). However, the dependence of the winter snow cover was also strongly influenced by weather conditions and precipitation amounts. This means that the change in mean snow depth in Austria varied spatially. A significant decrease in the south (-12 cm/decade) contrasted with only a slight decrease in the north-east resulting in an overall trend for Austria of -3 cm/decade for 1961–2020. Mean snow depth trends at low elevations have been driven by changes in air temperature, while those at the highest elevation sites of the Austrian Alps have been driven by precipitation changes (Schöner et al., 2019).

In summary, regarding the snow in the Alps, temperature increase has led to an increase of zero-degree line altitude by about 130 m/decade in the northern part of the Alps and by about 120 m/decade in the southern part of the Alps (derived for 1984–2018) (*medium evidence, low agreement*). Compared to the zero-degree line elevation the increasing trend of the snowline was much weaker for 1984–2018, with about 40 m/decade in the north and 90 m/decade in the south (*medium evidence, low agreement*). Snow depth has generally decreased in the Austrian Alps over the last 50 years but with clear spatial patterns (strongest decreasing trend in the south and non-significant trend in the northeast (*robust evidence, medium agreement*)).

High-quality measurements of radiation in Austria have only been available since 2012 (ARAD Measurement Network) (Olefs et al., 2016). Measurements of sunshine duration (as a proxy for global radiation dating back to the 1880s in Austria) showed a clear increase since about 1980, especially in summer (see Section 1.2.1). Altitude-depen-

dent effects are difficult to interpret due to data uncertainty and small differences in measurements. A recent study by Correa et al. (2022) detected a west-east trend in surface solar radiation in the Austrian-Swiss Alps. The trend was positive/negative in the east/west for the period 1980–1995, but negative/positive for the east/west for the more recent period of 1996–2015 (see also Section 1.2.1). According to Correa et al. (2022), trends of surface solar radiation at low elevations were likely driven by clear sky forcing, while at high-elevation sites cloud optical properties and surface albedo seemed to be the main drivers of the trends.

7.3.2. Future climate change in the Austrian Alps

Given the rugged terrain and correspondingly steep horizontal gradients, even the 'high-resolution' CORDEX simulations (see below) are too coarse to adequately resolve the relevant atmospheric processes over mountainous terrain like the Alps (Rotach et al., 2022). Climate simulations are therefore more challenging and have potentially greater uncertainties than those over flat terrain (Rotach et al., 2022).

The most comprehensive information on the possible development of climate variables comes from so-called ensemble simulations. For the Alpine region they stem from EURO-CORDEX (Jacob et al., 2020), an initiative under the umbrella of the World Climate Research Program of the WMO, in which coordinated numerical experiments are carried out. The coordination concerns the emission scenarios, the grid spacing, the time span, etc. so that the results are comparable. The latest EURO-CORDEX results are available for 3 scenarios (RCP2.6/4.5/8.5) and for medium resolution (about 50 km grid spacing) and high resolution (about 12.5 km grid spacing). For the Alpine region, an update and extension of the earlier work of Gobiet et al. (2014) and Smiatek et al. (2016) is presented by Kotlarski et al. (2023), with a special focus on characteristic areas (ALPS NW, ALPS NE, ALPS S – and all three considered together as ALPS). The Austrian Alps are best represented by ALPS NE, so the numbers given below refer to the results for this region, where available. In this study, 24 RCM simulations of high resolution for scenarios RCP2.6/4.5/8.5 are used and evaluated for the 'climate period 2070–2099' (as 'end of the 21st century'). Temperature, precipitation and snow cover (i.e., snow water equivalent, SWE) are considered. The results of these studies are translated to Global Warming Levels (GWLs) below.

Within the CORDEX framework, a Flagship Pilot Study (CORDEX-FPS) with convection-permitting (resolving/allowing) or 'kilometer-scale' dynamical downscaling ex-

periments (from about 12.5 km to a few km grid spacing) has been established (Coppola et al., 2020), which also has the ‘greater Alpine region’ as a focus. Due to the immense requirements of computing power, the resulting ensemble simulations typically consist of fewer members and are performed as ‘time-slices’ for the reference period (‘current climate’ 1996–2005), mid-century (2041–2050) and end-of-century (2090–2099) 10-year periods. Initial analyses focus on the validation (Ban et al., 2020, 2021, for precipitation; Soares et al., 2024, for temperature) of the current climate. Pichelli et al. (2021) is the first available study using the CORDEX-FPS to assess future climate change signals for precipitation in the Alpine region.

Single-model future climate simulations for the Alpine region at the km scale are furthermore available and typically focus on specific variables (Ban et al., 2015, 2020 – precipitation; Lüthi et al., 2019 – snow cover; Vergara-Temprado et al., 2021 – sub-hourly precipitation; Peleg et al., 2022 – spatial storm structure).

In summary, the general characteristics of the future climate in the Austrian Alps are as follows:

Regarding the **temperature**, a consistent increase is expected in all regions, in all seasons (all models) (*high confidence*) (Figure 7.3). The magnitude strongly depends on the scenario. Temperature changes are elevation dependent: Simulation studies consistently find a stronger heating signal at higher elevations – but the details (seasonal behavior) depend on model choice and resolution (Lüthi et al., 2019) (*medium evidence, low agreement*).

Concerning **precipitation**, the mean annual precipitation amount does not show a clear signal because it is the result of a seasonal redistribution (Figure 7.4): A decrease in summer precipitation and an increase in winter precipitation (*medium evidence, high agreement*). The magnitude of the (seasonal) changes is strongly dependent on the forcing (strongest for RCP8.5, which corresponds to a GWL of 3.8°C for the shown period 2070–90, shown in Figure 7.4) and strong signals are only emerging in the second half of the century

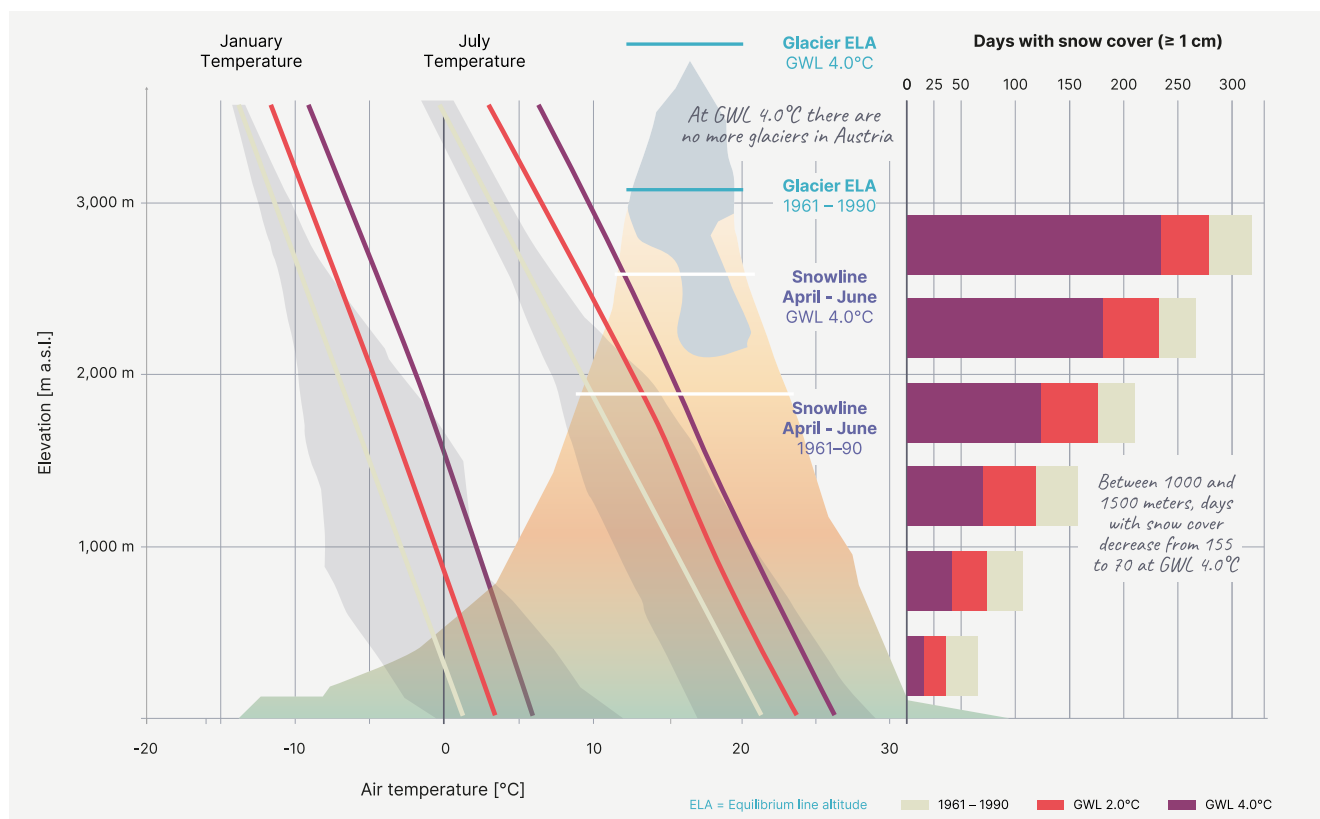


Figure 7.3 Synthesis for key variables of altitude-dependent climate change in the Austrian Alps for the future compared to the 1961–1990 reference (1984–2018 for the snow line). The altitude dependence of the air temperature for January and July is taken from Hiebl et al. (2009), with the variation within the Alps shown by the shaded areas in light gray. The median temperature increases for GWL 2.0°C and GWL 4.0°C were derived from Kotlarski et al. (2023), based on the EURO-CORDEX cmIP5 ensemble for the Alps. Days with snow cover (>1 cm) for 1961–1990 and for GWL 4.0°C are taken from Chapter Box 1.1 of this report (derived from the FUSE-AT project). The snow line estimates (period April to June) are satellite data analyzed by Hu et al. (2020), using the values for the Salzach catchment and the temperature sensitivity of the snow line from Hantel et al. (2012) to project the snow line for GWL 4.0°C. The equilibrium line altitude (ELA) of glaciers in the Alps for 1961–1990 and for GWL 4.0°C is based on the study by Žebre et al. (2021).

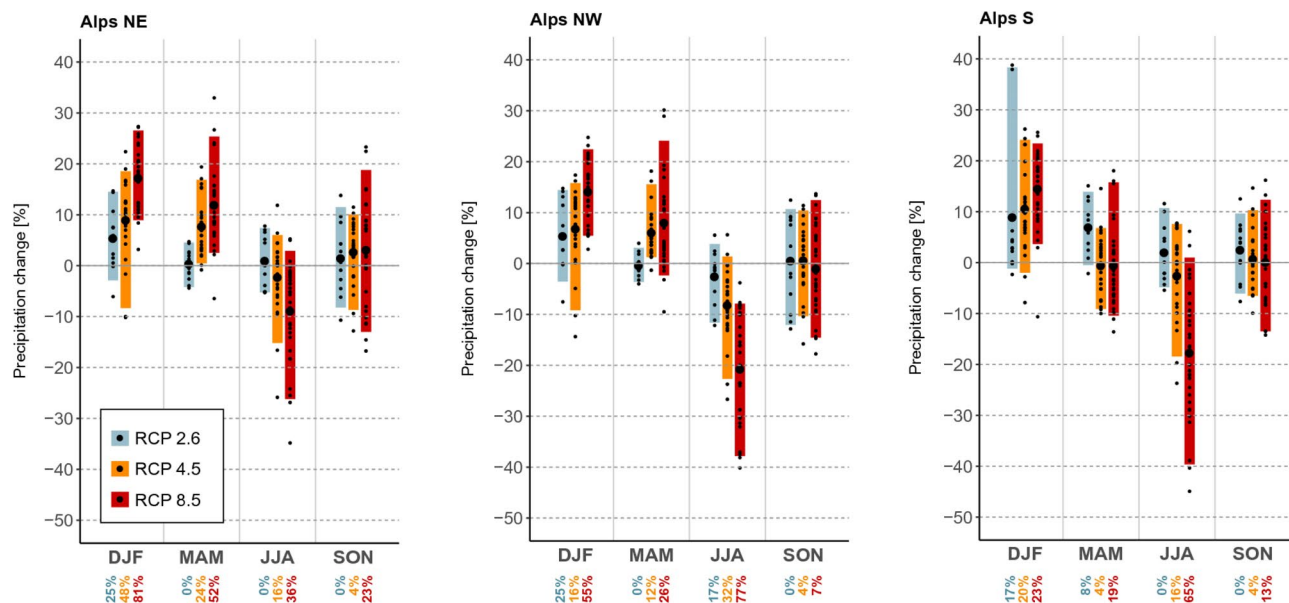


Figure 7.4 Future precipitation changes in the Alps. The figure shows change of seasonal mean precipitation [%] between 1981–2010 and 2070–2099 in the three sub-domains and for the three emission scenarios RCP 2.6, 4.5 and 8.5. RCP 4.5 is equivalent to a GWL 2.2°C, RCP 8.5 to a GWL 3.8°C. Small dots refer to the individual simulations of the full model ensemble (EUR-11 and EUR-44, based on the EURO-CORDEX cmlP5 ensemble), bold dots to the multi-model ensemble mean. Colored bars indicate the ensemble uncertainty range as given by the lower (p5) and upper estimate (p95). The numbers below the panels refer to the percentage of simulations (rounded to full numbers) in the respective ensemble that shows a statistically significant change of seasonal mean precipitation (two-sided unpaired t test, p value of 0.05) (figure from Kotlarski et al., 2023).

(*medium confidence*). The winter increase is accompanied by a shift from solid to liquid, thus resulting in a reduction of 20–40 % in seasonal (Sept.–May) snow amount (Frei et al., 2018) (*limited evidence, medium agreement*). Summer precipitation is characterized by a decrease in the precipitation frequency and number of precipitation ‘events’, while the intensity of extreme events increases (Ban et al., 2020, 2021) (*medium confidence*).

Regarding the snow cover (measured as snow depth), there is an overall consistent decrease in seasonal snow cover, that is strongly scenario-dependent (strongest in RCP 8.5 of course) (*high confidence*). Future changes in snow cover are expected to be strongly elevation-dependent (*high confidence*). Changes for the Austrian Alps are assessed by the Fuse-AT project (Gobiet, 2021). Snow cover days (SCD) in Austria will continue to decrease by 10–15 days under GWL 2.0°C and by 60 to 80 days under GWL 4.0°C. A case study for Obergurgl (Ötztal) by Kotlarski et al. (2023), shows that in the scenario with the highest emissions, the reduction in the number of snow days at 1,920 m a.s.l. (Obergurgl) leads to a reduction in season length: -40 % by 2050, -80 % by 2100; in the ski area (i.e., at 2,500 m a.s.l.), the changes are -10 % by 2050, -35 % by 2100 (not including artificial snow production).

7.4. Impacts of climate change on the Austrian Alps

7.4.1. The Alps as natural environment

The hydrosphere and cryosphere

A detailed assessment of the impacts of climate change on the hydrosphere, including runoff generation processes, magnitude, seasonality, and frequency of fluxes in streams, is presented in detail for Austria in Section 1.4. The most important impacts are briefly summarized here, where possible with a special focus on the Alpine region.

The role of the Alps as a water tower for downstream areas, even far away from the Alps, has been discussed for a long time, but it is only in the last decades that it has been thoroughly documented by quantitative studies (Viviroli et al., 2007; Rounce et al., 2023). For Austria and even more for Central Europe, the influence of the Alps on the water cycle is evident from the climatic water balance, which is positive with an average of 466 mm for the period 1981–2010 (Haslinger et al., 2023) (*high confidence*), and from the comparison of the runoff contribution to the area-related moun-

tain share of individual river basins. Such a comparison shows that the runoff contribution exceeds the area share (33 to 17 % for the entire Danube catchment, 38 to 21 % for the entire Rhine catchment) (Messerli et al., 2004) (*high confidence*).

Hydrological regimes of mountain regions are expected to be strongly affected by climate change by 2050 and further altered by the end of the 21st century, as also shown by several studies for the Austrian Alps (Eitzinger et al., 2014; Nachtnebel et al., 2014; Laaha et al., 2016; Blöschl et al., 2018; Pistotnik et al., 2020; Schöner and Haslinger, 2020; Hanus et al., 2021). Generally, future surface water availability is characterized by both a more positive water balance and an increase in temporary droughts. Changes in precipitation and snowmelt are the main drivers of this future water balance alteration in Austria (Haslinger et al., 2022). Increasing air temperature leads to an increase in evaporation, exacerbating the summer low-flow situation. A more rapid decline in runoff is expected in the spring, resulting in an earlier start of the summer low-flow period. The winter months are characterized by an upward shift of the snow line elevation and a weakening of frost processes (*high confidence*), resulting in a higher low-flow discharge. Snowmelt is shifted towards winter, changing the annual runoff pattern (Blöschl et al., 2011a). Trend projections of runoff under different climate scenarios consistently show increasing low flows (Q95-values) of about 10–30 % by 2021–2050 (Blöschl et al., 2011a; Eitzinger et al., 2014; Nachtnebel et al., 2014; Laaha et al., 2016; Pistotnik et al., 2020; Schöner and Haslinger, 2020) (*high confidence*) and a decrease of the mean summer runoff of up to about 10 % by 2050 (Blöschl et al., 2011a, 2011b, 2018) (*limited evidence, high agreement*). These changes are expected to intensify by the end of the 21st century (Blöschl et al., 2011a, 2011b, 2018) (*medium evidence, high agreement*). Glaciers can significantly dampen the low-flow discharges during summer in the Alpine basins of rivers such as the Salzach, Inn or Ill (Koboltschnig et al., 2008; Koboltschnig and Schöner, 2011; Stahl et al., 2022) but with a decreasing meltwater contribution in the future, as many glaciers in the Austrian Alps have already passed their peak (Wimberly et al., 2024).

Recent updates of mean flow conditions for Austria, which represent the average water availability in the catchment as the difference between precipitation and evapotranspiration, have been provided by Duethmann et al. (2020). They found an increase in annual precipitation totals of approximately 120 mm over the last 35 years. This increase offsets a rise in evapotranspiration of approximately 110 mm over

the same period, resulting in nearly unchanged mean runoff conditions. In particular, an increasing trend in mean flow conditions has been observed in the Alps. Regarding future conditions, Blöschl et al. (2017) and Haslinger et al. (2023) reaffirm the water balance assessment of the previous AAR14 report as largely valid. They anticipate an increase in winter runoff in the Alps due to a shift in snowmelt to winter and a higher proportion of liquid precipitation.

Flood events, triggered by significant and/or intense precipitation, combined with antecedent snow and wet conditions, as well as complex runoff generation processes, have increased significantly in 21 % of Austrian catchments for the period 1978–2020, especially in small catchments north of the Alpine ridge (Blöschl et al., 2017; Laaha et al., 2025). The trend averages +11.8 % in 43 years (+2.7 %/decade), with more pronounced values in the winter period (5.2 %/decade; see [Section 1.4.1](#)).

Given the physical reasons for a 7 % increase in the intensity of heavy precipitation events per degree Celsius, the current positive trends in hourly precipitation totals or extreme precipitation (98th percentile) are likely to persist (see [Section 1.2.1](#)). While some of the heavy precipitation-related weather patterns are expected to become less frequent in the coming decades, they may produce heavier amounts when they do occur (Blöschl et al., 2017). However, all projections of heavy precipitation are highly uncertain due to limitations in the model representation of convective processes. Blöschl et al. (2017) summarize the projections of climate change on future floods as follows: (i) Seasonal changes in precipitation will hardly impact HQ100 except in areas with increasing intensity of convective summer events; (ii) An increase in intense convective events may potentially increase floods throughout Austria; (iii) There will be a minimal effect on floods from a rise in the snow line; (iv) Earlier snowmelt and the resulting lower summer runoff coefficient, as well as higher evapotranspiration, will slightly reduce flooding; however, (v) floods (HQ100) along the northern rim of the Alps show hardly any change. Systematic investigations of pluvial floods over Austria or the Alpine region are currently limited and certainly deserve further attention.

Low flow generation is primarily attributed to freezing and temporary snow storage during the winter months, contrasting with summer precipitation deficits in the lowlands below 900 m a.s.l. (Laaha and Blöschl, 2006). During summer heatwaves, the water sectors can suffer significant impacts, while potential threats to ecosystems exist, e.g., due to high water temperatures during low flow conditions (see [Section 1.4.1](#)).

In recent years, low flow trends have become more pronounced, particularly in Alpine catchments. Drying trends, characterized by decreasing Q95-values (the 5th percentile of daily runoff), have been observed in the lowlands. Conversely, in alpine catchments above 900 m a.s.l., wetting trends with increasing low flow conditions prevail (Laaha et al., 2016) (Section 1.4.1). Moreover, the magnitude of mean low flows has intensified, with a decrease of 3.9 % per decade in lowland areas and an increase of 5.3 % in high-elevation catchments for the period 1977–2018 (Laaha et al., 2016; Blöschl et al., 2017). While future low flow scenarios for Austria yield different results, a significant increase of 10–15 % is projected for the Austrian Alps.

Changes in Austrian glaciers have been continuously monitored for more than a century documenting climate-induced glacier change in one of the longest records worldwide. Recent projections of future glacier change indicate a loss of 80–100 % of glaciers in the Central European Alps under warming scenarios between +1.5°C and +4°C (Rounce et al., 2023). Most of the ice loss will occur by 2050 and ice melt will increase significantly at elevations below 3,200 m a.s.l. (Zekollari et al., 2019; Sommer et al., 2020; Cook et al., 2023) (*high confidence*). Glaciers in Austria are located at lower elevations compared to the Western Alps (Switzerland, France) (Fischer et al., 2015; Sommer et al., 2020) indicating that their disappearance is expected to occur earlier than in the Western Alps (*high confidence*). Debris cover on glaciers can significantly delay the ice melt at individual glaciers and impact local changes in glacier runoff. Currently, debris cover on glaciers in Austria is increasing (Fleischer et al., 2021) (see Section 1.3.2).

The melting and disappearance of glaciers affect mountains in a variety of ways ranging from landscape changes, river runoff, slope stability, and biodiversity to tourism. Effects will occur at different temporal and spatial scales, and some impacts will show a transition towards new conditions once the glacier has melted. On-site impacts of glacier retreat locally modify previously ice-covered ground at high elevations. These impacts include the reworking of proglacial sediments and an increased sediment supply into rivers (Lane et al., 2017), the establishment of biodiversity through the colonization of ice-free ground, and the formation of new glacier lakes. The number of glacier lakes above 1,700 m a.s.l. has increased over the past century with formation rates increasing over the past 20 years (Buckel et al., 2018). This trend is expected to continue with lakes forming at higher elevations (Otto et al., 2022) (*medium evidence, low agreement*).

Glacierized catchments in Austria are considered to have passed the point of peak water beyond which runoff decreases due to decreasing glacier volume. For the major rivers draining the Alps (Danube, Rhine, Rhone, Po), peak water was reached in 2006 and glacier melt contribution to runoff has decreased since then (Huss and Hock, 2018). Ongoing glacier melt will lead to a seasonal shift of the glacier runoff peak from late summer to early summer towards the middle of the 21st century (Hanus et al., 2021). For example, the runoff contribution from glaciers in the Danube catchment is estimated to decrease by up to 60 % in August, September and October in 2090 (Huss and Hock, 2018).

Steep bedrock slopes and cirque headwalls may experience an increase in slope instabilities, such as rockfalls, as a result from the debuttressing of slopes and changing temperature conditions following glacier melt, as has been reported in a case study at Kitzsteinhorn (Hartmeyer et al., 2020). These slope instabilities may affect high alpine infrastructure and are likely to increase as glaciers continue to melt (*medium evidence, low agreement*) (Cross-Chapter Box 1).

Locally, rockfall events associated with glacier melt are interfering with changes in permafrost conditions. The distribution and temperature conditions of permafrost in Austria are largely unknown and limited to restricted areas (Schrott et al., 2012; Kellerer-Pirklbauer, 2019; Rode et al., 2020). Due to the diverse landscape patterns of the Austrian Alps, permafrost occurrence is highly fragmented and not exclusively limited to the upper altitudinal zones of the mountains. In the Hohe Tauern Range, permafrost occurs at elevations above 2,500–3,000 m a.s.l. on the northern and southern slopes (Schrott et al., 2012). Isolated patches of permafrost are reported from extreme locations at altitudes around 1,000 m a.s.l. (Stiegler et al., 2014). Borehole temperatures at permafrost sites throughout the European Alps show an increase in permafrost temperatures even at depths of 20 m (Biskaborn et al., 2019; Haberkorn et al., 2021). Existing borehole data from Austria report permafrost temperatures around -2 to -1°C at about 10 m depth (Schöner et al., 2012; Hartmeyer et al., 2020; Greilinger et al., 2023; Hartmeyer, 2023) and a near-surface increase of 0.1°C/yr (Hansche et al., 2023; Hartmeyer and Otto, 2024). Considering the ongoing rise of air temperatures, the permafrost area is likely to decline significantly (Chadburn et al., 2017; Magnin et al., 2017). Bedrock temperatures in Austria are likely to increase towards zero degrees in the coming decades (*medium evidence, high agreement*). In unfavorable locations, bedrock temperatures close to zero degrees

may lead to reduced slope stability, which favors increased frequency of rockfall processes and increased hazard potential at higher elevations (Haerberli et al., 2017) (*medium evidence, high agreement*). As glaciers continue to melt, water storage and discharge from permafrost landforms such as rock glaciers will become increasingly important. Rock glaciers in Austria are assumed to contain up to 2 km³ of freshwater and are capable of storing additional resources for several months (Wagner et al., 2021). Rock glaciers are assumed to be less affected by warming due to the protective effect of the rock above the ice content (see [Section 1.3.3](#) and [Cross-Chapter Box 1](#)).

The (terrestrial) biosphere

Within the Austrian Alps, two main zones can be distinguished with regard to the predominant vegetation types and human land use: (i) The valley bottom and the adjacent cultivated grassland and forest area upslope to the climatic forest line, comprising the montane belt and the lower part of the subalpine belt (addressed in [Section 2.2](#)); (ii) The high mountain area from the tree line ecotone to the highest elevations, comprising the upper part of the subalpine, the alpine, subnival and nival zones (see below). For consistency reasons, only the area above the timberline is considered in this section, whereas forests and agricultural areas are dealt with in [Section 7.4.2](#).

Due to their difficult accessibility and low temperatures, the Alps remain the only large more or less contiguous area of Austria, where ecosystems have not been completely or predominantly transformed into landscapes of intensive agricultural production, forest plantations, settlements, transport, commercial and industrial infrastructure. As the Alps cover more than 65 % of Austria, the country contains larger proportions of forested areas, mountain valleys, interspersed traditional cultural landscapes and naturally treeless alpine ecosystems than anywhere else in central Europe.

Effects of climate change above the tree line (high mountain area)

The area above the tree line comprises the majority of unmanaged land in Austria, where settlements and traditional land use practices cease and give way to naturally treeless alpine landscapes. However, the area above the tree line in the Austrian Alps is only partly unmanaged and partly used for tourism and low-intensity livestock grazing, mainly in the lower alpine zone, but occasionally extending to

above 3,000 m a.s.l. (Grabherr and Ringler, 2018). For the Alps as a whole, 29 % of its mountainous area lies above the elevation of 2,000 m and 10 % above 2,500 m a.s.l. (Körner, 2007). A similar proportion can be assumed for the Austrian Alps. On the European level, alpine ecosystems cover only 3 % of the continent, however, they are exceptionally rich in biodiversity. About 20 % of the continent's native vascular plant species have been reported to have their center of distribution in this area (Väre et al., 2003). In contrast to the Scandinavian mountains, which contain the largest proportion of alpine land, the Alps and the European mountains further south, host the largest proportion of endemic mountain species (Pauli et al., 2012). Austria, therefore, bears a great responsibility for the preservation of biodiversity in Europe's high mountain biome. Even if the immediate urgency of nature conservation measures in the high Alps is currently less pressing than in the small, fragmented and highly endangered remnant areas of the lowlands, the issue of nature conservation is a priority in alpine areas – particularly in the context of climate change. This is because climate change effects are pervasive and affect the most remote parts of the Alps. In addition, mountain areas such as the Austrian Alps will rapidly gain in importance as refugia for natural biota and in attractiveness for humans, who are increasingly suffering from a hotter and probably drier environment in the surrounding lowlands (Beniston et al., 2018). The low temperature regime, including a short growing season, is the strongest ecological factor determining ecosystems in the Alps and is the main ecological filter preventing the growth of woody plants (shrubs, trees) in the alpine zone (Körner, 2021). In addition, the amount of precipitation, especially the duration of snow cover, influences the position of the tree line. In the outer ranges, such as the northern, northeastern and southern Limestone Alps, the tree line is several hundred meters lower than in the central Alps due to higher rainfall and snow loads as well as fewer hours of sunshine ([Figure 7.1](#) and [Cross-Chapter Box 1](#)). Climate change leads to changes in the distribution patterns of species, of their interactions and community compositions. Differences in species' abilities to cope with rapid climate change, such as different rates of movement, and capabilities to newly establish and compete with new neighbors, are expected to result in substantial biodiversity losses (Alexander et al., 2015; Lenoir and Svenning, 2015) (see also [Cross-Chapter Box 1](#)). Climate warming affects all parts of the Austrian Alps, regardless of their remoteness, by shifting the low temperature filter uphill and from southern to northern

slopes. This has several implications for biota living in, and in many cases confined to, mountains:

(i) An upward shift of vascular plant species leads to increased species numbers, but also to competitive displacement of dwarf-growing light-demanding alpine plants by taller plants from lower elevations. Accelerating rates of plant species colonization at summit habitats at high elevations have been found to be highly synchronized with rising temperatures. This pattern was consistent across temperate to northern Europe, including the Alps and the Arctic (Steinbauer et al., 2018) (*high confidence*). The warmer slopes (i.e., the southern and eastern sides of the mountains) showed the highest number of vascular plant colonizations (Winkler et al., 2016) (*medium evidence, high agreement*) and in the Eastern Alps movement rates of 17–40 m of upward shift per decade have been reported (Vitasse et al., 2021). Besides the previously observed upslope shifts of upper range margins of species (Pauli et al., 2012), a more recent study showed that the lower range margins of vascular plants and the optimal ranges of plant species have been moving upslope, at least as fast as the upper range margins in the Eastern Alps (Rumpf et al., 2018) (*medium confidence*). Species of other organism groups have also been found to shift upward (*limited evidence, high agreement*) such as butterflies, albeit with concurrent declines in abundance (Kerner et al., 2023), and fruiting bodies of fungi (Diez et al., 2020). See Section 1.6.4 for further references on the upward shift of different taxonomic groups in Austria.

(ii) Changes in species abundances are generally a faster response than actual range shifts, however, detailed historical data for comparison are scarce. An increasing abundance of alpine vegetation has been detected by remote sensing techniques, showing a greening (i.e., productivity gain) in 77 % of the European Alps above the tree line, while <1 % showed a browning (productivity loss) (Rumpf et al., 2022). Increasing greening can be caused by the promotion of more warmth-demanding and more vigorously growing plants at the expense of the cold-adapted species. This process, first described for alpine areas as thermophilization by Gottfried et al. (2012), has been repeatedly confirmed in the Austrian Alps (Lamprecht et al., 2018) (*high confidence*). Plant species adapted to very cold conditions (cryophytes) continued to decline in abundance (Lamprecht et al., 2018) (*medium evidence, high agreement*). This dieback may have been caused by overly warm conditions, leading to direct physiological disadvantages for the cryophytes due to their inability to down-regulate dark respiration under warmer conditions, leading to a rapid loss of carbohydrates (Larigauderie and

Körner, 1995; Steinbauer et al., 2020) (*limited evidence, medium agreement*).

(iii) Further, a shift to longer growing seasons will change the duration of phenological development stages (Beniston et al., 2018). Leafing and flowering have occurred an average of 2.4–2.8 days/decade earlier over the past four decades (Vitasse et al., 2021), which can lead to both exposure to late frost events and mismatches in plant-pollinators interactions (*medium evidence, high agreement*). Earlier snowmelt is expected to have a strong influence on soil microbial life, because snowmelt triggers an abrupt transition in the composition of soil microbial communities, as has been confirmed by experimental snow cover manipulations in the Tyrolean Alps (Broadbent et al., 2021). This is closely linked to shifts in soil microbial functioning and biogeochemical pools and fluxes. Further, earlier snowmelt due to climate change could disrupt the synchronized seasonal dynamics of nutrient exchange between plant and soil microbiota, i.e., microbial organisms depend on carbon supply, plants on labile forms of nitrogen, which show strong seasonal variations (Bardgett et al., 2005; Bardgett and van der Putten, 2014) (*limited evidence, high agreement*). Some vertebrate species, such as the mountain hare (*Lepus timidus*) and the rock ptarmigan (*Lagopus muta*), undergo seasonal color change from brown to white for reasons of camouflage, which is mainly controlled by the photoperiod. Earlier snowmelt can, therefore, be detrimental for these species, as they become easily detectable prey (Zimova et al., 2018).

There is some debate regarding the extent and immediacy of the threat to high mountain species from climate change. Some authors argue that a rugged topography and the resulting variation in microclimate provide a buffer against the threatening effects of climate change, as plant and animal species may be able to find suitably cold refugia in nearby upslope or less sun-exposed locations (Körner and Hiltbrunner, 2021). Others point out that the high topographic variation and elevation differences in mountains have favored orographic isolation and thus the generation of many small-ranged endemic species (Dirnböck et al., 2011). In the Austrian Alps, endemic plant and animal species are concentrated in the subalpine to alpine zone of marginal mountain ranges, such as the northeastern Alps, which remained unglaciated during the Pleistocene, but where potential refugia are very limited due to lower elevations compared to the Central Alps (Semenchuk et al., 2021). Increasing warming-induced fragmentation and shrinkage of alpine areas and the associated competitive displacement of alpine plants by taller and more vigorous plants from lower

elevations, are therefore expected to accelerate extinction processes (Wessely et al., 2017). The generally slow-growing, but often long-lived, alpine plant species may persist in their increasingly climatically unsuitable habitats, but with declining populations until they reach their lifespan (Cotto et al., 2017), i.e., when their extinction debt is paid off (Dullinger et al., 2012; Alexander et al., 2018). In the case of the high central part of the Alps, from the Hohe Tauern westward, cold-enough refugia will be more abundant, however only in scattered patches where soil substrates are available (Kulonen et al., 2018). Moreover, even if such refugia did exist in nearby locations, the pronounced topographically determined variation in meso- and microclimates could form abrupt climatic barriers to the colonization of new habitats, e.g., toward a nearby north-exposed slope (Dobrowski and Parks, 2016). In this context, a recent study from the Stubai Alps suggests that the mesoscale topography and the overall elevation gradient are stronger determinants of plant distribution than the microscale (Chytrý et al., 2024), which does not support the hypothesis of climate change buffering effects through topographic variation. The role of the Alps as a biodiversity refugium and/or as a trap is an understudied topic (*medium evidence, low agreement*).

There is *medium evidence* but *high agreement* that shrub and forest vegetation will advance to currently treeless zones and thus outcompete dwarf-growing alpine species (Lenoir and Svenning, 2015). Yet, in the Alps, only a small percentage of forest advance could be attributed to responses to climate warming, rather than to land abandonment because actual tree lines are positioned well below their climatic limits (Gehrig-Fasel et al., 2007). Similarly, the recent expansion of shrubs in subalpine areas, mostly of green alder (*Alnus alnobetula*), was mainly explained as a consequence of land abandonment (Caviezal et al., 2017; Hohensinner et al., 2021).

The situation is different in the alpine zone. Repeatedly confirmed warming-related species enrichments and upward shifts of alpine plants (Matteodo et al., 2013; Winkler et al., 2016; Steinbauer et al., 2020; Nicklas et al., 2021; Vitasse et al., 2021) (*high confidence*) are of immediate relevance for nature conservation. Especially the alpine areas at the margins of the Alps, where many endemic species live, are of great concern because their fragmented alpine areas are already very limited in space. Due to the conical shape of mountains, shifts of the lower range margins of plant species to higher elevations, as detected in data from across the Eastern Alps (Rumpf et al., 2018) and confirmed for several other organisms (Rumpf et al., 2019), can lead

to rapid declines and species extirpation (*medium confidence*).

Two other ecological factors may amplify the vulnerability of alpine biota to climate change. First, rising temperatures may lead to drier conditions even with unchanged precipitation, due to increased evapotranspiration. This would expose alpine plants that grow, for example, on the humid northeastern margin of the Alps, to a climate to which they are not adapted. Experimental studies in the Alps have shown that alpine plants are more affected by drought than their relatives at lower elevations (De Boeck et al., 2016; Rosbakh et al., 2017) (*medium confidence*). The second factor is the increasing availability of soluble nitrogen, which may favor colonization by more warmth-demanding plants from lower elevations, resulting in a competitive displacement of alpine species. An increase in widespread nitrophilous plants and a concurrent loss of small-ranged species has been observed in protected areas in lowland meadows, forest understorey vegetation as well as on alpine summits (Staudé et al., 2022). While soluble nitrogen deposition from industrial agriculture is expected to be the primary cause at lower elevations, a combination of warming, leading to increased nitrogen availability and nitrogen deposition may explain the situation in alpine areas. Many parts of the Alps currently receive many times the pre-industrial rates of soluble nitrogen deposition, even in areas above the tree line (Körner et al., 2021), and alpine habitats are typically oligotrophic and, thus, sensitive to nutrient additions (*medium confidence*).

Effects of climate change on conservation areas

The Austrian Alps host several protected areas including three national parks, three UNESCO biosphere reserves, two UNESCO geoparks and several nature parks, nature reserves (ALPARC, 2019a) and Natura 2000 areas. They are in a rather difficult situation, especially the smaller ones with limited vertical extent, in the face of the effects of anthropogenic warming and nutrient deposition. Refugial areas on the margins of the Alps are already very small, and regions where receding glaciers are opening up land for new colonization (Fischer et al., 2019) are usually far away from the areas of endemic species. Besides, the future area of glacier forelands will be too small (see [Sections 1.3.2 and 1.3.3](#)), with their lower parts located in alpine climates, and will therefore be rapidly colonized (Fickert and Grüniger, 2018). Progressive succession will lead to closed vegetation

(Fickert, 2020), leaving no space for cold-adapted species (*medium evidence, high agreement*).

Nevertheless, the role of mountain protected areas will multiply in importance, especially if they are extended over large elevation gradients and connected to corridor areas (Elsen et al., 2018). In this way, the potential of the Austrian Alps as a top priority biodiversity refugium can be significantly enhanced. An intact biosphere in the Alps will be decisive for the sustainable functioning of its ecosystems, such as water supply, slope stabilization, biodiversity refugium, and recreation. As warming and drought influence human activities such as tourist infrastructure, hydroelectric, wind, and solar power development, careful consideration of their impacts in the context of the biodiversity crisis is essential. Traditional grazing with low livestock numbers is important for the conservation of species-rich pastures in the montane zone and may slow down uphill migration of tall and competitive plants in the lower alpine zone, but additional inputs of manure or other fertilizers can rapidly lead to species impoverishment (Grabherr and Ringler, 2018). Under changing climatic conditions, protected areas in the Alps need to be more flexible, adapted to the local situation including the local population, and large enough to effectively protect biodiversity (ALPARC, 2019b; Job et al., 2022). Maintaining or rewilding alpine ecosystems and restoring parts of the forest belt (Pereira and Navarro, 2015) will become particularly important in the course of an amplifying climate crisis.

Natural hazards

The natural hazards described below are in line with [Table 1.A.3](#) and [Section 1.8](#). According to this table, rockfall and rock avalanches are particularly affected by climate change in high alpine regions. Furthermore, according to this table, all the hazards described below show an upward trend, except for snow avalanches, which show a diverse trend depending on the elevation.

River and torrential flooding

In the coming decades, climate change-induced changes in river flooding in Austria are expected to be relatively small compared to the observed natural variability (Blöschl et al., 2018; Blöschl, 2020) (*high confidence*) ([Section 1.4.1](#)). Large-scale (stratiform) precipitation events (especially due to Vb cyclones) (van Bebber, 1891; Messmer et al., 2015), which lead to large-scale flooding events, are not expect-

ed to increase in frequency (Hofstätter et al., 2015; Blöschl et al., 2018; Blöschl, 2020), while there are indications that summer convective precipitation is expected to increase over the Alps (Giorgi et al., 2016). The intensity of short heavy precipitation events is expected to increase in summer (Ban et al., 2015; Chimani et al., 2015; Hofstätter et al., 2015; Formayer and Fritz, 2016; Blöschl et al., 2018; Blöschl, 2020; Hanus et al., 2021) (*medium confidence*). The existing trend towards increasing magnitudes of small to moderate floods outside the summer season (especially of winter floods; [Section 1.4.1](#)) as well as the lengthening of the season of summer low-pressure systems with particularly high precipitation, is expected to increase in the Austrian mountain regions in the future (*medium confidence*), as it is expected in the Swiss mountain regions and on a European scale (Beniston, 2006; Blöschl et al., 2011a, 2011b; Hall et al., 2014; Nachtnebel et al., 2014; Beniston et al., 2018; Brönnimann et al., 2018; Pistotnik et al., 2020; Hanus et al., 2021; Schlögl et al., 2021; Laaha et al., 2025). Equally, extreme floods (return periods >10 years) are expected to occur in the summer and increase in intensity (Brönnimann et al., 2018) (*low confidence*).

Concerning torrential floods, studies on the Austrian Alps and comparable Swiss studies (Stoffel et al., 2014; Heiser et al., 2019; Prenner et al., 2019; Schlögl et al., 2021), do not show a clear trend for damage-causing processes despite increasing exposure of elements at risk (Fuchs et al., 2015b), partly due to a compensatory effect of an increasing number of technical protection measures. At medium elevations, rain-on-snow events may become more frequent by the end of the 21st century (Stoffel et al., 2014; Stoffel and Corona, 2018; Prenner et al., 2019), extending the debris flow and flood season into the March-December period (Stoffel et al., 2014; Prenner et al., 2019; Hanus et al., 2021). The likelihood of critical triggering conditions for debris flows may vary regionally and seasonally, extending to earlier in the year (Stoffel et al., 2014; Hirschberg et al., 2021; Kaitna, 2022) (*limited evidence, medium agreement*). Early season debris flows are expected to remain small, given the current climate and sediment potential, and to increase in size as rain-on-snow events become increasingly relevant. Late summer season events are expected to become more critical due to the increasing sediment potential (Stoffel et al., 2014) (*low confidence*).

From a local to regional perspective, the sediment potential is expected to increase at high altitudes where (i) glacier retreat, (ii) permafrost degradation and (iii) increased physical weathering occur. At medium elevations, sediment

potential may decrease due to weaker physical weathering, potentially causing decreased debris flow activity in sediment-limited catchments. The decrease in summer precipitation may increase sediment accumulation, potentially increasing the magnitude of debris flows (Lugon and Stoffel, 2010; Blöschl et al., 2011a; Sattler et al., 2011; Stoffel et al., 2011; Eitzinger et al., 2014; Gems et al., 2020; Kaitna et al., 2020; Hanus et al., 2021; Hirschberg et al., 2021; Kaitna, 2022; Maraun and Jury, 2022) (*high confidence*). In larger catchments, the expected change in sediment potential is within the natural variation (Blöschl et al., 2011a) (*medium evidence, low agreement*).

Historical and future human-induced land use changes in mountain catchments are expected to have a major impact on flood generation processes. With the knowledge from currently available studies, a robust assessment of the contributions of land use and climate change to the alteration of the flood generation processes is not possible (Habersack et al., 2011) (*low confidence*).

Landslides

Evidence of the impact of climate change on landslide activity in Austria is mainly site-dependent, especially with respect to the altitude. Due to changes in permafrost conditions, increased glacier melt and destabilization of rock glaciers, local accelerations of slope movements are being recorded (Schoeneich et al., 2015; Hartmeyer et al., 2020; Hartl et al., 2023) (*high confidence*) (see also [Section 1.7](#)). In the lower regions, especially those not affected by permafrost and glacier retreat, there is no evidence yet of an increase in either the frequency or the magnitude of slide and fall events (Sass and Oberlechner, 2012) (*limited evidence, medium agreement*). Rock, earth and debris slide and fall occurrence, and velocities are, however, strongly dependent on groundwater flow, which has been numerically demonstrated (Zieher et al., 2017a; Schneider-Muntau, 2020; Schneider-Muntau et al., 2022) (*high confidence*). A direct correlation between precipitation and slide or fall occurrence has been often postulated (Walter et al., 2011; Zieher et al., 2017b, 2023; Stumvoll et al., 2020), although this correlation is difficult to assess and is only based on case studies due to the different duration of precipitation to groundwater flow (Gassner et al., 2015; Zieher et al., 2023) and the still unclear influence of long-term precipitation events versus short-term but extreme events (Offenthaler et al., 2020) (*medium confidence*) (see also [Section 1.7](#)). Recent research indicates that there may also be a significant difference be-

tween the influence of precipitation and snowmelt, with snowmelt appearing to have greater effect on creep velocity (Holzmann and Perzlsmaier, 2022). However, a robust correlation between snowmelt, precipitation, and groundwater levels, which would fill the current gap in understanding the effects of climate change on slide and fall occurrence, has not yet been found.

Snow avalanches

The relationship between avalanche activity and climate change can be direct (effect of changes in snow and meteorological drivers on avalanche release and propagation on short timescales), or indirect, as a consequence of changes in land cover due to climate change. For example, the warming-induced rise of the tree line affects avalanche release (Eckert et al., 2024). With ongoing climate change, the types of avalanches as well as their frequency may change. There is *high agreement* with *medium evidence* that temperature increase will cause changes in the frequency, intensity, and types of snowfall (Hock et al., 2019). Depending on elevation, this will affect the quantity and quality of snow cover, leading to changes in the magnitude and frequency of avalanches. While it seems clear how climate change will affect mountain snow cover at lower elevations, changes above the tree line (1,800–2,200 m a.s.l. in the European Alps) are less well studied (Strapazzon et al., 2021) (*limited evidence, high agreement*). The effects of climate change on snow avalanches, therefore, remain vague, especially since most avalanche release zones in the Austrian Alps are located above the tree line. A common view, expressed with *medium confidence* in a recent IPCC special report (Hock et al., 2019), is that the number of avalanches and runout distances will decrease at lower elevations. Due to warmer temperatures, the snow volume may respond with a reduction of 90–50 % at mid-elevation sites (1,000–2,000 m a.s.l.) and 35 % at high-elevation sites over the next few decades (Keiler et al., 2010). Future snow avalanche hazards will depend on interactions between increasing air temperatures and, possibly, increasing precipitation intensities (Reuter et al., 2020). An increase in air temperature will raise the snowfall line, leading to more liquid precipitation and less solid precipitation (Blöschl et al., 2018) (*medium evidence, high agreement*). Furthermore, the duration of snow cover will be greatly reduced, mainly due to earlier spring snowmelt.

The number of studies focusing on the effect of future environmental change on the frequency and magnitude of snow avalanches is limited (Fuchs et al., 2015a). However, a

few papers provide insights into the climatic control of snow avalanches (Eckert et al., 2010). For the period between 1950 and 2017, Eckert et al. (2024) reported a 19 % decrease in the number of avalanches in the French Alps, with a significant correlation with increases in mean winter temperature ($R = -0.42$, $p = 0.002$) and decreases in snow depth at 2,400 m a.s.l. There is no doubt, that changes in temperature, precipitation (amount and solid/liquid share) and wind characteristics influence the structure and stratigraphy of the snowpack and, consequently, the release and properties of snow avalanches. On the one hand, this leads to a decrease in snow cover duration at lower altitudes (*high confidence*), and on the other hand, more precipitation – due to warming – is expected to negatively influence snow cover stability (*medium evidence, high agreement*) (see also Glade et al., 2014). The study by Eckert et al. (2010) focused on changing annual avalanche runouts in the French Alps and correlated them to climate variability using an advanced statistical framework. The results indicate no change in the mean avalanche runout altitude during the last 60 years, despite an increase in temperature. In contrast, it is reported that the release zones of avalanches migrated upslope during the period of 1850–1920, together with a more than sevenfold reduction in the annual number of avalanches, a severe shrinkage of avalanche size, and shorter avalanche seasons as well as a reduction in the extent of avalanche-prone terrain (Giacona et al., 2021). Corresponding to the high variability of snow depth and snow cover in mountain areas, possible effects on snow avalanche activity will cover a wide range from a decrease or an increase in occurrence to a shift from dry to wet snow avalanches (*limited evidence, high agreement*). Results from downscaled climate models under climate change scenarios coupled with snow models, calculated that spontaneous avalanche activity in the French Alps will decrease by 20 % and 30 % by the mid and late twenty-first century, respectively, relative to a 1960–1990 baseline. However, high winter avalanche activity is expected to increase in the mid and late twenty-first century relative to the same baseline, due to an earlier transition from dry to wet snow conditions (Castebrunet et al., 2014). This is consistent with studies by Zgheib et al. (2022) who reported a general increase in the annual avalanche frequency from 1946 to 2009 in the French Alps, and by Pielmeier et al. (2013) and Mayer et al. (2024a) for the Swiss Alps.

For the French Alps, it has been reported that despite the anticipated stability of precipitation sums, the interaction between temperature increase and topography will con-

strain the evolution of snow-related variables on all considered spatio-temporal scales. This will result in a decrease of the dry snowpack and an increase of the wet snowpack. Wet snow conditions are projected to occur at high elevations earlier in the season (Castebrunet et al., 2014). In AAR14 it was reported that a decrease in avalanche activity was expected, however, this decrease was not supported by data or other evidence (APCC, 2014). Following Castebrunet et al. (2014), a general decrease in mean (20–30 %) and inter-annual variability of avalanche activity is projected. These changes are relatively strong compared to changes in snow and meteorological variables. The decrease is amplified in spring and at lower elevations. In contrast, an increase in avalanche activity is expected at high altitudes in winter due to conditions favorable for wet snow avalanches early in the season (Castebrunet et al., 2014) (*limited evidence, high agreement*).

Glacial Lake Outburst Floods (GLOFs)

The release of previously covered bedrock after glacier retreat leads to a debuiting of slopes and the establishment of different thermal conditions in the rock. An increase in rockfall processes is reported for deglaciated bedrock slopes in an Austrian case study (Kitzsteinhorn) (Hartmeyer et al., 2020). Glacier retreat may also cause the formation of glacial lakes and landslides, in some cases with the potential for glacial lake outburst floods (GLOFs). GLOFs result from dam bursts or overtopping due to rockfall into the lakes. The most recent documented catastrophic GLOFs in the Austrian Alps occurred in the 17th–19th centuries with a maximum in the 1860s, when the surging Vernagtferner glacier repeatedly dammed lakes in the Ötz Valley in Tyrol (Hoinkes, 1969; Braun, 1995), producing several destructive GLOFs (Aulitzky et al., 1994; Embleton-Hamann, 2007). Even though the number of glacial lakes increased during the 20th century, none of the existing lakes are currently considered hazardous (Mergili et al., 2012; Buckel et al., 2018; Fuchs et al., 2022) (*medium confidence*). According to modeling studies, the number of lakes in Austria is expected to increase and changes in the hazard potential are possible, especially if future lakes form at higher elevations closer to steep bedrock slopes (Otto et al., 2022) (*medium evidence, low agreement*). Further studies on GLOF hazards in the Austrian Alps are currently lacking. Historical outlines of GLOFs are reported in Nicolussi (2013) and Richter (1889, 1892).

Wildfires

In the European context, wildfires are considered an emerging risk (see [Cross-Chapter Box 1](#)). The burnt area in Europe in 2021 is about 2.5 times higher than the area burnt between 2008 and 2020 (IFRC, 2021). It is particularly alarming that significant wildfires have recently occurred not only in countries of the European South but also in countries with a short record of wildfire events (e.g., Sweden, Austria). Wildfires in Austria are mainly human-induced (85 %) and related to tourism and recreational activities (Müller et al., 2020). Consequently, the wildfire risk in Austria is expected to change partly due to the expected increase of fire weather days (Müller et al., 2020) and partly due to the continuous development of the wildland-urban interface (Papathoma-Köhle et al., 2025) (see also [Cross-Chapter Box 1](#), [Sections 1.6.2](#) and [2.2.2](#)). In more detail, fire weather is the combination of certain conditions of surface temperature, humidity and wind (Clarke et al., 2022). Based on these characteristics, fire indices are developed and used to predict wildfire danger. According to Arpacı et al. (2013), the Canadian Fire Weather Index (FWI) is the best performing FWI in Austria. Models developed during the FIRIA (Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate Change) project (2011–2014), showed that not only the number of fire weather days in Tyrol will increase by more than 40 days by 2100 (2014–2100), but also that areas that have not experienced wildfires in the past will be at increased risk of wildfires in the future. Moreover, the fire seasons are expected to expand and shift throughout the year (Müller et al., 2020). Relatively recent wildfire events in Austria (e.g., Absam 2014, Lurnfeld 2015, Rax 2022), have shown that crown fires in combination with strong winds can challenge suppression efforts and can be highly dangerous to people, infrastructure and property, in addition to affecting the forests themselves. The term ‘forest fire’ which refers to wildfires affecting forests excluding grassland fires or other types of wildfires, is used elsewhere in this report (see [Sections 1.6.2](#) and [2.2.2](#)) since this is a very common type of wildfire in Austria. There is no study addressing wildfire risk only for the Austrian Alps, but it can be assumed that since the topography is one of the factors that influence the initiation and extent of a wildfire in mountainous areas (Airey-Lauvaux et al., 2022), and that the number of fire weather days are going to increase, the wildfire hazard will also increase, threatening settlements in the wildland-urban interface and ecosystems. On the other hand, significant changes are expected in the

exposure of people and ecosystems. In more detail, the wildland-urban interface and intermix (WUI) in Austria, where people live very close to or within the forest, occupies 13.6 % of the country (Bar-Massada et al., 2023). Additionally, the number of people living in the WUI in Europe is expected to increase according to different climate change scenarios. For the 3°C global warming scenario (GWL 3°C), an increase of 24 % of the population living in the WUI and exposed to high to extreme fire danger at least 10 days per year is expected. This percentage is reduced to 7.9 % for 1.5°C global warming (GWL 1.5°C) (Feyen et al., 2020). According to Feyen et al. (2020), the vulnerability of the ecosystems in the WUI is also expected to increase due to the northward shift of European ecological areas.

Multi-hazards (compound events, hazard cascades)

Many hazards occur, coincidentally or not, simultaneously or sequentially (see also [Section 1.8](#)). In general, preparedness and adaptation to multi hazard events are a prerequisite for a resilient society (UNDRR, 2015). Risk assessment for single hazards should be extended to include secondary effects (floods, landslides) or processes occurring simultaneously (wildfires, heatwaves, droughts) (Terzi et al., 2019). There are a few studies focusing exclusively on the influence of climate change on multi-hazards (occurrence, frequency, magnitude) for the Austrian Alps, although multi-hazard events have occurred frequently in the region in the past (Hübl et al., 2005; Eder et al., 2006; Pfurtscheller, 2014). Stoffel and Corona (2018), focusing on the wider Alpine space, argue that future winters will be characterized by multiple events triggered by changes in precipitation and temperature. However, the interactions between different hazardous processes in the Austrian Alps have often been the topic of research studies. For example, Sass et al. (2012) investigated the effects of wildfires on other geomorphological processes in Tyrol, and Kaitna et al. (2023) investigated the influence of hydrometeorological triggers on the occurrence of debris flows in the Austrian Alps. Some studies focused on specific elements at risk, such as the road network (Oberndorfer et al., 2020), while others focused on multi-hazard exposure mapping in Austria (Fuchs et al., 2015b; Nachappa et al., 2020), or in the Alps, including part of the Austrian Alps (Pittore et al., 2023). Terzi et al. (2019) have developed a framework for climate change and related multi-hazard for mountain areas. Nevertheless, it is not clear from the literature whether mountain areas are more

susceptible to multi-hazards and if climate change will affect multi-hazards differently in mountain areas than in the rest of the country.

Implications for vulnerability and risk

In summary, changes in the frequency and intensity of natural hazards in the Austrian Alps must be considered in order to adapt to climate change. The risk to natural hazards is subject to change not only due to changes in the frequency and intensity of natural hazards in the Alps but also due to increased exposure (Fuchs et al., 2015b) and vulnerability dynamics, according to a number of publications (Papathoma-Köhle et al., 2021, 2022a, 2022b) (see also [Sections 7.4.2 and 7.4.3](#)). Specifically, around 5 % of the building stock in Austria is exposed to torrential flooding, with hotels and guest houses as well as agricultural buildings showing an above-average exposure. The total number of properties exposed to torrential flooding has risen by a factor of six, from 18,797 to 111,673 buildings, over the last century. Considering these temporal dynamics, it can be assumed that if construction activity continues in the same pattern as in the last 100 years, the exposed buildings will increase by 2 % per year (Fuchs et al., 2015b, 2017).

7.4.2. The Alps as a provider of services, goods and livelihoods

Forestry and agriculture

Effects of climate change on forests

The Austrian Alpine area as delineated by the Alpine Convention is largely dominated by forests ([Figure 7.5](#)). Forests are divided into productive forests, recreational forests, and protective forests (BML, 2022). Timber production drives the forestry sector in Austria, which is mainly dependent on coniferous species that cover 53 % of the forested area, dominated by Norway spruce (42 %). Single-species spruce forests, established during the economic crisis following World War II, often exceeded ecological limits, resulting in ‘secondary spruce forests’ (BFW, 2022). Forestry is an important backbone of the regional economy in the mountain regions of Austria. It supports the local value chain of the bio-economy and provides energy in rural areas (Jandl, 2023). Due to climate change, a wide range of possible changes in forestry are expected, e.g., a change in tree species requires a change in wood processing technology (Pramreiter et al., 2023). However, recent research shows that the high proportion of

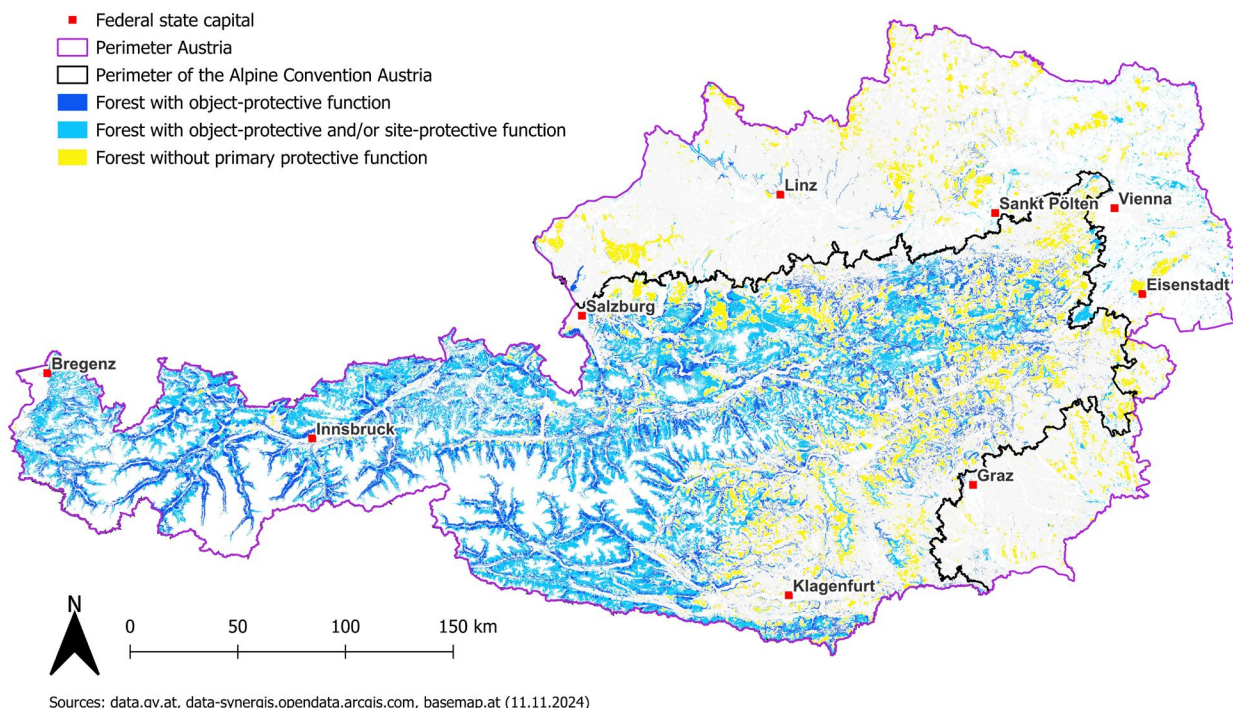


Figure 7.5 Protective forest in Austria.

private forest owners makes it difficult to estimate the implementation of necessary adaptation measures (Mostegl et al., 2019; Pröbstl-Haider et al., 2020a) (*limited evidence, high agreement*) (see Section 1.6.2). Effects of climate change on forestry and agriculture in Austria are discussed in Section 2.2. Here, the focus is on forests and agriculture in mountain areas. With regard to forestry, the focus in mountain areas is on protective forests.

Protective forests have the primary function of protecting people or assets from the effects of natural hazards (Brang et al., 2001). They are common in mountainous areas, and less common in low elevations (Figure 7.5) (Makino and Rudolf-Miklau, 2021). Strategic management concepts are implemented to sustainably maintain a desired forest structure that provides protection against gravitational and hydrological hazards (Perzl, 2014; Perzl et al., 2021; Teich et al., 2022; Moos et al., 2023; Gaube et al., 2024). Protective forests are uneven and multi-layered stands with trees of all sizes and age classes, a minimum canopy cover of about 40 %, only small openings and a sufficient presence of natural regeneration (Frehner et al., 2005; Perzl, 2008). However, species composition and specific silvicultural objectives for protective forest management are highly dependent on the natural hazard process while the assessment of the protective effects is still subject to uncertainties (Perzl et al., 2021).

Global warming poses several challenges for mountain forests. However, at high elevations (montane and subalpine forests), the pressures from climate change are not as manifest as in valleys. Temporarily, climate change even promotes productivity and the upward shift of the tree line. Over several decades, the positive effects of warming will be outweighed by the negative effects that reduce forest productivity (Bebi et al., 2009; Lexer et al., 2015; Irauschek et al., 2017a, 2017b; Ledermann et al., 2022; Gaube et al., 2024). In addition, mountain forests will be more frequently and severely affected by natural disturbances (Seidl et al., 2017). In a warmer world, pests and pathogens will become an increasing challenge (Netherer et al., 2015; Hlásny et al., 2019; Hoch et al., 2019; Steyrer et al., 2023). For example, epidemic bark beetle outbreaks are becoming more common as bark beetle habitat shifts upward due to rising air temperatures, causing increasing problems in high-elevation forests (Jakoby et al., 2019; Hallas et al., 2024) (*high confidence*).

Rising air temperatures and more frequent and severe droughts will lead to shifts in tree species distribution and forest composition (Hanewinkel et al., 2013; Mauri et al., 2022; Amt der Steiermärkischen Landesregierung, 2023a, 2023b). The dynamics of natural forest disturbances such

as wind, fire, pests and insects are accelerated by climate change such as the ongoing unprecedented bark beetle outbreak in protective forests in Austria and other countries in Central Europe, which may result in a temporary or irreversible loss of their protective effects (Seidl et al., 2017; Albrich et al., 2020; Senf and Seidl, 2020; Moos et al., 2023) (*high confidence*). However, post-disturbance management decisions have an important impact on the protection. For example, remaining deadwood after windthrow and bark beetle disturbances, can have a positive effect on rockfall and avalanche protection, especially during the first 15 years (Wohlgemuth et al., 2017; Teich et al., 2019; Caduff et al., 2022). However, a careful balance between salvage logging to reduce bark beetle infestations, and salvage logging to maintain the protective function is of paramount importance and depends heavily on the local conditions as well as the severity and the stage of the disturbance.

Mitigation

The role of forests in mitigating climate change has been analyzed in the Special Report Land Use (Jandl et al., 2024), including the carbon storage in the tree biomass and in soils, and its impact on the Austrian greenhouse gas (GHG) emissions budget (Gingrich et al., 2024). Since 1990, forests have compensated between 4 and 35 % (on average 15 %) of the GHG emissions of other sectors (Umweltbundesamt, 2023b). The mitigation role of forest management has been investigated in simulation projects (Braun et al., 2016; Weiss et al., 2020; Kraxner et al., 2024). The publications cover the entire Austrian forest and not only mountain forests. The simulations suggest that the climate change mitigation effect of forests is temporary. With sustainably managed forests in a regime of moderate climate change, the carbon pools in soils, biomass, and wood products can be maintained. Unabated warming trends threaten the sink capacity of forests. The scientific discourse on the future role of forests and forest management in mitigating climate change is compromised by opinionated views on the desirable intensity of forest management (*robust evidence, medium agreement*).

Adaptation

Adaptation measures for forests in non-mountainous areas in Austria are discussed in Section 2.3. Here, the focus is on adaptation for forests in the Alpine region. Some measures to adapt forests to climate change are controversial. One aspect is to reduce the population of ungulates (red deer,

roe deer, chamois), as natural regeneration of various tree species is low due to browsing damage (Reimoser, 2003; Mayer et al., 2017). A decade-long dialog between foresters and hunters has not resolved the issue (BML, 2022) (*robust evidence, low agreement*). Another controversy is the choice of tree species. Foresters assert the need to establish stands of non-native tree species in locations where they are promising alternatives to native species that are struggling, or for use in locations where native tree species or provenances are not competitive in a future climate (Hanewinkel et al., 2013; Baumgarten et al., 2024; Chakraborty et al., 2024) (see also Section 4.3). The option of introducing non-native tree species is heavily debated (Bauhus et al., 2021) (*robust evidence, low agreement*). A fallback position for unstable and particularly vulnerable forests is to reduce the rotation cycle to avoid premature stand collapse. Common ground is reached when mixed-species stands are to replace single-species stands. From an adaptation perspective, this strategy simply distributes the externally applied risk agents (fire, storm, bark beetle, endemic pathogens) among tree species with different traits. The expectation is that a disturbance event will not destroy the entire forest stand, but only some elements that are particularly vulnerable with respect to the relevant disturbance agent (Pluess et al., 2016; Pretzsch et al., 2017; Yousefpour and Gray, 2022) (*high confidence*).

Recommendations for the management of protective forests to cope with the impacts of climate change on their protective effects are site-specific. Studies examining different management interventions such as thinning and regeneration cuts in combination with different climate scenarios show contrasting impacts on the protective effects of forests against natural hazards, also suggesting strong local context dependencies (Moos et al., 2023).

Vulnerability

Disturbance-induced tree mortality and regeneration failure may seriously compromise the provision of protective services against avalanches, rockfall and landslides (Temperli et al., 2017). The exposure of communities, the built environment and infrastructure to natural hazards will eventually increase. Although protection forests may not be more vulnerable to climate change than other forests in Austria, alpine communities that depend on the protection of these forests are, therefore, more vulnerable than other communities in the country that are not protected by nature-based solutions that may be affected by climate change.

Effects of climate change on agriculture

Overall, the agricultural sector is characterized by a rather extensive production compared to the lowlands. The dominant form of agriculture in mountain areas is grassland. In Austria the grassland area has decreased from 1,812,380 ha (1990) to 1,611,521 ha (2022). During these 32 years, 85,927 ha were converted to forest, 54,972 ha to cropland, and 27,995 ha to settlements (Umweltbundesamt, 2024) (see also Section 2.2.1). As far as grassland and alpine/mountain pastures are concerned, climate change would allow a shift towards cropland. Economically, such a change in land-use reduces the importance of dairy production. Ecologically, a decline in soil carbon stocks and in plant diversity is expected (Bohner et al., 2017; Bohner, 2023). The boldest changes in agriculture are shifts in production areas for climatic reasons. The current main agricultural production area is located in the northeast of Austria. This area is expected to be subject to more frequent and intense drought events (Haslinger et al., 2019, 2022). Accordingly, the main agricultural area is expected to shift westward and upward where climatic conditions are more conducive to crop production (Haslmayr et al., 2018). However, future site conditions are highly uncertain. Longer and more frequent droughts will reduce the yield of grasslands and the quality of fodder (Bohner, 2022, 2023). There is greater certainty about future pest and pathogen pressure and the adverse effects of extreme climate events.

Mitigation

Climate change mitigation in agriculture has some peculiarities. Carbon capture in the biomass will be of little relevance. A prominent role is given to consumer demands, or social transformation (APCC, 2023) (see also Sections 2.3 and 2.A.9). Currently, a meat-producing farm uses more than 5 ha for corn production to supply feed. Additional feed can be purchased from other countries at an ecological cost (soy imports). The ecological footprint is therefore significant.

Grassland soils have higher soil carbon stocks than cropland soils (Baumgarten et al., 2024; Umweltbundesamt, 2024). Many realistic mitigation strategies aim to maintain rather than increase current soil carbon stocks (Zosso et al., 2023). Further mitigation strategies include the integration of landscape elements that increase the plant species diversity and the implementation of agroforestry. However, the increase in soil carbon stocks after the reforestation of ex-

tensively used grassland is low (Hiltbrunner et al., 2013; De Stefano and Jacobson, 2017).

Adaptation

Climate change will require agriculture to adapt. In some areas, technological adaptation will be required, such as irrigation of crops, in others different crop varieties and the introduction of non-traditional crops may be the solution. Soil protection and sustainable forms of soil management are well studied. The carbon sequestration potential of soils is not well understood. Soil processes leading to an increase in soil carbon stocks are usually slow. Many strategies have already been implemented in Austria. Further increases in soil carbon stocks are expected to be small (Tiefenbacher et al., 2021; Wenzel et al., 2022) (*medium evidence, high agreement*).

In Austria, permanent grassland soils are important for organic carbon (C) storage due to their high soil organic matter (SOM) stocks and large areas. Especially, subsoils have a high potential for long-term soil carbon storage (SCS). In permanent grassland, soil organic carbon stocks are controlled by climate, soil properties (particularly soil moisture status and soil thickness), vegetation type (root biomass) and management intensity. Plant roots, microbial necromass and C-rich organic fertilizers (cattle manure, composted cattle manure) are most important for soil organic matter accumulation, which is generally a slow process. In Austrian permanent grassland, soil organic carbon storage is highest at an intermediate management intensity (2–4 mowings per year, annual application of cattle manure or composted cattle manure). Management practices that increase annual soil organic matter turnover are more important than those that increase the soil organic matter stocks.

In permanent grassland, the following measures and strategies are important to maintain or increase soil organic carbon stocks (Bohner, 2023; Meyer et al., 2024):

- No conservation of permanent grassland to cropland;
- Conversion of temporary grassland to permanent grassland (no plowing of grassland);
- Maintaining moderate management intensity (2–4 cuts per year), avoiding further intensification in currently intensively managed grasslands;
- Moderate grazing intensity (no long-term overgrazing);
- Increasing root growth, root biomass and rooting depth in soils by reducing management intensity in intensively managed grasslands (particularly intensively managed pastures);
- Annual application of farmyard manure (cattle manure or composted cattle manure);
- Favoring plant species with large and deep root systems;
- Maintaining or increasing the groundwater table in grassland soils affected by groundwater (particularly clay and peat soils).

Vulnerability

The vulnerability of individual crops depends mainly on their water requirements. On the one hand, in drought-prone karst landscapes, crops with high water requirements are particularly vulnerable. On the other hand, sites with high water tables are less susceptible to drought and therefore more suitable for crops with higher water requirements. Providing water through irrigation is not realistic due to high investment costs and conflicting water interests of different groups. There are two additional issues related to the vulnerability of agriculture. First, the water supply for livestock in mountain areas, which may also be reduced in the future due to climate change, makes them particularly vulnerable compared to livestock in other parts of Austria. Second, the dependence of mountain farms on forests, which are also affected by climate change, makes mountain farming more vulnerable than in other areas of the country where this dependence does not exist. Conversion of land from agricultural use to alpine tourism to mitigate losses has been proposed as a solution but has been rejected by farmers (Wanner et al., 2021).

Energy

This section describes the specific role of the Alps in the energy system. For more information on the overall energy system and its transformation, see [Section 4.5](#). The Alpine region plays an important role in Austria's energy supply, mainly through electricity generation from hydropower reservoirs and pumped storage, run-of-river hydropower and wind power plants in exposed locations.

Solar power is currently less developed at higher altitudes, although there are potential benefits for the overall energy system from increased winter solar generation in the mountains compared to lower altitudes (Kahl et al., 2019; Đukan et al., 2024) (see [Section 4.5.2](#)). Hydropower pumped storage and reservoir power plants are located exclusively in Alpine regions due to the topographic requirements of storage power plants. Run-of-river hydropower plants are scattered throughout the country. However, the Alpine regions have a

cascading effect on almost all hydro run-of-river hydropower plants in Austria due to the high water inflow resulting from the topographic setting, which determines their importance for the local and downstream hydropower utilization (Fatichi et al., 2015). In 2019, about 9 % of the installed wind power capacity in Austria was located in the Austrian Alps, with two-thirds of them located above 1,400 m a.s.l. (Austrian Wind Energy Association, 2019; APG, 2024). The majority of Austrian Alpine wind power plants are located in Styria (Austrian Wind Energy Association, 2019).

The literature base on renewable energy potentials for the Austrian Alps is limited. At the NUTS2 level, data availability is higher, with an approximation of the Alpine region in Austria using the states of Carinthia, Styria, Salzburg, Tyrol, and Vorarlberg. These federal provinces account for about 19–46 % of the technical wind potential (European Commission and Joint Research Centre (JRC), 2021; Kakoulaki et al., 2021), 39 % of the technical solar power potential, 40 % of the technical biomass potential (European Commission and Joint Research Centre (JRC), 2021), and 64 % of the technical hydropower potential, with the electricity demand of this area only accounting for around 37 % of Austria (2019) (Kakoulaki et al., 2021). In addition to the flat agricultural lowlands in northeastern Austria, remote locations in the Alps host the majority of Austria's wind potential (Brudermann et al., 2019). Generally, most of the wind potential in the Alpine federal provinces is located in non-alpine areas. However, if only the alpine areas in those federal provinces are considered, exposed sites offer the best wind potential (Ciolli et al., 2015). One third of Austria's theoretical Alpine wind power potential is located in protected areas, and the potential outside of protected areas is mainly at relatively low altitudes (Balest et al., 2015).

The sustainable potential for renewable energy in the Alps is limited by the consideration of conflicting interests such as nature conservation (Balest et al., 2015) and economic activities in tourism (Brudermann et al., 2019). The potential wind power plant sites in the Alps are sparsely populated or uninhabited, so conflicts with residential structures are less pronounced than in the lowlands (Brudermann et al., 2019). However, wind turbines at high altitudes mean increased visual intrusion at longer distances, which can lead to reduced acceptance (Kraxner et al., 2015) and conflicts with nature conservation management strategies and recreational activities such as hiking, skiing or cycling, for locals and tourists (Brudermann et al., 2019). A quarter of the total theoretical potential for wind and solar power generation in the Alps in general is located in Natura 2000 areas (Balest et

al., 2015). The wide range of protected areas means different administrative and management regulations, with different levels of allowance for renewable energy expansion, which must fit within the management objectives of the protected areas (Kraxner et al., 2015). These facts highlight the potential conflicts that may arise from the expansion of renewable energy production in the Alpine region and that need to be considered in climate change mitigation and adaptation measures.

Electricity from the Alpine area is largely supplied to the neighboring urban areas due to the higher concentration of electricity demand (Kakoulaki et al., 2021). The energy demand in Alpine regions differs from other parts of Austria in that tourism is more important and snow management plays a significant role in the energy demand of certain regions (see Section 7.4.2). This has implications for the energy demand profile, such as seasonality or concentrated peak demand corresponding to the ski season. From a tourism perspective, there is a growing demand for energy for tourism infrastructure, especially for ski resorts and large wellness facilities, as well as for charging electric vehicles of visitors/tourists at the destination. However, the acceptance by tourists, who expect pristine tourism landscapes, is rather low, especially when alternative destinations are available (Broekel and Alfken, 2015). They would prefer small-scale solutions using existing infrastructure (Jiricka-Pürerer et al., 2019). Therefore, the trade-off for tourism destinations is rather difficult.

Effects of climate change

A potential impact of climate change on energy supply from the Alpine region could occur through reduced precipitation as snow, recurrent droughts, and water scarcity (see Section 7.3). The effects of climate change are expected to lead to a change in the annual production of renewable energy and to changes in seasonality (see Section 4.6.2). The effects of climate change on biomass, which is mainly relevant for the heating sector (see Sections 3.3 and 4.5.2), are described in Section 7.4.2.

Mitigation

Transforming the energy system towards a climate-neutral system is a key requirement for mitigating climate change. Due to the current potential for renewable energy production and storage in the Alps, this region can make a significant contribution to these efforts. The aim of the Alpine

Convention is to make a long-term contribution to meeting Europe's energy needs while limiting the negative effects of power plants on the environment and the landscape (European Union, 2005). Specific challenges for renewable energy expansion and operation in Alpine areas are steep slopes and a lack of connectivity to electricity and road networks (Kraxner et al., 2015).

Alpine regions can support the renewable energy transition, especially by providing flexibility to the overall electricity system through hydropower (pumped storage), which helps integrating high shares of highly volatile renewable energy sources into the energy system (see Section 4.6.2). Austria's topographical situation is an advantage in this case, as hydropower (pumped storage) can support the security of the energy supply in Austria as well as in the European interconnected electricity system.

For mutual benefits, it is important to consider the compatibility of biodiversity conservation and climate change mitigation through renewable energy use which has been demonstrated in best practice examples (Brudermann et al., 2019). It is unclear how sensitive the attractiveness of tourist destinations is to the installation of large-scale energy production facilities. Surveys show high levels of opposition, especially to wind turbines and large biomass or photovoltaic plants. Existing research suggests a trade-off between sustainable energy supply and tourism product development (Jiricka-Pürerer et al., 2019) (*limited evidence, high agreement*). Whether and under what conditions guests' attitudes toward sustainability will change in the long term is an open research question.

Adaptation

Climate change affects energy supply and demand and poses risks to infrastructure, making it important to consider these factors in adaptation of the alpine energy system (see Cross-Chapter Box 1). Possible hazards for Alpine energy infrastructure include glacier retreat, permafrost reduction, heavy precipitation and thunderstorms (Pröbstl-Haider et al., 2020b). In addition to the general trends of climate impacts on energy systems (see Section 4.6.2), the energy infrastructure in the Alps is confronted with rockfalls and rock and snow avalanches. Melting glaciers have a dual impact on local renewable energy production. First, the challenge of steep slopes for alpine (energy) infrastructure may be exacerbated by slope instability due to glacier melt (see Section 7.4.1). Second, local hydropower generation will be altered in terms of total production and seasonality which

will then have cascading downstream effects on the entire energy system (Wagner et al., 2017; Schöniger et al., 2023; Wechsler et al., 2023). Adaptation strategies can increase the adaptive capacity of water governance and management systems (Maran et al., 2014). Hydropower plant design discharge optimization can partially compensate for climate change-related power generation losses, with greater design optimization potential in summer than in winter (Wechsler et al., 2023). However, the overall adaptive capacity of alpine hydropower systems to climate change is assessed as being rather low (Anghileri et al., 2018; Soomro et al., 2024), especially in catchments dominated by ice melt (Anghileri et al., 2018).

Vulnerability

Concerning hydropower, there is *low agreement* in literature as to whether climate change impacts lead to an increase or decrease of total generation, with a strong dependence on the climate scenarios chosen and significant geographical differences (see Section 4.6.2). The majority of currently available studies project a small decrease in the national mean annual hydropower potential by the end of the 21st century (for different GWLs) (Kranzl et al., 2010; Blöschl et al., 2011a; Eitzinger et al., 2014), with more recent climate models and scenarios showing a slight increase (Formayer et al., 2023) (*medium evidence, low agreement*). Wagner et al. (2017) predict a range of average annual changes in electricity generation in the Alps between +5 and -8 % for the period 2031–2050 in different scenarios/GWLs compared to no climate change impact. Wechsler et al. (2023) find a decrease of annual run-of-river generation in the Swiss Alps of about 2–7 % by the end of the century. The impact of climate change on run-of-river hydropower production depends strongly on the elevation of the hydropower plants with production increasing for higher elevated power plants (Wechsler et al., 2023) (*limited evidence, medium agreement*).

There is a *high agreement* in the literature on a seasonal shift of hydropower production from the summer to the winter season with increasing climate change (see Section 4.6.2) due to changes in precipitation/snowfall and earlier runoff due to warmer spring temperatures (see Section 1.4.1) (*medium evidence, high agreement*). This pattern is even more pronounced for the Alpine region than to Austria as a whole (see Figure 7.6). The projected seasonal shift in hydropower generation corresponds to the projected increase in mean and low winter flows in the Alps (see Sec-

tion 1.4.1). The projected decrease of hydropower potential in summer and increase in winter has been shown for the entire Alpine region (Wagner et al., 2017), the Austrian Alps (Blöschl et al., 2011a; Formayer et al., 2023; Schöniger et al., 2023), and the Swiss Alps (Finger et al., 2012; Wechsler et al., 2023). A decrease in summer hydropower potential in mountain regions by about 2–22 % is expected (Blöschl et al., 2011a; Eitzinger et al., 2014; Wechsler et al., 2023) (*limited evidence, medium agreement*). For specific periods, a decrease of up to 70 % was found in the summer months of July and August for warm-dry periods by 2050 compared to 1961–1990 (Wagner et al., 2017). For Alpine winter run-of-river generation, an increase of 4–9 % by the end of the century is reported (Wechsler et al., 2023).

Figure 7.6 compares the hydropower generation from run-of-river-power plants in the Austrian Alps and all of Austria for the periods 1971–2005 and the 20-year period up to GWL 3.0°C, according to the considered climate scenario (Formayer et al., 2023; Schöniger et al., 2023). The monthly mean production for the periods 1971–2005 and GWL 3.0°C is compared with the mean generation of the entire period 1971–2005. Although weaker and stronger GWLs are not shown in the figure, they do show the same trend.

(Pumped) storage power plants are expected to face these developments robustly, as their storage capacities buffer runoff fluctuations (Haas et al., 2008; Kranzl et al., 2010; Maran et al., 2014). However, the impact of glacier melt on the operations of reservoirs is still an open research question. For run-of-river hydropower power plants, climate-induced changes in hydrological regimes may require operational impairments and increased attention to structural and operational impacts of flooding (Habersack et al., 2011) (*low confidence*). Potential changes in sediment potential and transport dynamics further exacerbate the already existing challenges related to sediment management strategies at hydropower reservoirs (Habersack et al., 2011) (*low confidence*).

Tourism

Effects of climate change and vulnerability

Alpine regions account for 53 % of overnight stays in Austria during the summer season and 70 % during the winter season (Burton et al., 2024), making them the most important sub-sector of tourism in Austria. At the same time, tourism contributes a significant share to regional domestic products,

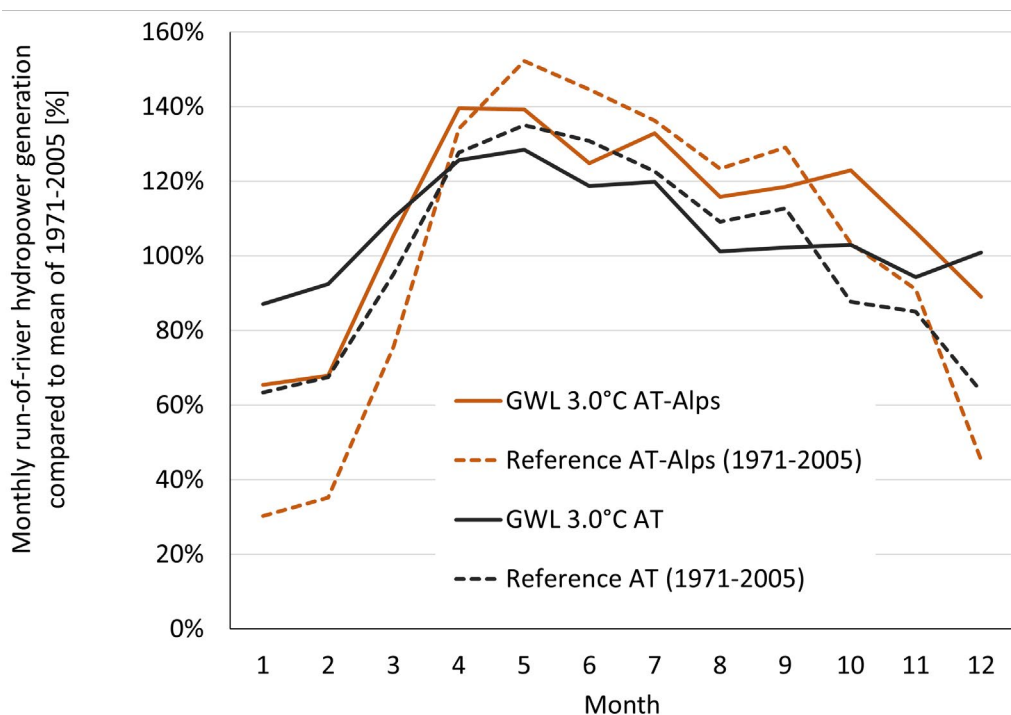


Figure 7.6 Changes in the mean run-of-river hydropower generation for the Austrian Alps and whole Austria for 1971–2005 and GWL 3.0°C (Source: Based on SECURES project runoff calculated by E-hype driven by RCP 8.5 RCM RACMO22E (KNMI, Netherlands) and GCM EC-EARTH (ICHEC, Ireland), see Formayer et al. (2023) and Schöniger et al. (2023)).

e.g., 19.7 % including indirect effects in the federal province of Tyrol (Fritz et al., 2021), and is the backbone of the regional economy in many rural Alpine municipalities (Steiger and Scott, 2020). As most tourism products in alpine tourism are dependent on natural resources (Steiger et al., 2020), climate change can have far-reaching consequences. While direct impacts refer to a change in the natural resources necessary for specific activities and tourism types (e.g., snow for skiing), indirect impacts refer to changes in landscape aesthetics (e.g., due to land use changes, shifting tree line, loss of glaciers) (Pröbstl-Haider et al., 2021). Snow- and ice-based forms of tourism are projected to face a higher risk of discontinued operation (Steiger et al., 2021a). However, the remaining regions that still provide reliable snow and ice conditions (whether due to natural or artificial snow and ice) could gain a competitive advantage as these resources become scarcer, which could even result in increasing tourism demand and pressure on tourism development (Steiger and Scott, 2020; Steiger et al., 2021a) (*high confidence*). In summer, the Alpine region is likely to benefit from the heat islands in the pre-Alpine area and urban areas, potentially stimulating summer tourism (Weber et al., 2017). In addition, summer tourism could benefit from warmer and more stable weather conditions, especially during periods of low demand such as the spring and fall months (Pröbstl-Haider et al., 2021). However, many summer tourism activities such as climbing, fishing, kayaking, hiking, and all types of aviation sports are affected by an increasing number of hot days and changes in the flow regime of alpine rivers (Pröbstl-Haider et al., 2021). Recent research reports an increasing safety risk on alpine trails due to thawing permafrost, heavy rainfall and thunderstorms (Pröbstl-Haider et al., 2020b) (*limited evidence, high agreement*). Human health problems (such as heat stress, allergies from neophytes, and deterioration of the water quality in lakes) are likely to increase in the Alps, but will occur less frequently than in the lowlands, representing a comparative advantage (Pröbstl-Haider et al., 2021).

There is a high likelihood that the costs for restoring and maintaining the extensive hiking and climbing infrastructure will increase (Pröbstl-Haider et al., 2021). The maintenance of this infrastructure is currently mainly in the hands of alpine NGOs. The demographic change on the one hand, and the increasing need for restoration and maintenance of the Austrian trail system in the mountains on the other hand, will require new adaptation strategies with significant financial support. Otherwise, the trail network which is the backbone of any kind of summer tourism will lose its current high quality and reliability. Exposure to dangerous sit-

uations could increase in the absence of professional monitoring (Pröbstl-Haider et al., 2016). For summer ski tourism, a strong decline between 2002 and 2019 was observed (-48.3 % in the summer half-year) (Mayer and Abegg, 2024). However, climate change impacts on glaciers and summer snow only explain part of this development, as societal trends (declining interest in summer skiing) also play an important role (Mayer and Abegg, 2024).

Mitigation

The biggest lever for reducing GHG emissions from tourism is mobility (see [Section 4.3.3](#)). Although rough estimates for tourism-related GHG emissions exist at the national level (Neger et al., 2021), there is a lack of more detailed monitoring of emissions at the subnational level that takes into account destination-specific factors such as the place of origin of tourists, the structure of the accommodation sector and the main tourist activities (high vs. low energy consumption). Opportunities to reduce GHG emissions in the tourism sector in the Alps differ from those in non-alpine areas in several ways:

Public transport to tourist destinations has been enhanced in several mountain regions in recent years, for example with night train connections from major source markets, such as Germany. While the German Railway (DB) discontinued its night train service in 2016, the Austrian Federal Railways (ÖBB) has very successfully taken over some of DB's connections and has since expanded them to other European markets; more high-speed train connections and more frequent public transport at the destination level (Gühnemann et al., 2021). However, in order to achieve a relevant shift from the car to public transport, the tourism sector depends on the tourists' willingness to consider alternatives to their usual mobility choices (for details, see [Section 7.4.3](#)). The greatest potential for reducing emissions in the lodging sector lies in improving the building structure (insulation), energy efficiency measures (room temperature, hot water use) and lighting (Energieinstitut der Wirtschaft GmbH, 2012). In Austria, the energy demand for heating buildings will decrease while energy demand for cooling buildings will increase as climate change continues (Prettenthaler et al., 2008; Dowling, 2013; Berger et al., 2014a). The net balance is estimated to be zero (Berger et al., 2014b) or even negative (i.e., decreasing energy demand) (Prettenthaler et al., 2008). Taking this into account, it can be concluded that the energy demand for the accommodation sector in Austria's mountain regions will rather decrease, since in many destinations

there will be no need to cool buildings due to the higher altitude and therefore lower temperatures, and less heating of buildings will be required.

Providers of infrastructure for tourism activities can reduce GHG emissions by purchasing and/or producing green energy, increasing the share of lower emission fuels in the fleet, or promoting public transportation to/from the attraction. Ski resorts are one of the main providers of infrastructure for tourism activities in mountain regions. Ski resorts can purchase green electricity, and produce their own green electricity with wind, photovoltaics and hydro-power facilities (the latter sometimes in combination with snowmaking infrastructure) (Steiger et al., 2021a). Certification (ISO, EMAS, Österreichisches Umweltzeichen), sustainability and energy concepts, support the transition in winter tourism (Pröbstl-Haider et al., 2018). A ski resort in Salzburg (Snow Space Salzburg Bergbahnen) is testing e-fuel snow groomers which have the potential to reduce emissions by up to 90 % (Umwelt Journal, 2023). The same ski resort is incentivizing public transportation by offering free transportation within the federal province when a lift ticket is purchased online (Snow Space Salzburg, 2024).

Significant potential for GHG emission reduction also lies in the composition of the countries of origin of the visitors. Although far-away source markets such as China account for only a small share of overnight stays (2.2 %), their share of tourism-related emissions is disproportionately high (18.5 %) (Neger et al., 2021). The number of overnight stays from long-haul source countries increased before the pandemic, and is expected to increase in the coming years (Lehner-Telič, 2024). Therefore, demarketing strategies for long-haul source markets could slow down demand growth and associated GHG emissions.

Adaptation

Snowmaking in ski resorts is commonly regarded as a climate change adaptation strategy although Steiger and Mayer (2008) showed that the underlying reasons for investing in snowmaking are multifaceted. Nevertheless, snowmaking provides an opportunity to sustain ski operations in a warming climate (Steiger et al., 2022). The amount of natural snowfall and the duration of snow cover have been decreasing in recent decades and will continue to do so in the future (see Section 1.3.1). For Austrian ski resorts, Steiger and Scott (2020) show that the season length with natural snow will decrease from 80 days in the reference period (1981–2010) to 63 days (GWL 1.8°C), 44 days (GWL 2.6°C) and 19 days

(GWL 4.3°C). With snowmaking, ski seasons would be 125 days long in the reference period, 120 days (GWL 1.8°C), 111 days (GWL 2.6°C) and 84 days (GWL 4.3°C). More relevant than the average shortening of the ski season, however, is the share of ski resorts with reliable snow conditions. While in the reference period (1981–2010), 99 % of the ski resorts in Austria can be considered technically snow reliable (i.e., considering modern snowmaking systems), this share decreases to 93 % (GWL 1.8°C), 80 % (GWL 2.6°C) and 31 % (GWL 4.3°C). However, despite shortened ski seasons, a substantial increase in water for snowmaking is required: 33 % (GWL 1.8°C), 60 % (GWL 2.6°C) and 73 % (GWL 4.3°C) (Steiger and Scott, 2020). Some Austrian ski resorts will therefore have to find alternative solutions for increasingly difficult winter operations, as it may no longer be technically possible to provide sufficient snow cover in some locations.

Another adaptation measure is to consolidate the existing ski area by concentrating ski operations and related infrastructure to reduce costs and operate more efficiently. In a ski area in Lower Austria, a part of the ski area was closed, and the snowmaking infrastructure was transferred to the remaining ski area, increasing the snowmaking capacity of that part (Scherrer and Begert, 2019; Redl, 2024).

In addition, a decrease in the size of large glaciers, as well as the disappearance of Austria's small and medium-sized glaciers is expected (Helfricht et al., 2019; François et al., 2023) (see Section 1.3.2). In the short to medium term, shrinking glaciers may provide some potential for increased demand, so-called 'last-chance tourism'. However, as noted by Mayer et al. (2024b), this may not be an appropriate long-term strategy. Adaptation options for summer skiing include the cessation of summer skiing operations and shifting to excursionists and technical adaptation measures such as geotextiles to reduce snow and ice melt, and depot snowmaking to ensure the opening of the ski season in the snow-scarce fall months (Mayer and Abegg, 2024).

Broadening the winter offer to include activities that are also possible without snow, will become increasingly important. It can also be used to address leisure trends. The proportion of winter-holidaymakers whose main activity is winter hiking increased from 3 to 13 % between 2012 and 2018 (Steiger et al., 2021a). In principle, a range of summer activities can be extended to the (snow-free) winter. For example, during the extremely snow-poor Christmas holidays of 2022/23, mountain bike trails, summer toboggan runs, and motor skills parks were reopened in some Lower Austrian ski resorts (NÖN-Redaktion, 2023).

Strengthening the summer season can reduce dependence on the winter operations. Many destinations are already successful in this respect, as shown by the stronger growth in overnight stays in recent summer seasons. Escaping the heat may provide some potential for summer tourism in alpine areas (Juschten et al., 2019). However, daily spending by guests in winter (EUR 205 on average) is still significantly higher than in summer (EUR 163) (Österreich Werbung, 2023). Although the number of tourists could be increased, social and ecological impacts could be exceeded and should therefore be considered in adaptation strategies.

Vulnerability

Compared to urban tourism, the vulnerability of alpine tourism is significantly higher, as many destinations are still dependent on winter tourism. However, the importance of summer tourism has increased in mountainous areas reducing the dependence on snow over time (Pröbstl-Haider et al., 2021). Currently, the additional income in summer does not compensate for the losses in winter, as tourist spending is 25 % higher in winter than in summer and therefore the total value added is likely to be different as well (Burton et al., 2024). For summer tourism, increasing risks from natural hazards (e.g., by thawing permafrost and glaciers) and maintenance of the hiking infrastructure are significant challenges.

Family firms, which make up the majority of tourism businesses in the Alps, have to cope with competitive disadvantages that include poor economies of scale and scope, minimal potential for diversification and innovation and limited access to capital markets. Therefore, this structure is perceived as very fragile and less resilient due to the small company size, low growth rates, weak internationalization, relatively low market entry barriers (allowing fewer professional entrepreneurs to enter the market), limited potential for diversification, high debt-to-capital-ratios and limited qualification levels (Zehrer and Mössenlechner, 2009; Pikkemaat and Zehrer, 2016). This structural weakness could lead to significant economic impacts, if many of these family businesses were to go out of business due to climate change. Economic vulnerability is therefore higher in the Alpine region than in the lowlands of Austria. In the Alps, alternative employment opportunities outside of tourism and agriculture are limited.

7.4.3. The Alps as home to communities

Demography and settlements

Effects of climate change

Changes in demography and land use are mainly driven by socio-economic factors. Currently there is no evidence that climate change significantly influences demographic changes as well as allocation and distribution of settlements and infrastructure in the Austrian Alps. Conversely, it is evident that demography and existing settlement structures influence GHG emissions mainly through the associated energy and mobility demand (Stöglehner et al., 2016a; Stöglehner and Abart-Heriszt, 2022; Haberl et al., 2023) (*medium evidence, high agreement*) (see [Section 3.2.2](#)). Furthermore, demography, settlement and built infrastructure influence the potential exposure to climate-related impacts, such as heat waves (Oleson et al., 2015; GeoSphere Austria, 2022) and various natural hazards (Cammerer et al., 2013; Fuchs et al., 2015b; Löschner et al., 2017; Junger et al., 2022) (*high confidence*).

The regional divide in population development in the Austrian Alps (see [Section 7.2.2](#)) will continue to increase, as will the unbalanced intra-regional population development between the main valley areas on the one hand and the side valleys and peripheral locations on the other hand. Population forecasts at the district level until 2050 largely confirm and extend these trends for the coming decades (Österreichische Raumordnungskonferenz, 2023c). Household forecasts at the district level until 2030 indicate an increase in households in the vast majority of the Austrian Alpine districts (Österreichische Raumordnungskonferenz, 2024). The development of households is more strongly correlated with settlement development (resulting in further land take) than with population development. A decrease in average household size is projected for all Alpine districts (Österreichische Raumordnungskonferenz, 2024).

Based on these demographic trends, an increase in building, land use and infrastructure can be expected in growth areas, particularly in the already densely populated urban centers and ribbon-like settlement structures in the valleys and, depending on the development of tourism, also in tourism resorts with distinct urban characteristics. Whether the expansion of built-up land also takes place in scattered settlement areas with low densities, depends primarily on spatial planning policy (e.g., the willingness to regionally restrict settlement development to central locations), since a

decline in the population and a slight increase in the number of households do not necessarily lead to a stagnation in the expansion of build-up land. There is no confirmed evidence whether and to what extent climate change is currently influencing these demographic and land use trends. Prolonged heat waves and their impacts on densely built-up urban areas (predominantly outside the Alps) could increase the attractiveness of currently sparsely populated Alpine areas as residential locations in the future, leading to an increase in population and building land uses there (Membretti et al., 2023). A substantial reduction in the intensity of winter tourism due to rising snowlines could lead to a population decline in Alpine tourist resorts (Steiger et al., 2021b).

Land competition in Alpine valleys is likely to intensify (see Section 3.2.2). This will put additional pressure on open spaces and the various ecosystem services they provide. Whether increasing settlement development in the valley areas will lead to an increase in GHG emissions, depends on how additional development is coordinated through spatial planning and the extent to which increasing mobility demands can be met by public transport. Increasing land use and population densities influence exposure to climate-related impacts (*medium evidence, high agreement*).

Comparable to the whole country, the share of older people (aged 65 and over) in the Alpine region is projected to increase (Österreichische Raumordnungskonferenz, 2023c). This development is most pronounced in Alpine regions, which are confronted with a significant population decline. It eventually leads to increased vulnerability to extreme weather events, particularly to heat waves (Hutter et al., 2007; Haas et al., 2014) (*high confidence*).

Finally, it should be noted that socio-economic development is based on complex interrelations. Related trends are therefore non-linear. Single, even minor causes may have largely unpredictable far-reaching consequences.

Mitigation

Density, together with the implementation of other spatial planning principles such as compactness and mix of spatial functions, urban redevelopment rather than greenfield development, and coordination of development with public mobility services (Jabareen, 2006), are crucial for energy demand, renewable energy supply (e.g., by district heating systems) and public transport systems. In contrast, low-density development and urban sprawl contribute substantially to an increase in energy consumption and motorized private transport and, thus, to an increase in GHG emissions

(Stöglehner et al., 2016b; Stöglehner and Abart-Herisz, 2022) (*high confidence*) (see Section 3.2.2).

Some spatial framework conditions in Alpine areas, particularly in densely populated urban centers and ribbon-like settlement structures in the valleys, potentially provide favorable conditions for climate change mitigation. Limited development space and higher land prices provide incentives for higher density housing and, thus, land-saving development (Österreichische Raumordnungskonferenz, 2021, 2024). Topography, limited development space and accessibility reasons (large transport infrastructure in valleys) lead to a concentration of commercial and industrial development in the valley areas. Both densification effects can be regarded as supportive of efforts to reduce GHG emissions (*limited evidence, high agreement*).

Without appropriate regional planning regulation, the development of peripheral settlements and scattered housing structures as well as decentralized tourism projects (e.g., chalets, holiday residences) carries the risk of low-density development and urban sprawl (Meyer and Job, 2022), which contributes to land take, requires substantial infrastructure efforts and increases motorized individual transport and related GHG emissions. Urban redevelopment and concentration of settlement development in local and regional development centers on the one hand, and limiting development in scattered housing areas on the other, are spatial planning strategies that support climate change mitigation (Stöglehner and Abart-Herisz, 2022) (*high confidence*). The unbalanced population development trends in the Austrian Alps provide opportunities to concentrate development in locations that are favorable in terms of energy demand, renewable energy supply and public transportation. Related trade-offs with rural development strategies should be considered.

Adaptation

Aiming at higher compactness in settlement development is regarded a key issue for climate change mitigation, however, trade-offs with the provision of sufficient open spaces (including those required for climate change adaptation) and potential increased exposure to heat stress and natural hazards need to be considered (see Section 3.2.3). Population development trends in the Austrian Alps are likely to result in higher settlement densities in urban centers and ribbon-like settlement structures in the valley areas. Additionally, limited development space and high land prices put pressure on open spaces making it more difficult to imple-

ment nature-based options for adaptation to climate change (Schindelegger et al., 2022).

The need for adaptation to heat stress is likely to increase in densely built-up areas, exacerbated by an ageing population. However, urban heat islands not only depend on building density and the degree of sealing, but also on topography and climate. In particular, the supply of cold air from forests, agricultural areas, urban green spaces, and other fresh air corridors is important. In alpine areas, warm nights are less frequent than in the lowlands due to the nocturnal flow of cold air down the slopes into the valleys (Gerersdorfer et al., 2009). As Schöner and Haslinger (2020) point out, temperature extremes will play a comparatively minor role at altitudes above 800 m a.s.l. (Schöner and Haslinger, 2020). At altitudes below 800 m, temperature extremes have increased in recent decades and will continue to increase in the future. The altitude range below 800 m includes all urban centers and densely built-up ribbon-like settlement structures in the Austrian Alps (*medium evidence, high agreement*).

Whether settlement development and, especially densification, affects the need for adaptation to natural hazards depends on the location of the development and whether current and potential future hazard zones can be avoided. Due to the topography, limited development space and accessibility reasons, building and infrastructure densities and, thus, potential exposure to natural hazards are high in Alpine valley areas (Fuchs et al., 2015b). This is particularly the case for areas with a lower hazard intensity where development is not restricted by spatial planning regulations (Nachtnebel and Apperl, 2015; Löschner et al., 2017) (*high confidence*). With regard to river floods, for example, a damage potential of EUR 357 million was calculated for a 20 km stretch in the Lower Inn Valley in Tyrol in the event of a 100-year flood. In the case of a 300-year flood, the corresponding damage potential is EUR 736 million (Bundeswasserbauverwaltung Tirol, 2016; Blöschl, 2020). If flood hazards are exacerbated by the effects of climate change, this would result in further adaptation needs, particularly in urban centers and ribbon-like settlement structures. Stagnation or population decline usually do not result in a reduction in built-up areas. It is therefore likely that adaptation needs regarding natural hazards are also relevant for other Alpine settlements. In particular, the tradition of scattered housing outside the valleys has led to an extensive rural road network connecting (former) single farms to the main transport infrastructure in the valleys, which is considerably exposed to natural hazards such as flash floods or landslides (*limited evidence, high agreement*).

Alpine settlements and their development, including associated infrastructure, are highly dependent on the functioning of protective forests. Climate change impacts challenge their stability, mainly by windthrow, infestation by bark beetles or wildfires (Vacik et al., 2020). These impacts are likely to influence long-term hazard exposure of settlements and infrastructure (Schindelegger et al., 2022) and may result in further adaptation needs (*limited evidence, high agreement*).

Vulnerability

There is no confirmed evidence that climate change impacts are currently influencing the number and distribution of people and building land uses in the Austrian Alps. Related changes are solely triggered by socio-economic factors. Population and household projections indicate a further increase in building land uses (settlements and infrastructure), particularly in the main valley areas of the western Austrian Alps, which will most likely lead to increased land competition and further pressure on existing open spaces. This is likely to lead to increased exposure to natural hazards and reduced scope for adaptation to climate change. These effects are less pronounced in most of the valleys of the eastern Austrian Alps as well as in areas with low settlement densities. Spatial and temporal variability leads to differentiated vulnerability patterns.

Mobility and transport infrastructure

Effects of climate change

Mobility in the Alpine region is characterized by the overlapping of the everyday and leisure mobility of the (local) population, the arrival and departure of tourists and their on-site mobility (including day trips from neighboring (urban) regions) and tourists passing through (passenger transit). Likewise, the goods traffic of the local economy and supply overlaps with long-distance freight transit traffic. The following figures demonstrate the extent of this overlap. In Tyrol in 2022, the prominently discussed truck transit accounted for about 2.56 million trips per year (Land Tirol, 2023). In the tourism sector, there were about 11 million tourist arrivals, leading to 22 million arrivals and departures in that year (Statistik Austria, 2023b), while the local population made about 1.25 million car trips per day (Köll and Bader, 2022; Land Tirol, 2023). Due to the topographical conditions in the valley, the transport network does not offer any alternatives so that this overlapping takes place on the few main roads and leads to corresponding (temporary and seasonal)

congestion and negative effects, e.g., through noise and emissions, on the population in the densely populated valleys, but also in the adjacent hillside locations (*high confidence*).

The spatial pattern of the Alpine region also leads to special characteristics of everyday and leisure mobility. Due to the high density in the central valleys, the shares of walking and cycling are comparatively high (Tomschy et al., 2016). There is also an expectation that climate change will increase the popularity of cycling, which is currently very seasonal. However, there are no reliable findings on this in the literature. On the other hand, long supply and commuting routes in peripheral valley locations are (or have to be) covered by motorized transport. This also leads to high traffic loads and congestion at the valley entrances (e.g., Zillertal Brettfall Tunnel, outer Ötztal). The valley locations have comparatively good, linear public transport connections. However, the quality of service is poor in peripheral locations, where regular service is not economically justifiable (*medium evidence, high agreement*).

Tourist mobility in the Alpine region also has special characteristics. Arrivals and departures are predominantly by car (over 80 % in winter and summer), the share of rail is relatively low at approximately 6 % (e.g., for Tyrol) (Bursa et al., 2022). Relevant winter air traffic comes from more distant source markets to regional airports (Innsbruck, Salzburg, Klagenfurt) and nearby major airports (Munich, Zurich). Although the tourism sector is of great importance for the national economy with a share of 7.6 % of the gross domestic product (in 2019 including direct and indirect effects) and even higher shares in the Alpine regions (e.g., Tyrol 16.9 %, Salzburg 13.7 %; according to Statistik Austria (2021)), it is largely unknown how much emissions the Austrian tourism sector causes. Neger et al. (2021) attribute this mainly to the fact that most products and services consumed by tourists are not exclusively related to tourism. They provide an estimate based on available data with a destination-based accounting approach that includes not only emissions within Austria but also those caused by international guests traveling abroad. They estimate the total emissions of the tourism sector in Austria at 4.31 MtCO₂eq, which is a share of 4.2 % of the total emissions in Austria. Of this, 92.2 % of CO₂eq is attributable to travel. As they note, this high share is mainly due to air travel by international guests. In alpine tourism, however, this share is significantly lower, with more than 80 % of the guests arriving by car. Accordingly, in a case study of a Tyrolean destination (Alpbach), Unger et al. (2016) determined the share of transport in tourism emissions to be 54 %. Studies show that holidaymakers are well

aware of the high CO₂ emissions associated with vacations but that they indicate a low willingness to change their behavior significantly in this regard (less frequent but longer vacations, closer destinations, no air travel), thus creating an awareness–behavior gap (Mailer et al., 2019).

The transport infrastructure is characterized, on the one hand, by the fact that there are only a few efficient routes or connections in the main valleys (transit areas). When the motorways become congested, traffic increasingly tries to use the less efficient parallel rural roads, causing high levels of congestion in the settlement areas. Recently, this has been countered by banning motorway exits forcing passing vehicles to stay on the motorways. Due to the topography, railways are only present in a few side valleys. On the other hand, transport infrastructures in Alpine regions are particularly exposed to natural hazards (rockfall, debris flows, snow avalanches), which require protective structures (it should be noted, that roads and railways are already more expensive to build and maintain due to the higher demand for artificial structures such as bridges and tunnels) and there is still the risk of temporary closures that restrict the accessibility of valleys. In addition, there is increased operational effort (winter service, maintenance of railway lines with narrow bends, etc.) (*high confidence*).

Population growth is leading to an increase in everyday and leisure mobility. Tourism also continues to focus on growth in the number of guests and overnight stays. Attempts to promote rail travel have not yet yielded the desired results. Shorter stays are also leading to a disproportionate increase in arrivals and departures.

While in the 1970s, guests in Austria spent on average just under 7 nights (for guests from abroad), or 6 nights (for domestic guests) in holiday accommodation, this number has now been reduced to just under 3.5 or 2.8 overnight stays (BMLRT, 2020), in line with international trends in length-of-stay (Gössling et al., 2018). Correspondingly, the number of arrivals at accommodation establishments in Austria tripled as the number of overnight stays increased by 50 % (Statistik Austria, 2019a, 2019b). This means that the intensity of travel has increased and that there is a greater overlap of arrival and departure traffic with local traffic, even on weekdays. Travelers' demands for flexibility and speed of the available means of transportation have increased significantly, in order to keep the travel time as short as possible and to spend as much time as possible at the destination. This favors the private car as the mode of transport of choice and poses major challenges for destinations that rely on climate-friendly travel (Gronau and Kagermeier, 2007).

By 2019, the number of guests from more distant growth markets had been increasing, which is also reflected in the growing number of passengers at airports near tourist destinations (e.g., Innsbruck). These markets have an above-average share of arrivals and departures by air, which also has an increasing impact on GHG emissions (Zech et al., 2013; Peters et al., 2016) (*high confidence*).

Restricting freight transit traffic is contrary to the demands of neighboring countries and the principle of free movement of goods and people in the EU. Even with great efforts (Brenner Base Tunnel), with current measures, a shift to rail seems to be limited to absorbing not much more than the increase in freight traffic. A higher shift can only be reached with additional powerful policy measures (BCP – Brenner Corridor Platform, 2021). Efforts to increase tourist traffic in the southern neighboring countries such as Italy/South Tyrol, Slovenia and Croatia will result in an increase in passenger transit (*high confidence*).

The impact of climate change on tourism has already been addressed in [Section 4.3.3](#). This has particular implications for Alpine regions. Changing climatic conditions can alter travel and thus mobility behavior of tourists. For example, a lack of snow in some areas and a shorter winter season, can lead to higher numbers of visitors in a shorter timeframe, to tourists traveling to more snow-reliable but also more distant winter destinations in the inner Alps, or to tourists switching to other non-snow holiday destinations (e.g., the Canary Islands), which involves a switch of transport mode (from car to air) and increases travel distance. Changes in travel behavior and thus mobility behavior can also be seen in the summer season. Hot summers, in particular, drive city dwellers to the surrounding areas and nearby alpine destinations, and short summer breaks are becoming increasingly important (Cavallaro et al., 2017; Thurm et al., 2017; Juschten et al., 2019; Juschten and Hössinger, 2021) (*high confidence*).

Climate change also increases the potential for some natural hazard types to affect infrastructure (see [Section 7.4.1](#)), thus, increasing the vulnerability of transport relationships (accessibility and mobility). Increasing traffic flows and dependence on motorized (long-distance) transport will also increase this effect. In alpine regions, the expected rise in temperature is likely to have ambivalent effects on the infrastructure. On the one hand, roads will require less effort in terms of frost resistance and spring thaw. On the other hand, higher surface temperatures require higher quality materials. The same applies to railways, where the mountain routes are characterized by narrow curves, and where

rising temperatures have a stressing effect and increase the risk of buckling, while less snow leads to less maintenance and operational effort and related emissions (snow removal, prevention of icing) (*medium evidence, high agreement*).

The supply of transport services can be affected by potential climate impacts. In particular, extreme weather events such as heat waves, extreme rainfall, and storms can severely restrict traffic flow and disrupt operations. But also associated hazards, triggered by events such as landslides and floods, can lead to significant damage to the transport infrastructure and disrupt traffic flows and logistics (Stahel et al., 2013; Cavallaro et al., 2017). In this context, adaptation measures are needed to strengthen the resilience of the transport systems through improved traffic management in the event of a crisis, as well as to adapt the infrastructure to ensure (not only, but in particular) the accessibility of tourist destinations (Gühnemann et al., 2021) (*high confidence*).

Mitigation

Avoid/shift/improve strategies and the potential of virtual mobility (see [Sections 3.4.2, 3.4.3, 3.4.4](#)) have to be considered regarding the special conditions in the Alpine region. For decarbonization, e.g., through alternative drives, there are special requirements due to the topography and the (winter) climate regarding e-mobility and the charging infrastructure due to the massive tourist travel flows and the need for on-trip charging (*medium evidence, high agreement*).

A significant reduction of travel-related GHG emissions in tourism cannot be solely achieved with technological solutions (electric vehicles) or trends (sharing); it also requires shifts in transportation patterns, such as increased use of rail and public transport over air and private road travel. Similarly, rail travel can be supported by improving on-site mobility and services along the entire travel chain (from pre-booking information to return). Due to the mentioned awareness and behavioral gap among tourists, this calls for measures that not only offer incentives (fast and direct train and bus connections, climate-friendly local transport, luggage services, attractive all-inclusive packages, etc.), but also focus on closer rather than distant home markets, encourage longer stays, and offer awareness campaigns for local stakeholders and tourists, as well as push and pull strategies (*high confidence*). Several case studies show significant effects of improving public transport services (e.g., free arrival by train) (Blättler et al., 2024) or local mobility services at the destination such as bus services and mobility hubs (BMNT, 2017; Bursa et al., 2024). The awareness created by

COVID-19 and the climate crisis can be seen as an opportunity to take appropriate measures (Gühnemann et al., 2021) even if current developments clearly indicate that there is a risk of falling back into old patterns.

Adaptation

There will be a need to increase resilience by upgrading and protecting transportation infrastructure against natural hazards, but also in the context of spatial planning that strengthens local supply (amenities) and thus local mobility. This is also important to ensure escape routes and supplies in the event of natural hazards. Developing emergency plans and strategies can help enhance preparedness and response efforts. When protecting the infrastructure, it is important to remember that the constructional measures themselves have a climate impact. These rebound effects can be minimized through careful selection of construction methods and materials (*medium evidence, high agreement*).

In order to keep public transport as an attractive offer both for arrivals and departures as well as for local mobility, the following measures from the adaptation strategy (BMNT, 2017) are also relevant in response to increasing heat days: (i) Ensuring thermal comfort by reducing the thermal loads in transport stations and their surroundings; (ii) Reducing possible thermal loads for passengers and staff in public transport through appropriate air conditioning (*limited evidence, high agreement*).

Vulnerability

In the Alpine regions, natural hazards can restrict the mobility of the population and the accessibility of places for daily needs, as there are often no alternative routes due to the limited space. The remoteness and lack of redundancy of the road network make the Alpine region particularly vulnerable. On the other hand, the expansion of protective measures for transport routes is associated with significant CO₂ emissions (*high confidence*).

7.5. Needs for resilient mountain regions in Austria

In mountain areas in general, most existing adaptation measures (structural and non-structural) are reactive rather than proactive to climate change and are often part of a post-disaster recovery strategy (McDowell et al., 2021) (*robust evidence, medium agreement*).

Although many adaptation measures have been adopted in Austria, specifically for mountain regions, there are still gaps in effective adaptation. To close these gaps, transformative adaptation in different sectors is needed in mountain regions (McDowell et al., 2021) (see Section 7.5.2). However, as suggested by Salim et al. (2021), coping and incremental approaches are also needed, in addition to transformative adaptation approaches. For this reason, the section on adaptation and mitigation needs in the Austrian Alps is structured as follows: Monitoring (7.5.1), (socio-economic) transformation (7.5.2), non-structural protection measures and nature-based solutions (7.5.3), and structural measures (7.5.4). The adaptation options for mountain areas in Austria are presented in Table 7.1, according to the ASI principle (Avoid, Shift, Improve; see Cross-Chapter Box 4).

7.5.1. Monitoring of natural processes/hazards and provision of climate services

Continued and improved monitoring of environmental conditions and processes (e.g., climate, hydrology, glacier and permafrost changes, natural hazards) may serve as a basis for information on climate adaptation. Climate model scenarios for the Alps are still subject to high uncertainties (Section 7.3.2), especially for precipitation. Climate services of the same quality for mountain regions, as for the rest of Austria, must be advanced in regional climate modeling for the Alpine region (e.g., convection-permitting models). Monitoring of runoff and sediment dynamics of alpine rivers needs to be further improved, especially in torrent catchments that have not been monitored to date and pose a significant hazard potential and risk to the built environment (this includes also monitoring of soil properties, e.g., water storage capacity and carbon stock). Monitoring of hazardous conditions in tourist areas (e.g., hiking trails) could be used to better inform tourism stakeholders and tourists about potential risks. Moreover, monitoring and management of invasive species (Permanent Secretariat of the Alpine Convention, 2019) can support the conservation of Europe's high mountain biome. In terms of biodiversity, monitoring of species shifts, and changes in abundance and growing seasons could be beneficial. Additionally, it is important to monitor biodiversity changes of different organism groups (e.g., plants but also animal groups and soil organisms). Monitoring and mitigation of natural forest disturbances (wind, fire, pests) may also support adaptation to climate change. Monitoring of permafrost and erosion and their short- and long-term

effects (Permanent Secretariat of the Alpine Convention, 2019) is also important for the assessment of changing risks to infrastructure in high alpine terrain (huts, alpine routes, ski lifts). Generally, an improved and denser monitoring network for hazard triggers and hazard processes could improve monitoring results.

According to the WMO, early warning systems (EWS) are a top priority for climate change adaptation and could be a valuable tool for disaster risk reduction in Austria's alpine region. According to Pappenberger et al. (2015), there are significant monetary benefits related to early flood warnings in Europe. Specifically, for every EUR 1 invested in early flood warning, there is a benefit of EUR 400. According to the same source, the avoided damage due to early flood warning may reach 32.85 % of the total damage. While the drivers of natural processes such as temperature and precipitation have been affected by climate change, there is *limited evidence* that this has affected the number of natural hazards occurring in mountain areas. However, there is *high confidence* that the exposure in mountain areas has increased (Fuchs et al., 2015b, 2017). In view of the particularly strong changes in the frequency and intensity of hazard processes due to climate change, it may be beneficial to reconsider the current delimitation criteria for hazard zones (avalanches, debris flows, floods).

7.5.2. Transformation

Several mountain areas in Austria are characterized by climate change-related impacts (e.g., reduced snow cover), land use changes as well as other societal and structural problems, and require a significant change based on holistic analyses and awareness of the interrelated challenges. In other words, transformation is required in several sectors.

More specifically, as far as **agriculture** is concerned, adaptation measures in mountain areas may be related to transformation. Some of them are not directly related to climate change (hidden adaptation, e.g., organic farming), but to other challenges (e.g., changing agricultural policies and market conditions) (Grüneis et al., 2016). However, some hidden adaptation actions, which include measures such as long-term learning processes, self-organization, local knowledge, and adaptive governance, may be more effective. Transformation could include the cultivation of non-traditional crops, the transformation of consumer demands (consumption of local products) as well as the energy efficiency of farms (Permanent Secretariat of the Alpine Convention, 2019). In addition, shifting agricultural land upwards and improving

soil properties could also contribute to adaptation (see [Section 7.4.2](#)). With regard to **forests**, the conversion of forest ecosystems to include endemic species that have been adapted to climate change (Permanent Secretariat of the Alpine Convention, 2019) as well as a shift from single tree types to multiple tree type forest could support adaptation to climate change (see [Section 7.4.2](#)). Nevertheless, the choice of tree species is often highly controversial. Regarding **tourism**, transformative adaptation measures may include alternative hiking routes and season shifting with mixed results (Adler et al., 2022) but also the promotion of activities that can be carried out without snow, the extension of summer activities in winter and the strengthening of the summer season (see [Section 7.4.2](#)). Finally, the expectation that the Alps will benefit from a shift of tourism from the Mediterranean to the Alps, due to high temperatures, is not supported by the existing literature, although the modeling of tourism demand in Europe showed that it is expected to decrease (under different climate change scenarios) for southern Europe while tourism demand for northern Europe is expected to increase (Matei et al., 2023). Further, since tourism requires energy, the transition to green fuels and investments in hydrogen drives, sustainability and energy concepts could support adaptation. Decision-making tools have been developed for other locations in the European Alps to support ski resorts in the assessment of their energy demand and provide them with information on available renewable energy resources (Polderman et al., 2020). Moreover, a transition in the accommodation sector (e.g., improving infrastructure efficiency, behavioral changes, greening energy production and carbon off-setting) would be beneficial since it is a substantial contributor (10 %) to total GHG emissions from the tourism sector. Improving infrastructure efficiency alone can reduce 15–20 % of emissions from the accommodation sector (EY Parthenon et al., 2021). However, financing can be a challenge, especially in small resorts. In addition, minimizing the carbon footprint of alpine hotels and gastronomy (regional products) should be an aim (Permanent Secretariat of the Alpine Convention, 2019). Ski areas can purchase green electricity to reduce CO₂ emissions from lift operation and snowmaking. For slope grooming, emissions can be effectively reduced by using alternative forms of propulsion (e-drive) or fuels (e.g., HVO) (Steiger et al. 2021a). In the energy sector, alongside efforts to improve energy efficiency and savings across all areas, there is potential for expanding renewable energy and decentralizing its production (Permanent Secretariat of the Alpine Convention, 2019). The **built environment** in the Austrian Alps also needs to be trans-

formed to adapt to the effects of climate change, including the avoidance of new development in hazard-prone areas and the adaptation of the existing building stock. Regarding mitigation, spatial planning can be used to support the densification of existing settlement areas and guide new developments toward urban and regional centers (Section 7.4.3). In the **mobility sector**, mitigation measures could include the promotion of rail travel, on-site mobility with public transport and active transportation modes, climate-friendly local transport vehicles, a shift to short and medium distance source markets, and the provision of alternative or public transport options for tourists to and within Alpine destinations (Permanent Secretariat of the Alpine Convention, 2019). Adaptation could include a further expansion of information and early warning systems related to tourism and mobility, a functioning transport system, review/adaptation of legal standards for the construction and operation of transport infrastructure considering climate change, and ensuring thermal comfort within public transport and its surroundings (e.g., stations and stops) (Gühnemann et al., 2021).

7.5.3. Non-structural adaptation measures and nature-based solutions

River renaturation is crucial but there is also a need to focus on the decision-making context of nature-based solutions in the Alps, taking into account local climate projections (Dubo et al., 2022). With regard to biodiversity and ecology, more ecological connectivity projects are needed (Permanent Secretariat of the Alpine Convention, 2019). Examples of such projects already exist in Austria (e.g., project PORTAL, ‘Pathways of Transformation in the Alps’) (Observatoire des Sciences de l’Univers de Grenoble, 2024). Additional adaptation needs may include landscape preservation, avoidance, reduction and monitoring of soil sealing, improvement of soil quality and enhancement of the protective function of forests (Permanent Secretariat of the Alpine Convention, 2019). All of these should be supported by the appropriate legal frameworks. In protective forests, interventions such as thinning and regeneration cutting may support the coping capacity of forests (see Section 7.4.2).

To ensure effective implementation of adaptation measures, cost-benefit analyses, monitoring of adaptation plans, governance and participation as well as financing are needed, as is shown in the pilot program ‘Climate Change Adaptation Model Regions for Austria – KLAR! (Klimawandel-Anpassungsmodellregionen)’, which is funded by the Austrian Climate and Energy Fund. Transnational/transboundary cooperation could be emphasized, as well as communication

among regions, countries, scientists, practitioners, authorities, and the public. Implementation requires giving high priority to adaptation, climate-proofing in all activities, initiating pilot actions, promoting international information exchange among mountain regions, monitoring of all actions, and enabling communication and cooperation among stakeholders (Scott et al., 2022). An example of this type of collaboration is the AlpEs (‘Alpine Ecosystem Services’) project, which aims to map, maintain and manage ecosystem services in several Alpine countries including Austria (Interreg Alpine Space, 2021). Finally, involving people in the adaptation decision-making process and addressing multiple rather than single risks (Terzi et al., 2019) lead to more robust adaptation strategies (Owen, 2020).

7.5.4. Structural adaptation measures

Although there is a trend to move from structural to non-structural measures, structural protective measures for the alpine infrastructure and settlements are still necessary. Grüneis et al. (2016) suggested that the focus is on technical adaptation measures, which may also be vulnerable to climate-related extreme events (e.g., power failure). Local structural protection mitigates hazards at low cost (Papathoma-Köhle et al., 2019) and building codes may help adapt buildings to climate change, but also improve the Build Back Better (BBB) after disaster recovery. Insurance incentives and improved risk transfer support recovery.

Climate-proofing hydropower is crucial. Future changes in flow and sediment dynamics may require a reconsideration of operational policies for existing plants, including adaptive water targets and sediment management. Cost-benefit analyses for renewals and new plants should take into account long-term effects of climate change on flow and runoff (Permanent Secretariat of the Alpine Convention, 2019).

Finally, maladaptation (adaptation measures that increase rather than reduce vulnerability) should be avoided. In this respect, cross-sectoral policies may be the solution as adaptation measures in one sector may increase the vulnerability of another sector (Alpine Convention Guidelines). For example, it is not clear whether artificial snowmaking in alpine ski resorts is a maladaptation (Roncucci, 2020), but there is potential to improve its performance, which will determine whether it can be considered a maladaptive or successful adaptation (Scott et al., 2022). According to Schinko et al. (2013), artificial snow can reduce up to 75 % of the economic impacts of climate change on winter tourism, but at the same time it increases production costs.

Table 7.1 Adaptation options for the Austrian Alps presented considering the ASI principle (Avoid, Shift, Improve)

Thematic area	Avoid	Shift	Improve
Climate change	Further CO ₂ emissions through mobility and tourism in the Alps	Transitions in many sectors (e.g., mobility, tourism) to reduce further CO ₂ emissions	Improve climate scenarios for the alpine space Monitoring of atmospheric processes in the Alps
Natural hazards	Building in hazardous areas (considering variations due to climate change)	Reduce the vulnerability of the built environment and infrastructure to natural hazards by adapted design and local adaptation River renaturation to reduce flood events	Monitoring of hazards and triggering processes Risk transfer options (insurance) and incentives for local adaptation measures -Existing hazard mapping to include climate change Local and regional land use planning
Biodiversity	Impacts of human land use (agriculture, energy production and tourism development) on biodiversity	Improvement of spatial planning	Monitoring of biodiversity changes in the Alps Collaboration with nature conservation authorities to design management strategies Public awareness about the risk of losses Preservation of larger and better-connected areas to mitigate losses of alpine ecosystems
Forestry and agriculture	New development that could have negative effects on protective forests	Non-native species more resilient to climate change (debatable) From single species strands to mixed species strands Introduction of non-traditional crops Shift in consumer demands and preferences	Preservation and restoration of protective forest Financial support for the managers of protective forests Biological soil properties by nitrogen-fixing plants, the addition of organic material, and water conservation by a cutting height of at least 8 cm to tackle drought in the agricultural sector Irrigation of crops
Buildings, infrastructure and mobility	New development of energy inefficient buildings and infrastructure Reduce the need to travel (e.g., digitalization)	Shift from private car to public transport or non-motorized vehicles Adapt building stock to withstand natural hazards	Insulation of buildings (also relevant for the thematic area 'energy') Redundancy in the road network Improve the energy efficiency of vehicles
Energy	Impact from natural hazards on energy infrastructure	More green sources of energy (also relevant for the 'tourism' thematic area)	Acceptance of renewable sources of energy from the tourism sector
Tourism	Old practices that encourage further CO ₂ emissions (e.g., non-green electricity for powering ski lifts and snow making machines, diesel-powered slope preparation) Destruction of carbon sinks for new touristic development	Find employment alternatives through the economic strengthening of regional centers Identification and development of alternative tourism products Promote sustainable destinations Promote alternative transport modes (see transport)	Make existing infrastructure energy efficient (e.g., energy efficient hotels)

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