Report on the effects of Climate Change on the Alpine Space Snow Tourism Destinations

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Who should read this report?

The intended audience of this document are:

Local and Regional Public Authorities, to increase the knowledge base and the awareness of local and regional public administrators on this specific aspect of climate change in the Alpine territories they are responsible for.

Local and Regional DMOs, to increase their understanding of the systemic nature of the lack of snow coverage and give them the first necessary information to consider taking future transition steps to increase the resilience of Alpine Snow Tourism Destinations.

Tourism SMEs, to increase the knowledge base and the awareness on this specific aspect of climate change impacting on their activities, and to prepare them for the challenges and the necessary enhancement of climate and socio-economic resilience through sustainable development alternatives.

Local communities of STDs, because they are also negatively impacted by increasing lack of snow and the diminishment of the attractiveness of skiing. By reading this document and, in particular, its textual summary and infographics, STDs citizens can increase their knowledge of the problem and their awareness.

This report aims at explaining in simple words the basic and some advanced features of the effects of climate change on the Alpine Space Small Tourism Destinations, with specific focus on the lack of snow coverage. As Climate Change is a very complex issue, not every feature may be explained in this document.

This publication is available on the project website https://www.alpine-space.eu/project/beyondsnow/

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Mission Statements

To provide an overview on the main effects of climate change (CC) on the Alpine Space small Snow Tourism Destinations currently affected or that will be affected in the future by lack of snow coverage.

Disclaimer

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Acronyms used in this report

BeyondSnow-specific acronyms are **bold**.

Acronym	**Meaning**
ALPCONV	Alpine Convention
AS	Alpine Space
CC	Climate Change
CO2	Carbon dioxide
DMO	Destination Management Organisation
EAWS	European Avalanche Warning Services
EC	European Commission
EEA	European Environment Agency
ES	Ecosystem Services
EU	European Union
EUSALP	EU-Strategy for the Alpine Region
GHGs	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
OECD	Organisation for Economic Co-operation and Development
PWA	**Pilot Working Areas**
RAM	**Resilience Adaptation Model**
RCP	Representative Concentration Pathways
RDMDT	**Resilience Decision-Making Digital Tool**
SME	Small and Medium-sized Enterprises
STD	**Snow Tourism Destination**
SWT	Snow & Winter Tourism
UN	United Nations
UNFCCC	United Framework Convention on Climate Change
WMO	World Meteorological Organization

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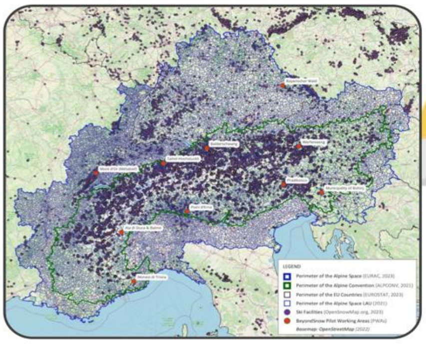

1 CLIMATE CHANGE **IS REAL**

2 THE **ALPS** ARE MORE **VULNERABLE**

3 THE **SNOW COVERAGE IS DECREASING**

4 THE **NEGATIVE EFFECTS** AFFECT **ALL SNOW** TOURISM DESTINATIONS

5 **ECOLOGICAL, ECONOMIC** & **SOCIETAL IMPACTS**

6 **SMALL SNOW TOURISM DESTINATIONS** AT LOW AND MEDIUM ALTITUDES ARE THE MOST SUFFERING

...IN WHICH MAINTAINING SNOW-RELATED ACTIVITIES WILL NO LONGER BE POSSIBLE AS AT PRESENT

REDUCTION IN SKIABLE DAYS

RISING COSTS

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LOSS OF ATTRACTIVENESS

NATURE & BIODIVERSITY

WINTER TOURISM

KEY HUMAN INFRASTRUCTURES

ECOSYSTEM SERVICES

TEMPERATURE AND RATES OF SNOWMELT

PRECIPITATION & SNOWFALL

WIND

SNOW COVER DURATION AND SNOW DEPTH

NEW (SNOW) TECHNOLOGIES & **YEAR-ROUND TOURISM ACTIVITIES**

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1 Introduction and background

According to the Intergovernmental Panel on Climate Change (IPCC, 2021) **there is no doubt that the human activities are the main causes of the current climate crisis, mainly due to** the burning of fossil fuels such as coal, oil and gas. Representatives of the IPCC also commented on the data pointing out that 'current negative trends are in no way compatible with a stabilisation of global warming' (Adaoust, 2023).

In the Alps, **the trends related to CC are occurring at a faster pace than elsewhere making them more vulnerable** (Beniston, 2005). According to the Alpine Convention (2017) "since the late 19th century temperatures have risen by almost 2°C, a rate about twice as large as the northern hemisphere average".

The European Alps have always been one of the top travel destinations in the world. The region is approximately 1,200 km long and 150-250 km wide, with altitudes ranging from 2,864 meters in Slovenia to 4,810 meters in France, where nature and culture provide unique attractions to the visitors (Bausch & Gartner, 2020). However, in recent years, **the Snow & Winter Tourism (SWT) sector in the European Alps**, as in many other mountainous areas of the world, has been dealing with different, and in some cases highly challenging, trends.

On the one hand, a **decrease in the snow-reliability** has been observed, paired with an **noticeable decrease of the attractiveness of the ski sector in areas** that are going through social and demographic changes. Next to a slight decrease of the number of skiers, also their length of stay diminishes every year. Damm et al. (2017) estimate a loss in winter overnight stays related to ski tourism in Europe of up to 10.1 million nights per winter in the upcoming years. On the other hand, **some snow-related activities**, such as cross-country skiing as well as snow and snowshoe hiking, **have seen an increase in their popularity**.

Furthermore, the 2°C temperature increase that the Alps have experienced since the beginning of the 20th century and the related **decrease in snow coverage have significantly shortened the snow season** (38 days between 1960 and 2017, according to Kluger (2018)), and increased the costs of technical snowmaking. It seems that an improvement of the situation in the future is highly improbable.

Scientists estimated that by 2100 the temperature in the Alps will increase by 1-2°C if emissions are kept low (RCP 2.6), and by 5-6Ge°C in the worst-case scenario (RCP 8.5). Over the same period, snow height reliability may increase beyond 2,400 m above sea level (Matiu & Hanzer, 2022).

Censuses, such as those carried out with the "Nevediversa" dossier by Legambiente (2023) on the state of health of the ski resorts in the Italian mountains, describe a particularly complex situation where abandoned or closed facilities, or those that survive solely with strong injections of public money, are increasingly frequent. The sector, which in the past has been one of the pillars of Alpine tourism, still provides work opportunities to a large number of people and sustains the economies of a multitude of communities and tourism destinations. As the economic viability of ski tourism in the Alps risks to falter, the largest and highest ski tourism destinations try to differentiate their offer, while still focusing on mass tourism and on skiing offers above 2,000 m. The situation is very different in the smaller, lower-altitude ones.

1.1 Envisioning a green and climate-resilient alpine region

A high number of small-medium altitude snow tourism destinations (hereinafter STDs) scattered across the Alps face the problems of lack of snow coverage, an increased dependency on technical snowmaking, outdated (ski) infrastructure and accommodation facilities in need of renovation. These challenges translate, among others, into a high probability of not being able to amortize the necessary investments. Some STDs are partners or have activated one of the partners of the Interreg Alpine Space project "BeyondSnow", which aims at elaborating concrete responses to specific territorial needs.

The Pilot Working Areas (hereinafter PWAs) of the project comprise 10 different destinations and their related communities, encompassing different sizes, levels of development and criticalities (Figure 1). Some of them have already started different adaptation paths, others still need to develop them. Nevertheless, all of them can benefit from a transnational cooperation, knowledge-exchange regarding the concrete impacts of CC, as well as the mitigation and adaptation measures that can be elaborated and implemented.

Many other similar tourism destinations in the Alpine Space area will benefit of the results of this cooperation focusing on the highlighted challenging issues.

A transition towards new, more sustainable tourism development models focusing on preserving and valorising territorial assets, unique tourist experiences based on natural and cultural heritage, as well as a more efficient spatial and temporal distribution of tourism assets (supporting transition from seasonal to year-round tourism) and improved, future-oriented and sustainable infrastructure management could help relaunch these challenged economies while strengthening the local communities and the attractiveness of these areas.

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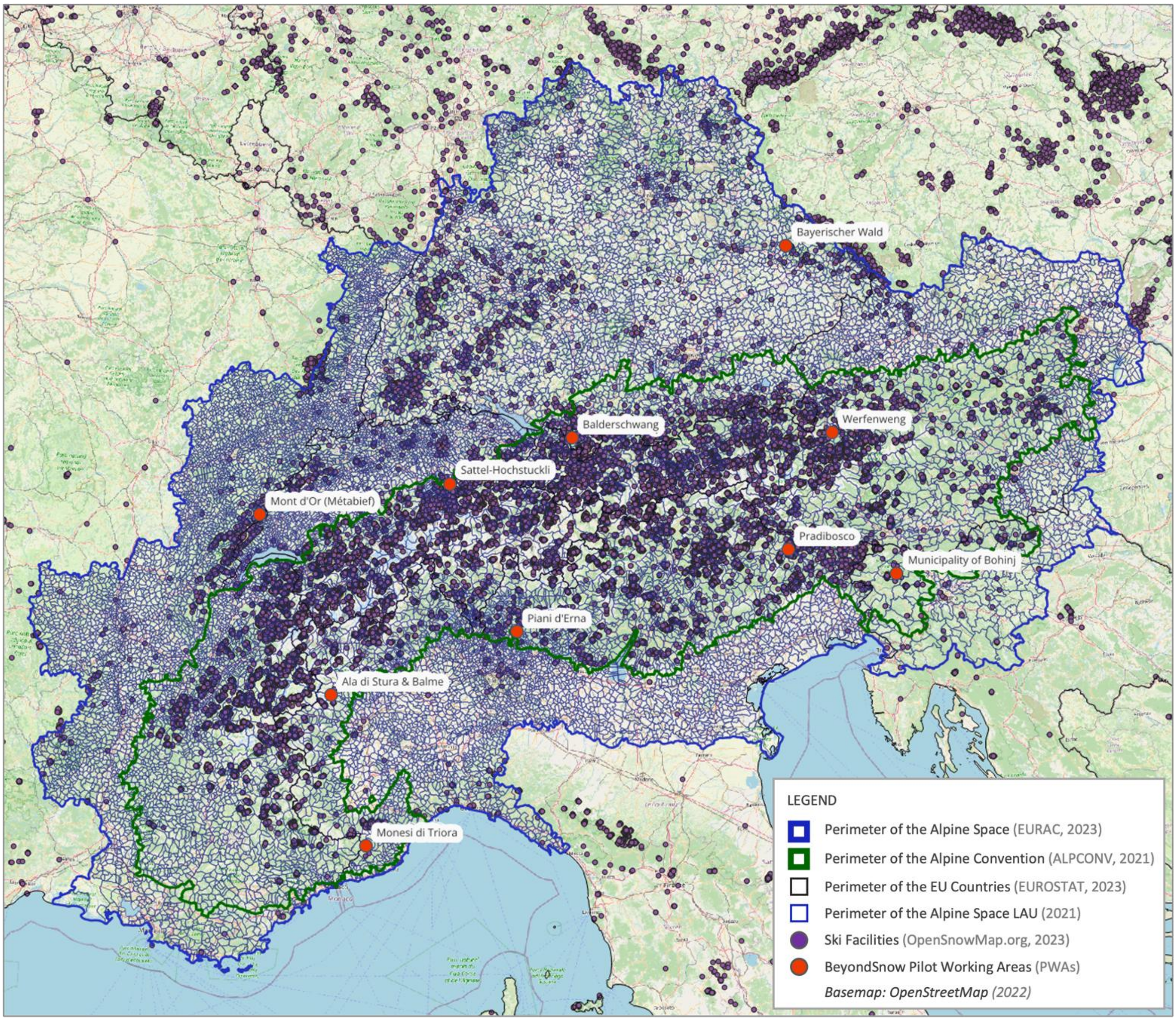

Figure 1. BeyondSnow Pilot Working Areas (PWAs) and ski facilities in the EU Alpine Space Programme cooperation area, 2023.

1.2 Key definitions

This subchapter aims at providing the reader with a common set of key definitions and explanations, which will be utilized throughout the present report as well as the AS project "BeyondSnow". Since some of the concepts are closely related, the key definitions are not listed alphabetically, but thematically.

Climate

Climate refers to the long-term average weather conditions prevailing in a specific area. The standard time span employed by the World Meteorological Organization to define and assess climate is a three-decade period (WMO, 2023b), depicting climate as the mean weather patterns spanning 30 years. Factors like temperature, precipitation, and wind can be examined to ascertain fundamental attributes of the prevailing climatic state during various time periods and to pinpoint changes across distinct time spans.

Climate Change (CC)

The UN defines climate change as "long-term shifts in temperatures and weather patterns" (UN, 2023), indicating that, although these shifts can be also of natural origin, anthropogenic activities have been one of the main drivers since the 1800s (see also (IPCC, 2022). According to the United Nations Framework Convention on Climate Change (UNFCCC), CC occurs “in addition to natural climate variability observed over comparable time periods” (UNFCCC, 2023). CC is caused by alterations to the composition of the Earth’s atmosphere, in particular, through emissions of GHGs such as CO2, and through changes to the land, such as through deforestation and land conversions.

Global temperature and warming

Global temperature is measured by combining measurements of near-surface air temperature from weather stations, satellite measurements and ocean surface temperatures (Hansen et al., 2006). In the early 1960s scientists recognized that carbon dioxide in the atmosphere was increasing. Later they discovered that methane, nitrous oxide and other gases were rising. Because these gases trap heat and warm the Earth, as a greenhouse traps heat from the sun, scientists concluded that increasing levels of “greenhouse gases” would increase global warming. According to the World Meteorological Organization (WMO), the years from 2015 to 2022 have been identified as the eight years with the warmest global temperature since the beginning of the observations in the mid-19th century (at least 1°C above pre-industrial levels) (WMO, 2023a).

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Greenhouse gases (GHGs)

Greenhouse gases encompass atmospheric gases, both of natural origin and human-made, which have the ability to absorb and release radiation at particular wavelengths found within the range of terrestrial radiation emitted by the Earth's surface, the atmosphere, and clouds. This characteristic gives rise to the greenhouse effect. The main greenhouse gases are water vapor (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) (Non-fluorinated gases) (European Commission, 2021). The fluorinated or man-made GHGs comprise hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). Human activity strongly influences the presence of the latter since these gases increase faster in the atmosphere as they degrade (European Commission, 2022).

Global Warming Potential (GWP)

The Global Warming Potential (GWP) refers to the ability of different GHGs to absorb energy compared to CO2 over a specified period of time, usually measured between 20 and 100 years. Furthermore, it considers also their different atmospheric residence times, namely the different rates at which they are removed from the atmosphere. For each time period, CO2 is always set at "1", and other GHGs are compared it for the same timeframe. For example, the sulfur hexafluoride's (SF_6) GWP at 10 years reaches 24,300, meaning that it has 24,300 times more warming potential than CO2 within the same timeframe (Shi et al., 2023).

Risk

Risk means any potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems (IPCC, 2022). According to the IPCC, the concept of risk in the context of CC has several nuances:

- Risks can arise from potential impacts of CC as well as human responses to CC.
- Considering CC **impacts**, risks result from dynamic interactions between climate-related **hazards** with the **exposure** and **vulnerability** of the affected socio-economic or ecological system to the hazards.
- A more specific denotation, namely the concept of compound risks, is utilized when such interactions are characterized by single extreme events or multiple coincident or sequential events that impact the exposed systems or sectors.
- Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence. Each may change over time and space due to socio-economic changes as well as human decision-making and actions.
- Regarding CC **responses**, risks can emerge from the potential for such responses not achieving the intended objective(s), or from potential trade-offs with or negative side-effects on, other environmental

and/or societal objectives, such as the Sustainable Development Goals (SDGs). Risks can arise for example from uncertainty in the implementation, effectiveness or outcomes of climate policy, climate-related investments, technology development or adoption, and system transitions.

- The remaining risk, after adaptation and mitigation efforts have been implemented, is called "**residual risk**".

Hazard

According to IPCC (2022) "a hazard is the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources". Examples of climate hazards can be persistent droughts, intense heatwaves, tropical storms, sea levels rise and floods.

Impact

An impact is the consequence of realized risks on natural and human systems, where risks result from the interaction of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services) and infrastructure (IPCC, 2022). Impacts may be referred to as consequences or outcomes and can be adverse or beneficial. When an extreme hazard generates a sequence of secondary events that result in physical, natural, social or economic disruptions to natural and/or human systems, this can be referred to as "cascading impact", whereby the resulting impact is significantly larger than the initial one. Cascading impacts are complex and multi-dimensional, and they are closely connected to the degree of systemic vulnerability (IPCC, 2022).

Climate Exposure

Climate exposure is the presence of different elements (such as people, resources, environmental services and functions, infrastructures, and cultural assets) in places and settings that could be adversely affected by climate-change-related events (IPCC, 2022).

Climate Sensitivity

Climate sensitivity is the degree to which systems or parts thereof are **either adversely or beneficially** affected by CC (IPCC, 2022).

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Climate Vulnerability

Climate vulnerability, or vulnerability to CC, refers to the degree to which a community experiences harm as a result of changes in climate and/or the degree to which natural, built, and human systems are at risk of exposure to CC impacts. These communities may be regional, sub-regional, national, sub-national, or other. Vulnerability encapsulates socio-economic concerns, such as income levels, access to information, education, social safety nets and other meaningful determinants of the resilience of communities. It also encompasses environmental or so-called “bio-physical” factors, such as geographic location, topography, natural resources, vegetation etc. A community’s vulnerability may be determined intrinsically, for example, through a local government’s aversion to corruption, or by exogenous factors, such as globalized markets. Vulnerable communities experience heightened risk and increased sensitivity to CC and have less capacity and fewer resources to cope with, adapt to, or recover from climate impacts. These disproportionate effects are caused by physical (built and environmental), social, political, and/ or economic factor(s), which are exacerbated by climate impacts. The definition of “vulnerability” used here aligns closely with the IPCC definition, termed “**outcome vulnerability**”. The latter implies that higher levels of harm are in large part the outcome of higher levels of vulnerability. Conversely, impacts are lower where vulnerability is lower (Füssel, 2010; IPCC, 2022).

Compound climate events

Compound climate events result from the complex combination of different climate drivers and/or hazards, giving rise to amplified impacts compared to what the single drivers and/or hazards might have generated (Zscheischler et al., 2020). These interactions can be spatially and/or temporally concurrent, but they can also take place at different dimensions and levels adding up over time.

Hydrological cycle

Hydrologic cycle is the process by which water moves around the earth. The cycle includes evaporation, precipitation, runoff, condensation, transpiration, and infiltration.

Snow Water Equivalent

The height of the water column if a snow sample is melted (measured in millimetres), with reference to the same area. The water equivalent of a 20 cm snow sample with a mean snow density of 100 kg/m³ is 20 mm. With a density of 500 kg/m³ the equivalent of a 20 cm snow sample is 100 mm of water (EAWS, 2023).

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2 Climate Change in the Alpine Space area

Snow is an important element of mountain regions around the world, such as the European Alps. Its presence or absence can have a range of consequences for the ecology of the area, and for many related socio-economic sectors. In the Alps, CC occurs more rapidly than in lowland areas and affects the living conditions of 14 million inhabitants, 30,000 animal species and 13,000 plant species (Alpine Convention, 2021). The **cryosphere**, the distinctive and fundamental element of high mountain regions, comprises snow, permafrost, glaciers, frozen lakes, and rivers. The effects of CC on these environments are impacting physical and biological systems, including human systems.

Recent observations of snow and glaciers show a general decline in the duration of snow cover at low altitudes in recent years, with an average of 5 snow cover days per decade. As for glaciers, their mass is estimated to have retreated of more than half of their volume since the 19th century (EEA, 2009; IPCC, 2022). Actually, the decline of snow, glaciers and permafrost has also altered the frequency, intensity, and location of most related natural hazards. In particular, the exposition of people and infrastructure to natural hazards has increased due to population growth, tourism, and socio-economic development. In fact, glacier retreat and permafrost thaw have reduced the stability of mountain slopes and the integrity of infrastructure. Moreover, CC is altering snowfall patterns. This means fewer days of snow cover and the snowpack melting earlier (Matiu et al., 2021). Furthermore, the risk of avalanches in the Alps has been increasing significantly (Zgheib et al., 2022) due to instability accentuated by CC phenomena.

The Alps have often been referred to as “the water tower of Europe” (EEA, 2009) because of the key contribution of alpine rivers to populated lowland water resources in Italy, France, Germany, as well as Central and Eastern Europe. Snow is probably the largest single contributor to seasonal runoff in hydrological basins when the snowpack releases water during the spring and summer through melting. Its presence at high elevations up to the middle/end of the summer ensures, along with seasonal glacier melting, a sustained discharge in most mountain rivers even during prolonged dry spells (Haeberli & Beniston, 1998).

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2.1 General ecological effects

In terms of ecosystem functioning, snow is a major determinant for many alpine plant species since the timing of snowmelt often signals to dormant plants the beginning of the annual vegetation cycle. The EU White Paper on Adaptation (European Commission, 2009) names mountain areas, in particular the Alps, as among the most vulnerable areas to CC in Europe. The Alps have undergone an exceptionally high temperature increase of around +2°C between the late 19th and early 21st century, more than twice the rate of warming average of the Northern hemisphere (Auer et al., 2007). These changes have also altered the amount and seasonality of river flows, with significant impacts on water resource management, hydropower productivity as well as agricultural activities. As temperatures rise, glaciers are melting, resulting in reduced water availability in the summer months, affecting local agriculture and livestock farming (Beniston, 2005).

The decrease in snow cover is also leading towards a reduction in soil humidity, which can have long-term implications for vegetation and wildlife. The increase in extreme weather events, such as floods and landslides, is causing significant damage to forests, resulting in loss of biodiversity and habitat for wildlife. In terms of biodiversity, the composition and quantity of species have changed considerably in alpine ecosystems: habitats for the establishment of previously absent species have opened or have been altered as a result of reduced snow cover, retreating glaciers and thawing permafrost. This can negatively influence the reproductive capacity of traditional animal and plant species, foraging and the predator-prey relationships. The migration of some species to higher altitudes influenced by CC has often increased the number of local endemic species with consequences on the impact of ecosystem services (hereinafter ES) on supply, regulation, and culture (Scotford & Marshall, 2023). In addition, drier and warmer conditions increased the risk of forest fires, seriously endangering alpine forests (Dupire et al., 2019).

2.2 General socio-economic effects

CC significantly influences also the economic sphere of many inhabited areas which depend, to a large extent, on the tourism and winter sports sector. The implications are already becoming evident due to reduced snowfall and a shortening of the ski season, which has led to a decrease in tourism revenues, oftentimes resulting in job losses and economic hardship for local communities. The increase in extreme weather events, such as floods and landslides, has also damaged infrastructure, resulting in significant repair and maintenance costs. Moreover, with the decrease in SWT, local communities are oftentimes experiencing a decline in social cohesion as well as the loss of traditional lifestyles and viability (Steiger et al., 2022).

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2.3 The Climate Action Plan

From a governance point of view, in the Alps the main strategic reference is the Climate Action Plan 2.0 of the ALPCONV that operationalizes the objectives laid out in the Alpine Climate Target System 2050 (Alpine Convention, 2019) and was adopted by the XVI Alpine Conference in December 2020. GHG emissions in the Alps are to be reduced by 2050 (Alpine Convention, 2021). The Alpine states, representing a rich region at the heart of Europe, albeit particularly sensitive to rising temperatures, are called upon to implement measures in the field of energy efficiency and renewable energies, and to develop a climate-neutral economy. This vision includes innovative approaches in terms of lifestyles and consumption patterns and the introduction of a more sustainable approach in all economic sectors, as well as in private activities.

In particular, the Climate Action Plan seeks out synergies between different activities across sectors and borders, closing the gaps between actions and activities in order to address CC. Sensitivity to CC and its effects must be included in long-term decision-making processes to minimise negative effects on ecosystems, communities, and local/regional economies, and to turn challenges into potential benefits. Following this vision, the Alps should adopt a proactive and holistic approach, focusing on soft and green adaptation measures, rather than defensive infrastructural measures. Soft interventions, focusing on raising awareness and improving adaptive capacities at all levels, will enable the development of intelligent and flexible approaches, in line with other planning and development processes. For example, the tourist regions should reflect on aspects of new lifestyles and new demand, while integrating CC adaptation issues into their planning processes. Ecological adaptation measures should focus on biodiversity, ecosystem-based approaches, and green infrastructures.

2.4 Main impacts

2.4.1 Impacts on snow cover

Snow cover in high-altitude regions has strong effects on the Earth's climate, environmental processes, and socio-economic activities. Over the last 50 years, the Alps experienced a reduction of 5.6% per decade in snow cover duration, which already affects regions where economy and culture revolve, to a large extent, around winter activities (Carrer et al., 2023). Snow cover in the Alps is a complex phenomenon that varies from year to year due to the natural variability of weather patterns, but there are some general trends that have been observed over time. According to Matiu et al. (2021), snow cover in the European Alps decreased by 18% between 1971 and 2019. The study revealed that this decline was most pronounced at the lowest altitudes, with a 34% decrease in snow cover, while higher altitudes experienced a smaller decline of about

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11%. This is largely due to the warming of temperatures, which causes more precipitation at lower altitudes to drop as rain instead of snow and earlier melting of snowpacks (Fontrodona Bach et al., 2018).

During the 20th century, significant changes in amount and duration of snow occurred, which generally exhibit a large degree of interannual and inter-decadal variability. Observational data show periods of snow-rich winters (e.g., in the 1960s) and snow-poor seasons (e.g., from the 1970s onwards, the latter part of the 1980s until the mid-1990s). In some cases, particularly snowy winters seem to be correlated with the positive (or warm) phase of the North Atlantic Oscillation (Beniston et al., 1997), although it is by no means the only explanatory factor for snow variability in the Alps. For example, Scherrer & Körner (2011) suggest that half of the variability in Alpine snow cover is related to the establishment of blocking patterns in Europe, which are not always related to the influence of the North Atlantic Oscillation.

As a 'rule of thumb', the average snowline level rises by approximately 150 m per degree Celsius, implying an upward shift in the snowline of 300 to 600 m. However, it should be noted that this simple concept may overestimate the snowfall limit rise, as it does not consider the effect of temperature inversions and cooling due to melting precipitation (Unterstrasser & Zängl, 2006).

Although changes in precipitation patterns may also influence the abundance and geographic distribution of snow, several studies (Damm et al., 2017; Klein et al., 2016; Steger et al., 2013) have emphasised the fact that, in a warmer climate, the temperature is likely to be the dominant control on snow cover, and increased winter precipitation will not compensate for the large losses in snow volume that higher temperatures will induce. However, assessing snow behaviour in complex topographies may also involve interfacility techniques that allow the estimation of snow depth and duration at a very local scale. Studies of Steger et al. (2013), among others, have been shown to be a very effective tool for assessing snow cover in the Alps. The general consensus implies, that a large reduction in snow quantity and duration below 1,500 m altitude, and even above 2,000 m, can be reasonably expected in the near future.

For higher altitudes, an increase in precipitation might lead to more snowfall in the central winter period, but the snow season will shorten because of rising temperatures. Hereby snow will accumulate later in fall and melt earlier and at a higher rate in spring (Gobiet et al., 2014). At the regional scale, the amount of snow will be significantly lower across all seasons, especially in spring. By the end of the century, snow cover could experience an elevation shift of 500 to 1,000 m, meaning that the snow conditions at the end of the century at an elevation of 2,000 m will be as they are today between 1,000 and 1,500 m. If climate targets are achieved - especially global warming held below 2°C - this elevation shift could be confined to 250-500 m. Overall, this reduction in snow cover has significant impacts on the Alpine ecosystem and economies, including effects on tourism, hydropower production and water resources. Furthermore, the

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decrease in snow cover may lead to an increased risk of natural hazards such as landslides and avalanches (Gruber et al., 2004; Martin et al., 2001).

Glacier retreat in the Alps has seen an acceleration in recent decades, with some glaciers losing up to 3% of their volume each year (Haeberli et al., 2007). Since the mid-19th century, the total area covered by glaciers in the Alps has decreased by more than half and it is estimated that most of the remaining glaciers could disappear by the end of the 21st century if current warming trends continue (Haeberli & Beniston, 1998). The trend of glacier retreat has already had a significant impact on the Alpine environment. For example, the loss of glacier mass has caused changes in river flows, with increased runoff in the summer months leading to a higher risk of flooding and water shortages in the dry season. The disappearance of glaciers has also had a strong impact on the unique alpine ecosystems that depend on these ice features, resulting in the loss of endemic species and biodiversity (Hock & Huss, 2021; Salim et al., 2021).

In addition, glacier retreat poses a significant risk to human settlements in the Alps. Melting glaciers can destabilise steep slopes and increase the risk of landslides and rockfalls. In addition, the loss of glacial meltwater can affect the availability of water for irrigation, hydropower and drinking water in many Alpine regions (Gruber et al., 2004).

2.4.2 Impacts on tourism

The Alps are — after the Mediterranean coast — the second most favoured holiday destination in Europe (EEA, 2003). More than 100 million guests visit the Alps every year (Becken & Hay, 2007), generating approx. 386 million commercial as well as 123 million non-commercial overnight stays (Roth et al., 2016). Within the regions of the AS, 15% of the labour force is directly or indirectly connected to the tourism sector (BAK, 2019).

Mountain tourism has the advantage of attracting diverse visitors throughout the year through a variety of summer and winter activities, including mountaineering, hiking, cycling and snow sports (e.g., skiing, snowboarding, sledding) (Romeo et al., 2021). Interestingly, some of the unique factors limiting economic development opportunities in the high mountains are the main attractions for visitors of these regions (e.g., nature, wilderness, topography, remoteness, climatic conditions). As a labour-intensive sector with several links in the economic value chain, investments in tourism facilities can enhance mountain resources by attracting visitors to mountain destinations (Keller, 2018). However, as mountain tourism facilities and activities rely on alpine climate, topography, landscape and seasonal cycles, CC is having and will continue to have an impact on current and future tourism development in mountain regions, affecting also the quality of life of residents in tourism-dependent mountain communities (Scott et al., 2012).

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Since the 1970s SWT has expanded substantially. With an annual turnover of 50 billion EUR, the SWT industry contributes significantly to the Alps' economy (OECD, 2007). In 2021, the Alpine countries counted a total of 1,643 ski areas, the most part (more than 1,100) located in the Alps with more than 10,000 ski installations, 85 % of which are in France, Switzerland, Austria and Italy (Vanat, 2022).

Being a rapidly growing sector, tourism has also the potential for negatively impacting the environment, in particular regarding water quantity and quality: water consumption by tourists tends to be much higher than that of local residents in holiday destinations leading to serious problems in dry summers with low water regimes. In winter, technical snowmaking is currently the most widespread strategy to extend and supplement natural snow cover and secure SWT. Technical snowmaking is not only very costly, but also has knock-on effects such as increased water consumption and energy demand as well as ecological damage, which may lead to negative externalities (Soboll & Schmude, 2011).

This includes potential disturbance of the hydrological cycle for habitats of high conservation value such as bogs, fens and wetlands at high altitude. To serve all 28,500 ha of ski runs that use technical snowmaking equipment (which is 0.15% of the total alpine area), 17–43 million m^3 of additional water supply would be needed per year (EEA, 2003). For technical snowmaking, water is taken from natural lakes, artificial water reservoirs, rivers or groundwater in a period of the year when the water level oftentimes is already low. Due to future CC effects, conflicts between drinking water supply, energy production, agriculture and technical snowmaking can be expected to increase (Reynard, 2020).

As CC accelerates, tourism professionals often indicate that warmer weather and longer summer seasons will lead to a simple shift towards increased summer activities in the mountains (Steiger et al., 2022). Some studies, particularly in Europe, have demonstrated this extension of the summer tourism season (Pröbstl-Haider et al., 2021). However, the present review of existing climate research focusing on nature-based tourism in mountain regions around the world, including - but not limited to - hiking and trekking, climbing, cycling, bird and wildlife watching and camping, demonstrates that the impacts are broad, multifaceted and non-uniform in terms of type and severity of impact. The main themes identified in the literature for summer tourism in mountain environments are changing seasonality, climate attractiveness and subsequent visitation, accessibility and risks, landscape attractiveness and biodiversity, as well as adaptation and involvement.

Major summer attractions in mountain tourism destinations are already affected by the increased risk of natural hazards and altered accessibility, both consequences of CC. In the Alps, retreating glaciers and thawing permafrost are steepening ice and rock slopes and destabilising moraines. As a result, the risk of debris flows, rock falls, ice collapses and glacial lake floods is increasing and more debris is accumulating on the surface of glaciers (Mourey et al., 2019). These hazards have increased the risk of tourists participating in activities also in summer such as climbing and mountaineering and have the potential to damage and destroy important tourism infrastructure such as trails and access roads (Gruber et al., 2004).

CC is also causing changes in the natural landscapes of the Alps, such as melting glaciers and receding snow lines. This affects the aesthetics of the Alpine region and can be a deterrent to tourists coming to enjoy the natural beauty. Rapid increases in temperature and reductions in snow cover due to CC have phenological, temporal and geographical impacts on the flora and fauna of Alpine ecosystems (Theurillat & Guisan, 2001). These interrelated changes emphasise climate-related and biodiversity-related crises that have a direct impact on nature-based summer activities in mountain destinations.

Changes that affect the ranges, habitats and behaviour of alpine species, such as invasive species, result in increasingly unfamiliar ecological contexts within which tourism operates. However, Sato et al. (2013) noted that research on the impact of recreational ecology is neither sufficient nor does it keep pace with the increase in summer use, the introduction of new high-impact activities such as off-road vehicles, or with mountain resorts developing four-season activities (Walters & Ruhanen, 2015).

2.4.3 Impacts on nature and biodiversity

CC is having a significant impact on biodiversity in the Alps, with changes in temperature, precipitation and snow cover affecting various species and ecosystems (Dullinger et al., 2020; Parisod, 2022; Scotford & Marshall, 2023):

- *Changes in species distribution*: as temperatures rise, some species are moving to higher altitudes to find cooler climates. This may lead to changes in the composition of plant and animal communities at the different altitude levels within the Alps.

- *Threats to mountain plant species*: alpine plant species are adapted to cold and harsh conditions and changes in temperature as well as precipitation may threaten their survival. Some species are already becoming rarer or disappearing from the Alps altogether.

- *Increased risk of invasive species*: as the climate warms, non-native animal and plant species that were once restricted to lower latitudes can now thrive in the Alps. These invasive species may outcompete native species, reducing biodiversity.

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- *Threats to mountain animals*: changes in temperature and snow cover can affect the availability of food and habitat for mountain animals, such as hares, mountain goats and ibex. These changes can also affect migration and hibernation times, with cascading effects on ecosystems.
- *Threats to freshwater biodiversity*: changes in temperature and precipitation can also affect freshwater ecosystems, which are important for the survival of many species in the Alps. Rising water temperatures can reduce the oxygen available to fish and other aquatic organisms, while changes in snowmelt patterns can alter the timing and amount of water available to these ecosystems.

The intrinsic value of biodiversity, beyond any direct human interest, is widely recognised, as it influences the provision of vital ES for humanity. It is generally assumed that maintaining the integrity and health of ecosystems supports the provision of ES. Loss of biodiversity implies loss of services and thus a reduction in human well-being. In the past, degradation of ecosystems has been shown to adversely affect human well-being (Millennium Ecosystem Assessment, 2005).

The Alps constitute an ancient cultural landscape with socio-ecological properties not found elsewhere on the planet. Society and nature in these mountains have co-evolved to form a unique and closely linked network of interactions, attracting people temporarily as tourists or permanently as migrants from near and far. Among the European mountains, the Alps, together with the Pyrenees, are the richest in plant species (Väre et al., 2003). They are home to around 4,500 plant species, accounting for more than a third of the recorded flora in Europe, with almost 400 endemic plants (prevalent in a particular area or region) (Theruillat, 1995). Plant biodiversity is particularly concentrated in the Alpine regions. The area above the tree line represents only 3% of Europe's total surface area but is home to 20% of its plant species richness (Thuiller et al., 2005). The fauna of the Alps includes up to 30,000 species (Chemini & Rizzoli, 2003).

CC and intensive agricultural practices are already threatening a number of unique species and habitats. Habitat loss, fragmentation, changes in agricultural practices and pollution act in concert with CC and are among the most significant reasons for biodiversity loss in the Alps. Rising temperatures and changing precipitation regimes (i.e., generally less precipitation in summer and more in winter), as well as increased climate variability and extreme events, will likely further affect natural and socio-economic systems and sectors in the Alps in the near future.

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2.4.4 Impacts on ecosystem services (ES)

The ES approach provides a framework for understanding the interconnections between sectors in relation to direct (e.g., forestry) or mostly indirect (e.g., industry) dependence on the environment. In recent decades, we have moved from a conception of humans as reactive towards the environment (prior to the 1980s), to a conception of environmental crises as caused by humans (1980s), to a conception of environmental crises as caused by socio-natural interaction (1990s) (van der Leeuw, 2001). In the current decade, we have begun to understand human crises also as caused by socio-natural interaction. A change in our environment can be considered a crisis when it threatens our livelihood or well-being. An environmental crisis often leads to a human crisis (Schröter, 2009). Humans depend on ecosystems because they depend on ES (de Groot, 1992).

According to Common International Classification of Ecosystem Services (CICES) classification (Haines-Young & Potschin, 2018), four types of ES can be distinguished:

- life-supporting services, cycles of nutrients, soil and primary productivity;
- provisioning services (food, water and materials);
- regulation services (e.g., climate, pollination, pests);
- cultural services (including artistic, spiritual, educational, but also leisure-related services).

Each of these mountain ES makes a specific contribution to lowland and highland economies. Traditionally, the effects of global changes on ecosystems (including CC) have been analysed separately from the effects on food and fibre production, health, recreation, settlements, etc. In contrast to this view, the concept of ES leads to the recognition that ecosystems mediate global change (Schröter, 2009). Therefore, environmental impacts of global change can increase human vulnerability by altering the provision of ES, which are crucial for human well-being.

Cultural ES are also of particular importance for Alpine populations. People and nature have evolved over the centuries to form a diverse entity that is world-renowned for its cultural and natural richness. This fame attracts tourists from the plains of Europe and further, creating an intense tourism industry in summer and winter and reshaping the Alpine landscape. To put this relationship back on a sustainable track, in addition to direct human impacts, the impacts of CC on cultural ES must be considered, with particular reference to dependence on Alpine water resources. The Alpine landscape is changing and with it the cultural services it provides.

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2.4.5 Impacts on key infrastructures

Alpine mountain areas (with very few exceptions) are not only suffering the negative effects of CC, but in recent years many are also facing a very serious trend of depopulation (Bätzing et al., 1996; Corrado, 2014). This has led to a wide range of issues: increase of hydrogeological risks, decline of biodiversity, loss of cultural values and the landscape, disappearance of the necessary conditions for those who have remained to inhabit the mountains, or, on the contrary, unsustainable development models characterized by intensive exploitation of the territory for tourism purposes (Maino et al., 2016). Thus, the combination of CC and the progressive abandonment of the highlands negatively affects the care and maintenance of the territory, also endangering the main human infrastructures.

Many Alpine areas have experienced strong development in the tourism sector during the last decades. This is the cause of a very rapid increase of tourism infrastructures (buildings, roads, facilities, …) and of a booming of second homes. Recently, due to the concomitance of the pandemic and of CC, several areas saw a reversal of this trend, leading also to an abandonment in the tourism sector: hotel complexes, buildings linked to the skiing industry, colonies, as well as border stations, have been left without a perspective. Between the more frequent causes of the abandonment there is the change of the tourism demand connected to the decrease of the snow cover, the necessity of large reinvestments of modernization, lack of technical adaptations, not weighted choices regarding the tourism flows, as well as speculations, which translated into the abandonment of structures before being used.

3 Snow & winter tourism and its importance for Alpine Space regions and countries

More than 100 million tourists visit alpine tourism destinations every year (Becken & Hay, 2007). In 2022 within the provinces of Tessin, St. Gallen, Graubünden, Bavaria, Vorarlberg, Tyrol, Salzburg, South Tyrol, Trentino, Sondrio, and Belluno, 123.4 million overnight stays were registered in commercial accommodation facilities (ASTAT, 2023). While summer had usually represented the core of Alpine tourism, over the years winter has become the main source of income for a large number of Alpine tourism destinations (Tranos & Davoudi, 2014). Today, winter sports, especially downhill skiing, and snowboarding, are at the centre of many alpine resorts, also due to the investments in lifts, ski lifts and snowmaking machines which allowed to extend ski areas and made it easier for people to use previously inaccessible slopes. As a result, modern ski resorts require significant capital investment in technical infrastructure (Bausch & Gartner, 2020). Today, the countries within the Alpine region are the largest inbound ski market on the planet, capturing 40% of worldwide attendance (Vanat, 2022). With more than 10,000 lifts in total, the Alpine region is also among the most equipped in the industry and is home to some of the major players in the ski business. Precisely, the region accounts for 37% of ski resorts worldwide and 80% of major resorts, which translates to 1 million skier visits per winter season (Pede et al., 2022).

3.1 Italy

Mountain tourism in Italy accounts for a significant share of the Italian GDP. Before the Covid-19 pandemic, around 13% of yearly overnight stays were in mountain areas, while foreign tourists' expenditure for mountain vacations was reported to amount to almost 2 billion € in 2019 (Mariani & Scalise, 2022). According to Confcommercio (2023), the Italian General Confederation of Enterprises, Professions and Self-Employment, 12 million Italians chose the mountains in the first quarter of 2023, 7.5 million of which stayed for a week or a slightly shorter period, whereas the remaining 4.5 million are day trips. The average expenditure was 540 € per person. Almost 9 out of 10 holidaymakers chose domestic destinations. The Alpine arc was the main focus, first and foremost the destinations in Trentino-Alto Adige/South Tyrol, followed by Lombardy and Valle d'Aosta, but with good performances also in Piedmont, Veneto and Friuli. However, there was quite a stark heterogeneity among the Italian alpine regions in terms of attendance. For instance, in 2013 the tourism destinations in Trentino-Alto Adige/South Tyrol hosted 44.4% of the Italian mountain tourists, followed by Lombardy (10.5%), Veneto (7.9%), and Piedmont (6.3%) (Alpine Convention, 2013). Considering the internal flows of tourists within Italy, the choice of the Alpine regions as the main mountain destination is mainly connected to the opportunity of practicing winter sports and the natural heritage. It influences 35.8% of Italians for visiting the Italian mountain destinations, followed by mainly practical reasons such as the availability of holiday-homes (16.5%) (Alpine Convention, 2013). Nonetheless, also influenced by the Covid-19 pandemic, based on the changing customer preference, a diversification beyond skiing is ongoing especially in terms of new sports in different seasons (such as mountain biking), cultural and food initiatives, wellness and trekking. These activities played also a role in the increase of the number of overnights after the year 2020 (Marasco et al., 2022). Another trend of Alpine tourism reinforced by the pandemic concerns the incidence of foreign demand. Over the last two decades, in fact, the presence of foreigners in the Alpine regions has increased significantly in general, with the sole exception of the Province of Bolzano where it was already very high. Thanks to the traditional attendance of German tourists, who accounted for almost 50% of total overnights before the pandemic (Marasco et al., 2022). When taking into account data from 2021, it is possible to notice that the foreign incidence has increased by about 10% in the Italian alpine provinces in 2019 compared to the year 2004 (excluding Bolzano), a significant growth if considering that mountain tourism destinations have always been a destination with a predominantly domestic demand (Marasco et al., 2022).

The Italian ski industry is quite fragmented with no major operator and there are considerable territorial differences. For example, the Trentino–Alto Adige / South Tyrol region alone accounted for approx. 80% of the overall tourist attendance in the Italian Alps in 2018 (Morvillo & Becheri, 2020). This region hosts some of the most dynamic players in the European ski industry, such as the Dolomiti Superski area featuring 450 lifts and 1,200 km of trails and representing about 35% of all Italian skier visits offering a high level of infrastructure and state-of-the-art lifts and snowmaking facilities under its common brand name (Vanat, 2022). The resorts making up the Dolomiti Superski area accounted for a total of almost 5 million daily entry tickets in the 2021-2022 winter (Marasco et al., 2022), whereas the total number of entries of the 30 largest ski resorts in Italy was close to 300 million in 2019, with a 2% increase compared to the previous year (Morvillo & Becheri, 2020). Over the last years, it has been estimated that the best performance in terms of tourist attendance in winter belongs to resorts at higher altitudes in comparison to the ones at a lower altitude. This is connected also to better facilities and snowmaking capacity, as well as more snow abundance. For instance, a significant increase was recorded in Livigno (+26,7%), Cervinia (+23%), La Thuile (+17,5%), Adamello Ski (+8%), Alta Pusteria (+7,9%) and Madonna di Campiglio (+7,4%), while a decrease is visible in the small-sized resorts of Mondolé Ski (-18,9%), Bardonecchia (-16,6%), Civetta (-9,3%) and S.Martino di Castrozza (-5,3%) (Morvillo & Becheri, 2020). In general, most of the small Alpine and pre-Alpine STDs participate only marginally to the winter tourist development being situated at low altitudes, with small ski areas and old facilities. They consist mainly of destinations in which facilities are generally co-financed by the Public Administration, favoring seasonal tourism (Alpine Convention, 2013). At the same time, it becomes apparent that local communities tend to be strongly dependent on the income from such a spatially concentrated and agglomerated economic sector (Mariani & Scalise, 2022). As a result, the development of tourist accommodations is often undertaken by the local population, which resulted in many small family-owned hotels and the letting of guest rooms in residential houses (Polderman et al., 2020). This decentralization allows for a good status of the skiing infrastructure maintenance: from 2002 to 2009 20% of the lifts were removed and a further 20% have been renewed, for a total of 445 new lifts (Vanat, 2022). However, a recent report from Legambiente has shown the degradation of many skiing resorts all over the country: by considering only the Alpine regions, in 2021 it was possible to map 91 resorts that were completely neglected and/or fallen into disuse, 24 that were temporarily closed, and 18 that survived solely thanks to heavy injections of public money, mostly in small stations that exhibit a high economic and snow safety vulnerability in the short and medium term (Legambiente, 2022).

3.2 France

With approximately 55 million skier visits annually, France ranks among the top ski tourism destinations in Europe. The French Alps account for more than 80% of the country's total annual skier visits and for 204 winter sport resorts (Berard-Chenu et al., 2021; Rech et al., 2019), with 7 out of the world's 20 most frequented stations located in its northern part (Alpine Convention, 2013). It has been estimated that the Country's ski area exceeds 1,100 km^2 (Moreno-Gené et al., 2018). The largest and most attended ski areas in France are primarily located in Savoie and Haute-Savoie, with a few that are spread between Isère and Alpes du Sud (Vanat, 2022). The ski industry provides significant employment opportunities, contributing to about 8% of tourism employment in the French Alps with around 120,000 jobs and generating approximately 6.5 billion EUR in tourism expenditures (Berard-Chenu et al., 2021, 2022). In 2013, the French Alpine tourism stations accounted for between 20% and 25% of total mountain tourism jobs in the region (Alpine Convention, 2013) and some studies concluded that financial profitability in French resorts tends to be higher compared to those in Italy and Austria (Moreno-Gené et al., 2018).

The ski industry in France has been shaped by far-reaching political decisions, including subsidies for sustainable ski resorts and the implementation of snowmaking equipment. In the 1980s, major French resorts underwent a transformation, with integrated operations being dismantled and lift operations distributed among multiple actors. This led to the establishment of the *Compagnie des Alpes*, which became the world's largest ski resort operator for a considerable period (Vanat, 2022). France stands out as the only European country with such a dominant operator running nearly all major resorts. *Compagnie des Alpes* operates 12 large Alpine resorts, totaling around 15 million skier visits (Vanat, 2022). Additionally, there are smaller operators such as Labellemontagne and Altiservice, while Savoie Stations Participation, a public/private company, holds interests in 17 ski areas (Vanat, 2022). Ski lifts in France are considered a public service, and some operating companies are partially owned or directly managed by municipalities. Supervision of ski lift installation and operation in France is handled by the STRMTG ("*Services Techniques de Remontées Mécaniques et Transports Guidés*"), a public service company ensuring safety control and authorizations for ski lift operations (Spandre, François, Verfaillie, Pons, et al., 2019).

The French ski industry has experienced profound changes over the years, including shifts in demand, changes in governance, and the impact of CC (Spandre, François, Verfaillie, Lafaysse, et al., 2019). France, being a leading destination in global tourism, primarily relies on the domestic market for its ski industry, which has nonetheless reached maturity, showing a slight declining trend in skier visits since the winter season of 2012/13. To compensate, around 2 million foreign skiers visit France each winter season (Vanat, 2022). The French Alps hold 84% of the country's 3,300 ski-lift facilities, which represent 18% of global capacity (Rech et al., 2019), supporting a significant portion of direct and indirect employment in mountain communities. Snowmaking has been a key development, although studies differ on its impact on skier visits in French resorts. Over the 1997–2018 period, snowmaking investments in the ski resorts of Savoie represented 35% of the snowmaking investments made in all French ski resorts while, regarding turnovers of major snowmaking companies operating in the French market over the 2012–2019 period, the snowmaking market was estimated to be worth about 35 million EUR per year (Berard-Chenu et al., 2022). At the same time, (Falk & Vanat, 2016) had previously estimated that above 6.5 million EUR invested, cumulated snowmaking investment does not lead to higher skier visits in French ski resorts.

The French Court of Auditors recently criticized some recent policies due to natural snow depth records and climate projections, highlighting the challenges faced by decision-makers at various levels due to the lack of appropriate information (Spandre, François, Verfaillie, Lafaysse, et al., 2019). In terms of resort management, 63 out of 139 ski resorts in the French Alps are publicly managed, accounting for 15% of the total ski lift power (Berard-Chenu et al., 2021). Similarly to other European alpine Countries, there is a dichotomy between large, prosperous resorts with extensive ski areas at higher altitudes and smaller resorts facing a decline in customers at lower altitudes (Rech et al., 2019). Another notable characteristic of French resorts, particularly the purpose-built ones, is the prevalence of apartment housing in respect to hotels (Vanat, 2022).

3.3 Switzerland

In Switzerland, the Alpine tourist source markets have always played a significant role in the tourism sector, accounting for approximately half of the total overnight stays in the country in 2010 (Alpine Convention, 2013). While winter tourism is focused on specific destinations such as Zermatt, St. Moritz, and Davos for foreign visitors, domestic tourists tend to prefer smaller stations (Leimgruber, 2021).

As resorts diversify their offerings to compensate for uncertainties in snow cover, tourism promotion has evolved to include a wider range of activities beyond skiing, such as snowshoe tours, walking, and wellness. Although tourism contributes 2.9% to Switzerland's Gross Domestic Income, it is not a primary driver of the national economy, which is dominated by manufacturing and financial services (Leimgruber, 2021). However, the tourism sector plays a significant role in creating employment opportunities, particularly in outlying mountain regions with structural underemployment (Gonseth & Vielle, 2019). In the Swiss mountain regions, winter tourism and the cableway industry are crucial, generating more than 80% of income during the winter season in many places (Lichtensteinische Landesverwaltung, 2023). For instance, the Swiss cable cars, which contribute to the winter tourism sector, generated revenues of 758 million CHF during the 2018/19 winter season, underscoring their substantial economic value (Vorkauf et al., 2022). However, Swiss ski areas have experienced changes in their foreign customer base over the years. While there has been an increase in Spanish, Russian, and Asian customers, this has not compensated for the decline in Switzerland's traditional foreign customer base, which has led to a decrease in overnight stays by 1.5 million (Vanat, 2022). Consequently, the proportion of foreign guests on the slopes has dropped below the 40% mark (Vanat, 2022). Starting in the early 2000s, Switzerland faced a period of stagnation followed by a decline in winter tourism, despite efforts to improve snowmaking facilities and lift infrastructure. Unfavorable snow conditions occurred for three consecutive years, starting from winter 2014/15, which affected many resorts during the Christmas and New Year holidays (Vanat, 2022). However, the winter season of 2017/18 experienced better conditions, resulting in a 10.3% increase in attendance figures compared to the previous season. The 2018/19 season also saw a growth of 6.2% in skier visits, which represented a recovery but did not fully compensate for the 25% decline in skier visits over the previous decade (Vanat, 2022). In response to the changing landscape, several ski areas in Switzerland adopted disruptive pricing strategies to attract customers and recover their market share. The introduction of heavily discounted season passes by Saas-Fee and the collaboration of 25 Swiss ski areas in offering the Magic Pass, a multi-resort season pass, resulted in increased skier visits by 30% and outperformed the Swiss average (Vanat, 2022).

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3.4 Liechtenstein

Given the small size of the Country, winter tourism is not as developed as the neighboring States. Liechtenstein has only one single ski resort, Malbun, which is located south-east of the capital Vaduz. The resort itself is tiny, with only a handful of hotels amongst the private chalets and houses, and it is equipped with 5 lifts that rise to a maximum altitude of 2000 meters (Vanat, 2022) In the winter season 2022/23 (months November 2022 to April 2023), guest arrivals and overnight stays in the hotel industry increased compared to the previous year. Hotels in Liechtenstein reported 35,880 guest arrivals and 73,263 overnight stays for the winter season 2022/23. In the winter season of the previous year, there were 29,226 guest arrivals and 66,043 overnight stays. The number of overnight stays thus increased by 10.9% compared to the previous year. However, at the alpine hotels in Steg and Malbun, 29,739 overnight stays were recorded: this is a decrease of 2.6% compared to the previous year (Lichtensteinische Landesverwaltung, 2023).

3.5 Germany

The German skiing landscape comprises approximately 500 ski areas, catering to Europe's largest population of skiers, which exceeds 14 million individuals (Vanat, 2022). However, nearly half of these areas consist of single-lift facilities, and Germans tend to carry out their skiing activities abroad. For instance, German citizens represent the largest foreign customer base for Austrian resorts (Vanat, 2022). The prominent ski resorts in Germany are situated along the southern border of the Black Forest and in the Bavarian Alps, which share borders with Switzerland and Austria. These regions encompass the German Alps, the Harz Mountains, the Black Forest, the Bavarian Forest, and the Thuringian Forest, characterized as middle-altitude mountains reaching heights of up to 1,500 meters above sea level (Vanat, 2022). In particular, Alpine tourism plays a crucial role in the overall tourism sector of Bavaria, which serves as a year-round travel destination, with around 60% of overnight stays occurring during the summer months (May to October) and 40% during winter (November to April) (Alpine Convention, 2013). Nature and active tourism, such as hiking, biking, and winter sports, health and wellness tourism, as well as cultural tourism, form significant segments of overnight stays and same-day journeys in the Alpine areas (Alpine Convention, 2013). Unsurprisingly, the two largest ski resorts in Germany are located in the Bavarian Alps, in the southernmost part of the Country at the border with Austria. The first one is Zugspitze, which is located near the town of Garmisch-Partenkirchen with around 20 km of runs covering an area of 2.4 km^2 (Vanat, 2022). The Zugspitze itself is the highest peak in Germany, reaching an elevation of about 2,962 meters. The second is the Sudelfeld ski area, spanning the municipalities of Bayrischzell and Oberaudorf, and it is part of the regional tourism association Alpenregion Tegernsee Schliersee (ATS). With an area of 2.3 km^2

and an average altitude of 1,216 meters, it falls within the average altitude range of German ski areas (Vanat, 2022). Bayrischzell, situated in close proximity to Munich, serves as a crucial destination for daily ski visitors for over 4 million inhabitants within a one-hour drive catchment area (Vanat, 2022). In both resorts, during winter seasons, approximately 78% of ski tourists are day guests, while overnight guests primarily originate from Germany (around 80-85%) and the Netherlands (approximately 5-10%) (Witting & Schmude, 2019). The average length of stay for overnight guests during the winter season is around four days, with hotels, holiday flats, and guesthouses being the top three lodging choices (Witting & Schmude, 2019). Over the past four years, winter overnight stays have ranged from 62,910 (2014/15) to 69,079 (2016/17) (Witting & Schmude, 2019). In comparison to Austrian and Swiss resorts, ski areas in Germany often occupy lower altitudes, leading to a higher susceptibility to snow conditions (Vanat, 2022), especially when considering that winter (sport) tourism holds significant economic importance for the German low mountain range and alpine destinations. To mitigate the meteorological risk, resorts have made significant investments in snowmaking systems. Over the past decade, ski visitor figures in Germany have followed a similar trend to those in the Alps, with the exception of an exceptional season in 2012/13. Between 2014 and 2017, winter vacations in Germany during November and March ranged from 8.8 million to approximately 10.4 million, and Alpine destinations accounted for a share ranging from 18.3% to 20.7% of these winter holidays (Bausch & Gartner, 2020).

3.6 Austria

Compared to other industrialized countries, tourist intensity in Austria is particularly high: in the face of 8.98 million inhabitants, there are 68,600 tourist accommodation facilities offering more than 1.15 million beds (Statistik AT, 2023a, 2023b). Winter tourism represents a paramount share of the overall tourism sector, as it accounts for nearly half (48%) of annual overnight stays - with the 2018/19 winter season (November to April) recording 73 million overnight stays (Österreich W, 2019). The economic importance of tourism in winter is even higher in terms of tourist spending, since winter tourists spending (€184/day) is higher than summer tourist spending (€160/day) (Österreich W, 2018). Furthermore, Austria has a larger proportion of returning tourist (77%) for winter tourism.

Austrian operators have spent more than 6 billion € in the past ten years in terms of skiing infrastructure, with almost 800 new lifts have been built between 2000 and 2020 (Vanat, 2022). Moreover, there have been huge investments in snowmaking: with a yearly expenditure of 140 million € over the last 10 years. Now more than 60% of slopes are served by snowmaking infrastructure (Vanat, 2022). Although around 66 % of overnight stays occurred in ski areas (namely, with at least three ski lifts), demand in ski resort destinations is not homogeneous throughout the country, as it has been falling in southern regions such as

Carinthia and increasing in western regions such as Tyrol (Firgo & Fritz, 2017; Fleischhacker, 2018). As an illustration, investments for winter season facilities in Tyrol aggregate to 2.79 billion € over the seasons 2009/2010 to 2018/2019 (Bausch & Gartner, 2020). That this region, with 79 ski areas and 480 major lifts, accounts for nearly half of Austrian skier visits (Vanat, 2022). The main activity is downhill skiing (59%), followed by winter hiking (13%) and snowboarding (9%), with 3% of winter visitors using cross-country skiing as a winter vacation activity (Steiger et al., 2020). Despite the second-largest ski area in the world, with 54.2 million skiers coming every year, the proportion of alpine skiing in Austria dropped from 65% to 59% in 2018 compared to 2012, while the proportion of winter hiking increased from 10% to 13% during the same period (Vanat, 2022). Moreover, skier visits have grown by an average of just 0.4% over the past decade, and this minor increase is typical for the late phase in the product and destination life cycle which is associated with an increasing competition (Steiger et al., 2020).

3.7 Slovenia

Slovenia represents a special case in tourism development in the Alps because its infrastructure was quite insufficient when the country was part of the Federal People's Republic of Yugoslavia, and tourism only played a marginal role in economic terms. However, tourism has been one the highest growing and increasingly competitive sectors over the past 20 years (Vanat, 2022), and winter tourism regions have undergone a shift towards modernization of available tourism infrastructure (Polderman et al., 2020). Changes in the volume of tourism demand were, above all, related to the decline in foreign tourist visits during the 90s, while domestic tourism remained stable or even slightly increased. The most attractive area for winter tourism is that of the Julian Alps due to the appealing mountain landscapes as well as opportunities for outdoor recreation mainly related to alpine skiing. Some communities in the Julian Alps are even more dependent on foreign tourism than the coastal region such as Slovenian Istria, where summer tourism is prominent. As an example, the resort of Kranjska Gora witnessed a total of 828.000 overnight stays in 2019 in almost 6,000 available beds offered across 186 accommodation establishments, of which 85% were represented by privately owned apartments (Koščak et al., 2023). After the breakup of Yugoslavia, the Julian Alps' share of Slovenian tourism fell from 23.4% in 1990 to 17.8% in 1992, and by 2010, the proportion of tourist overnights spent in the region was about 20% (Cigale, 2019). Changes over the past decade have led to a significant increase in the share of the Julian Alps, as it even reached 24.5% in 2018 (Cigale, 2019). Today, Slovenia hosts 44 resorts with a total of 200 ski lifts (Vanat, 2022).

However, it is important to underline how specific microclimate and topographical factors affect the Slovenian Alps in winter: for instance, the mountains are not high in elevation, and the influence of the Mediterranean Sea is reflected in the high precipitation, which is especially evident in the western,

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southern, and southwestern regions of the Slovenian Alps (Ogrin et al., 2011; Vanat, 2022). The influence of the sea is very pronounced in terms of higher temperatures in the south-facing mountains compared to the temperatures in the north or closer to the interior of Slovenia, and this effect is especially pronounced in winter. The effects of CC have added up to this scenario, and this led to the significant change in snow conditions at lower elevations (Ogrin et al., 2011), with the consequent need for resorts to introduce snow-making facilities as the main mitigation strategy (Polderman et al., 2020). For instance, the ski resort of Cerkno is fully served by an extensive snowmaking system that allows for a minimum of 70 ski days per winter (Vanat, 2022). This can be a problem for the smaller snow resorts which are present in a large number. In 2013, only 16% of ski resorts in the Country had more than five ski railways and more than 5km of ski slopes (Alpine Convention, 2013) and they may suffer extensively if the amount of skiing days per winter fall under 60 (Ogrin et al., 2011). Winter tourism remains steady despite issues related to unreliable snowpack. Its survival is achieved through investments in snowmaking equipment and the fact that in most cases summer has traditionally been of equal (if not even greater) importance in comparison to winter (Cigale, 2019).

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4 Tourism destinations and the four generations of ski resorts

The growth of SWT and the development of many SWT destinations in the Alps date back to the beginning of the 20th century. During the last century, SWT in the Alps knew different steps. In order to offer an interpretative scheme of this evolution, many researchers have focused their attention to the birth, development and adaptation of different Alpine ski resorts during time. A **model of four generations of ski resorts** can be found in literature (Lovato & Montagna, 2012). Although the archetypes derived from the model are diachronic, there are temporal overlaps in the development of ski resorts, because of the territorial specificity of the different Alpine countries which have affected the process and the dynamics of construction.

4.1 First generation of ski resorts

The **first generation of ski resorts** refers to those resorts that already experienced a good development of Alpine summer tourism due to their connection to wellness and health treatments between the end of the 19th and the beginning of the 20th century. With the development of skiing as a sport, they added the winter season to their offer from the 1930s onwards. These resorts developed around an original core constituted by mountain villages and their historical activities, i.e., agro-pastoralism and handicraft. These activities were oftentimes progressively abandoned by the mountain dwellers who started to devote themselves to the tourist economy by becoming mountain guides, ski instructors and hoteliers (Parisi & Andreotti, 2010). It was therefore a spontaneous and internal evolution, sustained by individual initiatives of local entrepreneurs who built accommodation facilities. They were inspired by the previous model of the thermal destinations for the wellbeing and health of the European élites, offering a high standard of services and a good integration with the pre-existing urban fabric, constituted by historic buildings. However, there is no lack of cases in which the new accommodation structures were isolated from the original villages, for example the Grand Hotels, today historical architectural examples of the Art Nouveau style.

In general, the location of these destinations is determined by the accessibility of that time (especially the railway), which became an integral part of the tourist offer (e.g., Swiss trains, funiculars, …) (Lovato & Montagna, 2012). The most striking examples are Chamonix, St. Moritz, Cortina d'Ampezzo, Courmayeur, Gressoney, Val Gardena, Val Badia and Madonna di Campiglio.

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4.2 Second generation of ski resorts

This development was followed by the **second generation of ski resorts** (1950s-60s), built at higher altitudes, where there were no stable inhabited villages but scattered houses or only shelters for the shepherds, utilized during the summer ascent of the transhumance practice. An *ante litteram* example of this development is given by the Sestriere ski resort, at 2,035 meters a.s.l., established as a municipality in 1934 where until that there were only the pastures for the flocks and herds of the communities of the Val Chisone and Alta Val di Susa. The construction of Sestriere redefined not only the local topography and toponymy, but also territorial belonging. The infrastructure of the second-generation resorts is functional to the practice of skiing, a sport that has become popular over time. In these resorts, first the slopes are developed, close to ancient mule tracks that have been transformed into real roads, and then the hotels, which are built directly on the slopes. Investors are mainly external and aim at mass tourism, also favoured by the development of the road infrastructure and highway network. They choose areas close to urban centres, which constitute the target market, but outside existing mountain villages in order to have fewer constraints related to property and urban plans (Lovato & Montagna, 2012). Many of these projects were born at higher altitudes, where it is often possible to ski even in the summer months due to the presence of glaciers.

Their proximity to the urban areas results in a high visitor frequency mainly during weekends, which can lead to the phenomenon of uncontrolled construction of second homes. Examples of this generation are: Chamrousse, Alpe d'Huez, Stelvio and Passo del Tonale. Deviating from previous models are the interventions pursued in Tyrol and in the Province of Bolzano, based on the search for an 'organic model': The choice of preserving the traditional settlement structure at the bottom of the valley integrated and revitalised by tourist activities; on local scale management under strong control of the administrations with lifts of small dimension; a limitation of second homes by encouraging hotel accommodation structures in their various forms.

4.3 Third generation of ski resorts

From the French stations in Savoy, the **third generation of ski resorts** subsequently started. In the 1970s, the first and the second-generation resorts began to show weaknesses. The third-generation ski resorts were the result of the various snow plans of the French governments from 1964 to 1977, which aimed to democratise skiing and winter sports. This led to major investments by big companies that entrusted town planners and architects with the design of entire destinations focusing especially on the necessities of skiers. The newborn “snow towns”, were constructed where nothing existed before but nature. Placed at

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altitudes above 1,500 meters a.s.l., they were designed as large residential complexes equipped with all the services required by the tourists (sports complexes, shopping centres, etc.) and with a direct connection to the slopes. Examples of architectural experimentation, they have suffered a certain coldness and inability over time which make a reconversion to summer tourism extremely challenging, resulting into “ghost towns” for many months during the year. The most exhaustive examples are, as mentioned, those of Savoy, with the resorts of Tignes, La Plagne, Flaine, Les Menuires, Avoriaz, and Les Arcs.

4.4 Fourth-generation ski resorts

A decade later, the **fourth-generation ski resorts**, also known as integrated destinations, were developed as an evolutionary response to the previous generations: located at lower altitudes (never above 1,400 metres), they are characterised by greater attention towards potential environmental impacts, influenced also by the development of environmentalist movements, as well as greater care for architecture. The attempt in designing an integrated destination is to avoid modularity and large hotel complexes to recreate some architectural features of mountain villages. These destinations are often built next to some ancient, often depopulated, settlements. Unfortunately, many of these ski resorts are now suffering from “the vrai faux tyrolean chalet” effect. This translates into the manifestation of an artificial effect in comparison to ancient villages. The most famous examples of the fourth generation can be found in the French Alps: Valmorel and the Aigues Blanches district (Parisi & Andreotti, 2010). But there are also Swiss examples, such as the bigger ski resort of the country, Verbier. In Italy, one of the most conspicuous example is the Asiago Plateau. In addition, the modest success of integrated destinations prompted architects to design more human-scale settlements through the renovation of old Alpine villages. New, modern technological applications were inserted into old houses, which were largely remodelled (Bermond, 2018). In this spirit, several peripheral villages in Bardonecchia and Courmayeur in the western Italian Alps have also been redeveloped.

With the evolution from the first to the fourth generation, the management model of the resorts themselves has also changed, moving from a community model, based on local management of the tourism sector, to a corporate model, managed by holding companies and multinationals as well as corporations (Flagestad & Hope, 2001). At the same time, there is a strong tendency towards expanding the areas at high altitudes dedicated to alpine ski slopes, with the construction of new cable cars, gondolas and ski lifts. Following the historical examples of the Funivia dei Ghiacciai cableway from Courmayeur to Chamonix and the domaine Cervinia-Zermatt, many of them have taken on a cross-border dimension, such as from Sestriere to Monginevro (Via Lattea), from La Thuile to La Rosière, from Bardonecchia to Valle Stretta, or

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trans-regional dimension, such as the Monterosa Ski complex, from Champoluc to Gressoney, to Alagna Valsesia.

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5 Main climate variables and their effects on Alpine SWT destinations

The amount, duration, and melting of the snow is of considerable importance for a large number of natural ecosystems and human activities such as agricultural irrigation, water supply, hydroelectric power production (Beniston et al., 2018; Magnusson et al., 2020), and STDs (Hanzer et al., 2020). As observed by Frei et al. (2012), the annual accumulation and melting of snow are among the environmental changes that have a significant impact on climatic, ecological, and hydrological processes, including the surface energy balance.

The snow covering the ground is composed of a unique material formed by a solid ice structure and interconnected spaces that allow all three forms of water to exist together. Over time, snow undergoes a transformation, transitioning from a fresh state to becoming moist or wet as it nears the melting point. This transformation, known as metamorphism, alters the composition of the snow crystals as they transform from being separated by air-filled voids to being surrounded by liquid water. The combination of intermittent precipitation, wind, and ongoing metamorphism creates distinct layers within the snow cover. Each layer possesses unique characteristics, including microstructure, density, hardness, liquid water content, snow temperature, and impurities. These differences in physical and mechanical properties are determined by the type and state of the snow within each layer and direct its evolution. Environmental factors, both natural and human-induced, impact the individual snow crystals and their bonds, leading to further changes in the snow cover over time. Snow quantity and snow cover can be quantified using different parameters. The most used are snow depth (HS), depth of fresh snow precipitation (HN, also denoted as snowfall), snow water equivalent (SWE), snow cover area (SCA) and snow cover duration (SCD) (Pirazzini, 2018). Many other snow properties are essential for predicting snow avalanche danger but also snow management, as snow temperature, liquid water content, density, hardness, crystal types and layering (AINEVA, 2019).

5.1 Interactions snow-environment

To understand the interactions between snow and the surrounding environment, it is necessary to consider the physical characteristics of the environment itself, such as elevation, temperature, humidity, and wind. These variables are closely interrelated and depend on geographic location, season, and weather conditions. Much of the knowledge on snow melting processes and its runoff prediction can be found in the report of the United States Army Corps of Engineers (Hardy et al., 1998) and the works of Anderson

(Anderson, 1975) and Colbeck (COLBECK, 1978). Nowadays, several physical snowpack models are available for an accurate simulation and prediction of the snow accumulation and melting in mountain regions (Mott et al., 2011). There is a great diversity of models to simulate cold region processes. Several models, such as Prairie BlowingSnow Model (PBSM) (Pomeroy, 1989), CATchment HYdrology (CATHY) (PANICONI & PUTTI, 1994), HydroGeoSphere (HGS) (Therrien & Sudicky, 1996), and Water balance Simulation Model ETH (WaSiM-ETH) (Schulla & Karsten, 2007) GEOtop (Endrizzi et al., 2014), represent the complexity of hydrological processes in a distributed manner, but only a few, such as ALPINE3D (Lehning et al., 2006) and SnowTran-3D (Liston & Sturm, 1998), have a full multilayer description of snow processes in complex terrain.

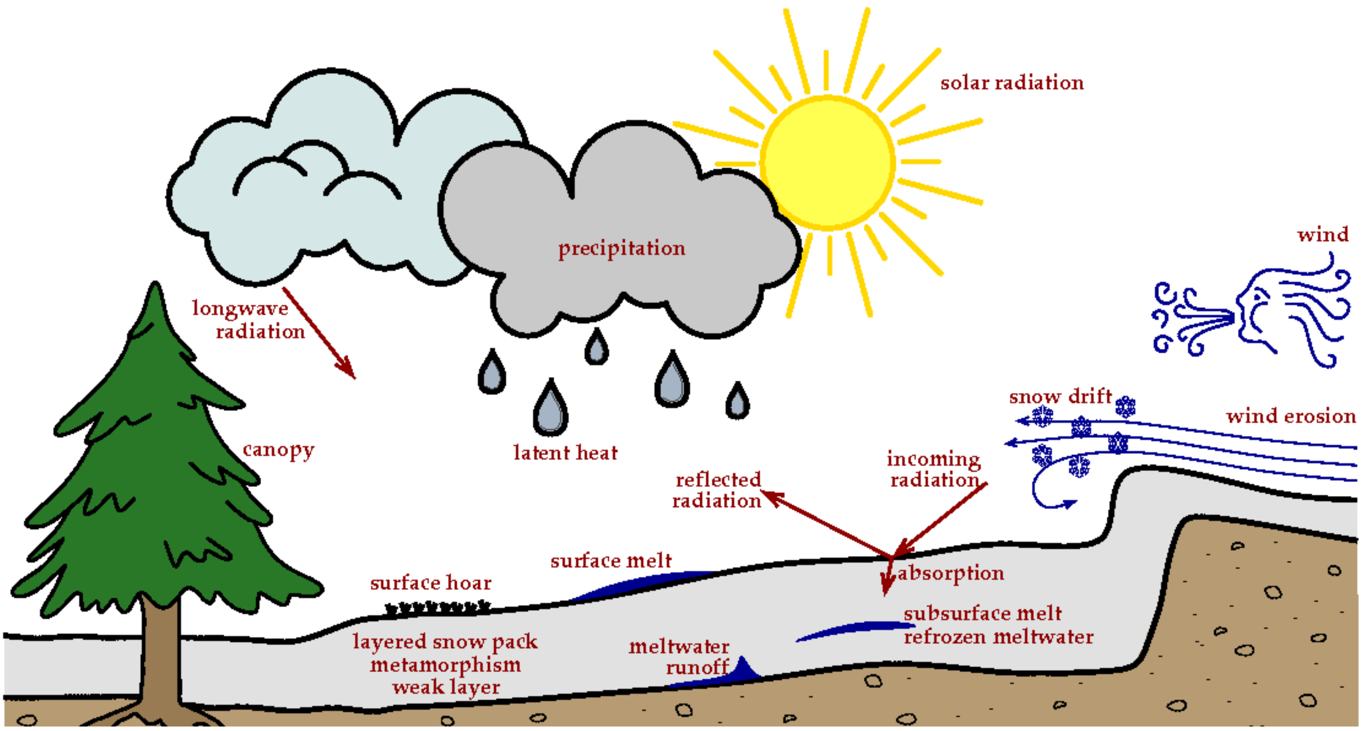

Figure 2: Infographic of the physical process of snowpacks. Source: SNOWPACK website, WSL/SLF SNOWPACK (slf.ch)

Today, the issue of CC and environmental sustainability is a highly relevant and concerning topic worldwide. The increase in temperatures is causing a decrease in snowfall, especially at low altitudes and latitudes (Bertoldi et al., 2023). In the future, all climate projection indicate that temperatures will continue to rise, with significant impacts on mountain cryosphere (Beniston et al., 2018). This does not mean that winters will be completely devoid of snow, but rather that snowfall will be less regular and result in accumulation followed in subsequent melting within winter season.

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Based on available CC scenarios, the observed general decrease in snowfall in the Alps in recent decades is expected to continue during the 21st century (Kotlarski et al., 2022). Recent studies by Eurac Research (Bertoldi et al., 2023; Matiu et al., 2021; Matiu & Hanzer, 2022), shows that in autumn and spring, snow depths decreased in all regions and at all altitudes in the Alps, which are subject to the influences of three climate regions: the Atlantic, the Mediterranean, and the continental climate. The main Alpine ridge represents the most prominent climatic boundary and separates the north from the south, while from west to east, the influence of the oceanic climate decreases and that of the continental climate increases. This has an impact on both temperature and precipitation. While the tendency of a temperature increase is rather homogenous in the Alpine region, the precipitation shows more different regional patterns and trends. The combination of the two factors has an impact on snow cover, as explained in the following sections.

5.2 Temperature and rates of snowmelt

One of the most direct effects of CC is the increase of global temperatures. Scientific evidence shows that human activities, particularly the emission of GHGs like CO2, are contributing to the greenhouse effect and trapping more heat in the Earth's atmosphere (Casty et al., 2005; Lal, 2004).

The European Alps are one region of the world where climate-driven changes are already perceptible, as exemplified by the general retreat of mountain glaciers over past decades. Temperatures have risen by up to 2°C since 1900 particularly at high elevations, a rate that is roughly three times the global-average 20th century warming. Regional climate models suggest that by 2100, winters in Switzerland may warm by 3–5°C and summers by 6–7°C according to greenhouse-gas emissions scenarios (IPCC, 2023).

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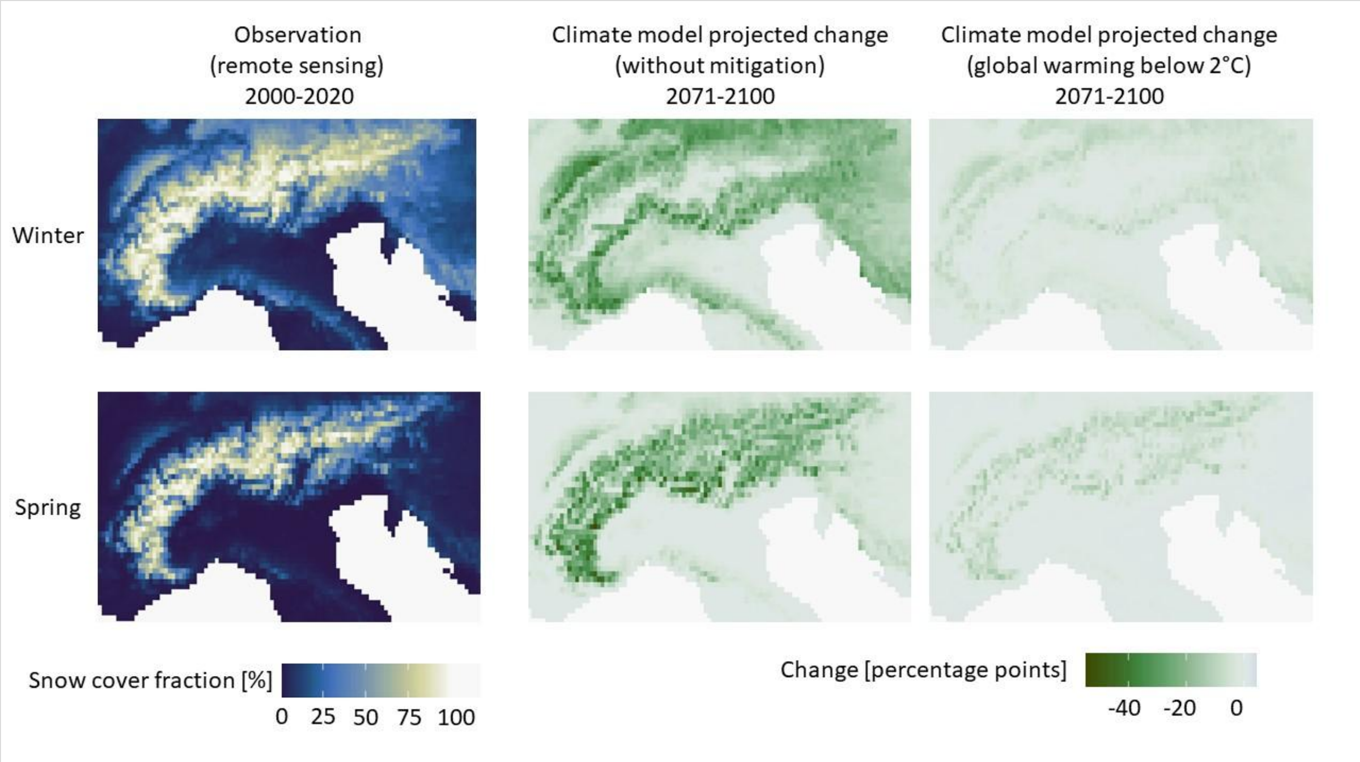

Figure 3: Snow cover in the present (2000-2020) and expected changes in the future (2071-2100 (Eurac Research, 2021).

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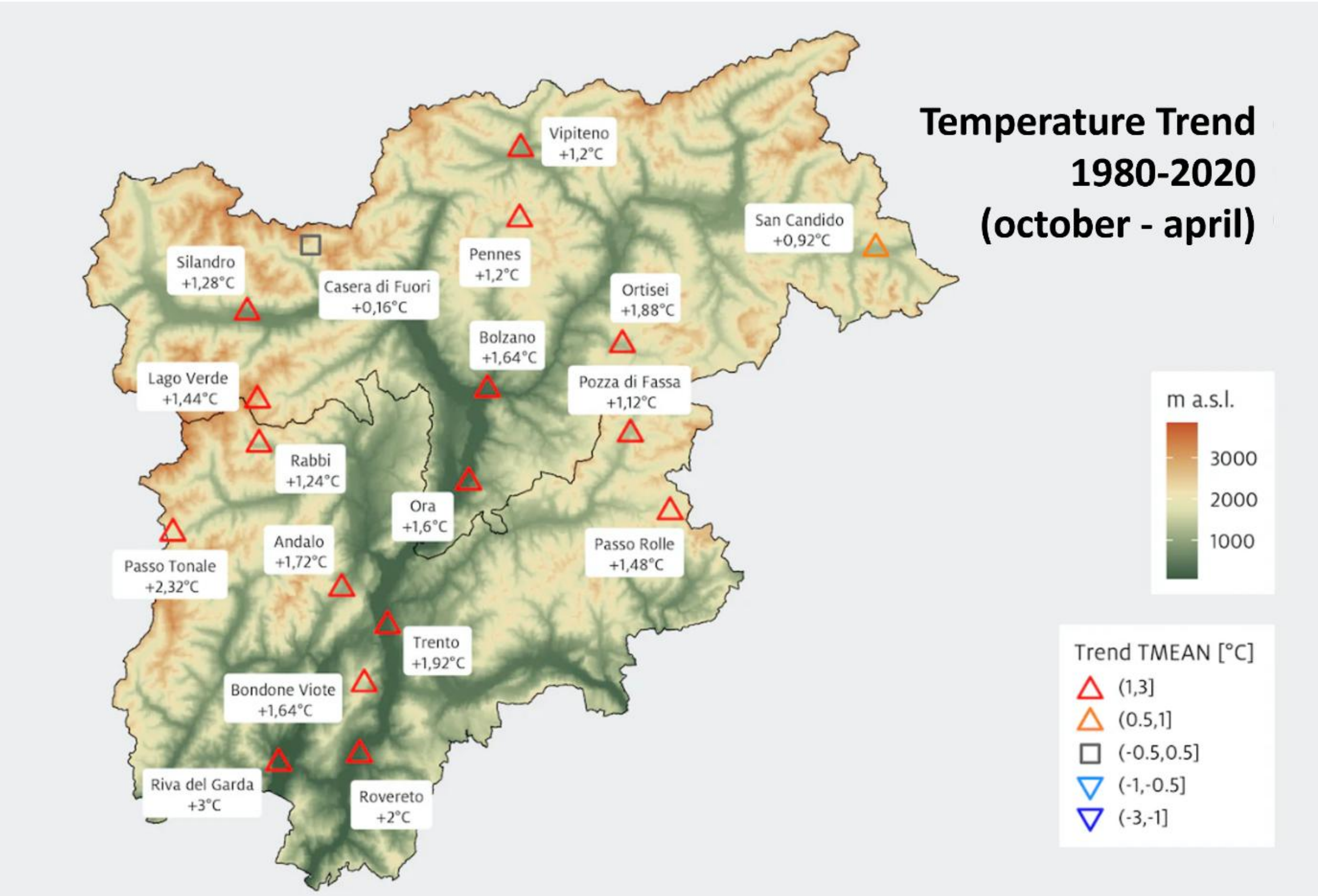

Figure 4. Example - Temperature Trend of Trentino – South Tyrol region, Italy (Bertoldi et al., 2023). Trends analysis for mean temperature shows that trends are positive for each investigated elevation, with the largest trends detected at low elevation.

In order for snow to form, a crucial combination of moisture and freezing temperatures must exist in the atmosphere. Usually, snowflakes start their descent when the temperature near the earth's surface drops below zero degrees Celsius. It is exceptionally uncommon for snowfall to occur at temperatures as high as five degrees above freezing, and this usually happens only under extraordinary conditions (Eurac Research, 2021). Once the snowpack is created, it is subject to the process of metamorphosis and thus to melting, since it is in contact with atmospheric forcing .The process of snow melting is a non-linear process and can generally be divided into three phases (Dingman, 2015): (i) warming, (ii) ripening (liquid water is present in the snowpack), and (iii) runoff (liquid water is released by the snowpack). Nevertheless, the melting of a snowpack does not constantly progress through the pure sequence of the three phases. Typically, when the air temperature stays above zero for extended periods during the ripening phase, a partial melting of the top layer of snow takes place. This causes the water released to seep into the snow layer and subsequently freeze again. As a result, the temperature within the snowpack rises due to the release of latent heat. In the same way, surface temperatures of snow can drop below zero during the melting period, and the superficial layer must warm up again before the melting can continue. The evolution of snow during the melting period is determined by the energy balance that forms between the snow and the surrounding environment. This energy balance is highly variable and depends on local factors. Snow is in contact with the ground on one side and the atmosphere on the other, exchanging energy in both directions. Furthermore, during the snowmelt process, an additional lateral exchange of energy occurs within the snowpack (Bartelt & Lehning, 2002).

5.3 Precipitation and snowfall

The Alpine mountains range is the origin area of four important river systems in Central Europe. Variations in precipitation distribution in this region have a huge relevance at a supra-regional level, as they influence the freshwater supply in broader environments. Mountains strongly influence precipitation distribution. This is mainly due to the influence of mountains on air movements. At higher altitudes, windward slopes generally experience greater levels of precipitation. Conversely, on leeward slopes, air masses tend to be drier, leading to reduced rainfall and snowfall. (Eurac Research, 2021).

The Alps are also called the water towers of Europe for this reason (Viviroli et al., 2020). In Figure 5, an example of the spatial distribution of seasonal precipitation.

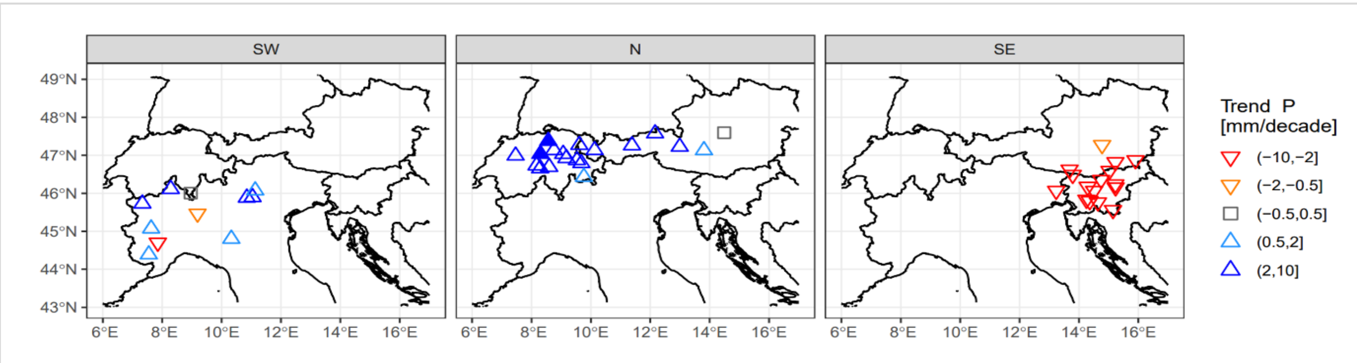

Figure 5. Spatial distribution of seasonal precipitation (P) expressed in [mm/decade] divided into 3 macro regions: South-West – North – South-East. Each point represents one station and the corresponding trend value: blue (red) triangles indicate positive (negative) trends; grey squares indicate negligible trends (i.e., between -0.5 and 0.5). Source: (Bertoldi et al., 2024).

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As Beniston (2012) claims, due to the CC, precipitation in the Alpine region is expected to increase in winter and sharply decrease in summer. The impacts of these levels of climatic change will affect both the natural environment and several economic activities. The altered timing of snowmelt affects the availability of water needed by alpine plants, having direct consequences on their growth and adaptability (Rammig et al., 2010). Over the past 40 years, snow depth has decreased at most measuring stations, but with differences depending on month, altitude and location (Eurac Research, 2021).

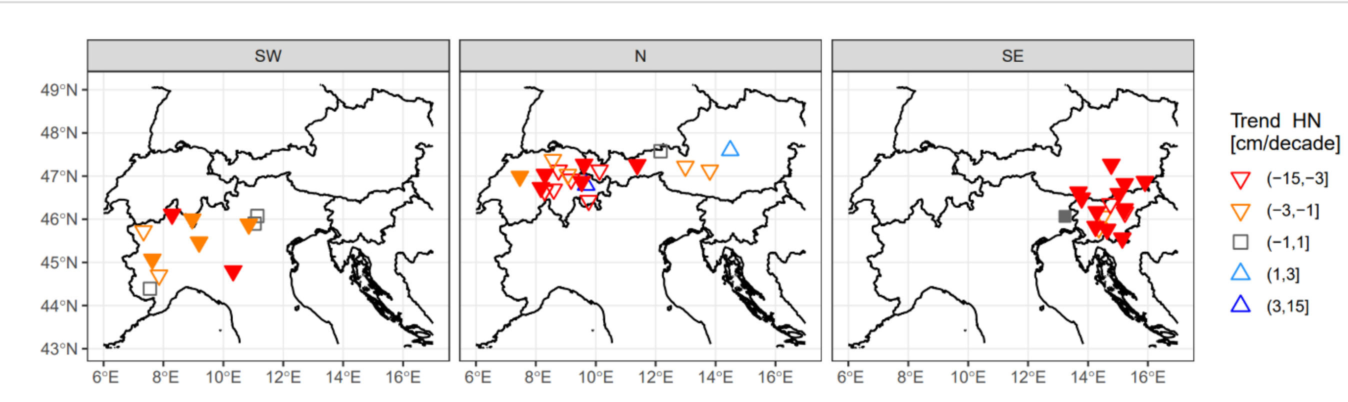

Figure 6. Spatial distribution of seasonal snowfall (HN) expressed in [cm/decade] divided into 3 macroregions: South-West – North – South-East. Each point represents one station and the corresponding trend value: blue (red) triangles indicate positive (negative) trends; grey squares indicate negligible trends (i.e., between -0.5 and 0.5). Source: (Bertoldi et al., 2024).

5.3.1 Precipitation and temperature Interactions

As altitude rises, temperatures typically decline of about 6 C every 1000 m. If CC is not slowed down, temperatures will certainly continue to rise, and the distribution of precipitation will also change. It is possible that precipitation will increase in the Alps in winter. However, also in this case due to higher temperatures, there will be less snow in autumn and spring (NOAA, 2022).

Recent studies (Bertoldi et al., 2023; Colombo et al., 2022), suggested that at lower elevations (below 1,700 m a.s.l. in the central Italian Alps) there is a clear decrease in snow abundance (HN) due to a significant increase in average temperature. Favourable circumstances for low-elevation snowfall are becoming increasingly rare and depend on favourable large-scale weather patterns. Additionally, due to global warming, there is a possibility that rain may occur instead of snow. On the other hand, at higher elevations a slight increase in precipitation and a slight increase in average temperature, which still allows for low temperatures during winter, both favour the presence of snow and potentially an increase in snow abundance. However, during spring, when even at higher elevations temperatures play a limiting role, an overall negative trend in snow abundance is observed.

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5.4 Wind

Wind is the movement of air on the earth's surface from an area where there is 'too much' air (dense air and/or high pressure) to an area where the air is not very dense and/or low pressure. Wind is a highly dynamic factor, particularly in regions characterized by intricate ambient wind patterns like those found in mountainous areas. It is now generally accepted that CC is accompanied by an increase in frequency and intensity (Trans-Alp Project, 2022) of extreme weather events (IPCC, 2021), which often include strong or very strong winds. One of the most important wind effects concerns the composition of the snowpack: by transporting snow from windward to leeward slopes, snow crystals are broken into smaller particles, loose snow crystals are pressed together, forming wind slabs as well as hard wind crusts and insulating the snow surface from solar warming. Wind is one of the major factors for avalanche risk and also a key factor controlling snow accumulation, especially above the treeline (Avalanche Canada, 2023). From a physical point of view, the wind contributes to the transformation of snow by increasing the impacts between the crystals and causing their structure to be destroyed and multiple flakes to merge. Three types of wind-induced snow transport effects can be distinguished according to wind intensity:

- Low wind (< 4 m/s): the grains are transported in the direction of the wind and are rounded off (rolling transport). Through this process, the snow accumulates in small depressions and smooths out irregularities, forming the characteristic undulations on the snow surface.
- Medium wind: the grains are lifted from 10 centimetres up to 1 metre (skip transport). This process leads to the development of concentrated deposits of snow, which can appear as surface creases or snowbanks driven by the wind, resembling snow dunes.
- High wind: condition in which snow clouds are created that can reach hundreds of metres (carried by wind turbulence). When this phenomenon is combined with falling snow, a blizzard occurs.

In practice, the snow transport by wind, and in particular by strong winds (Meister, 1989) is a primary factor in avalanche formation which in turn has an impact on the safety of people and infrastructure and thus on the STD activities. It can also have a negative impact on the attractiveness for tourists, as reported in a recent empirical study in a Greek ski area which confirms that skiers mostly find it unacceptable to ski during strong or very strong winds (Kapetanakis et al., 2022). Indeed, although is quite usual for skiers to believe that they can ski in any weather or wind speeds they feel comfortable with and skiing is normally possible also during high wind speeds up to about 60 km/h, when wind speeds exceed this limit, it becomes truly risky, forcing most ski areas to shut down lifts and cable cars. High wind speeds, that reach 130 km/h or more (MeteoSwiss, 2023) can easily blow skiers down or off a slope with a high risk of injuries (Carus & Castillo, 2021). Wind can also negatively impact the human comfort factor: Skiers who are comfortable skiing at the “current or normal” air temperature may not be prepared for how cold or hot the wind is, and frostbite, hypothermia and hot flashes can occur very quickly. Particularly intense and strong forms of wind, such as the recent "Vaia" Storm in Italy, can also cause substantial direct damages to infrastructure and landscape.

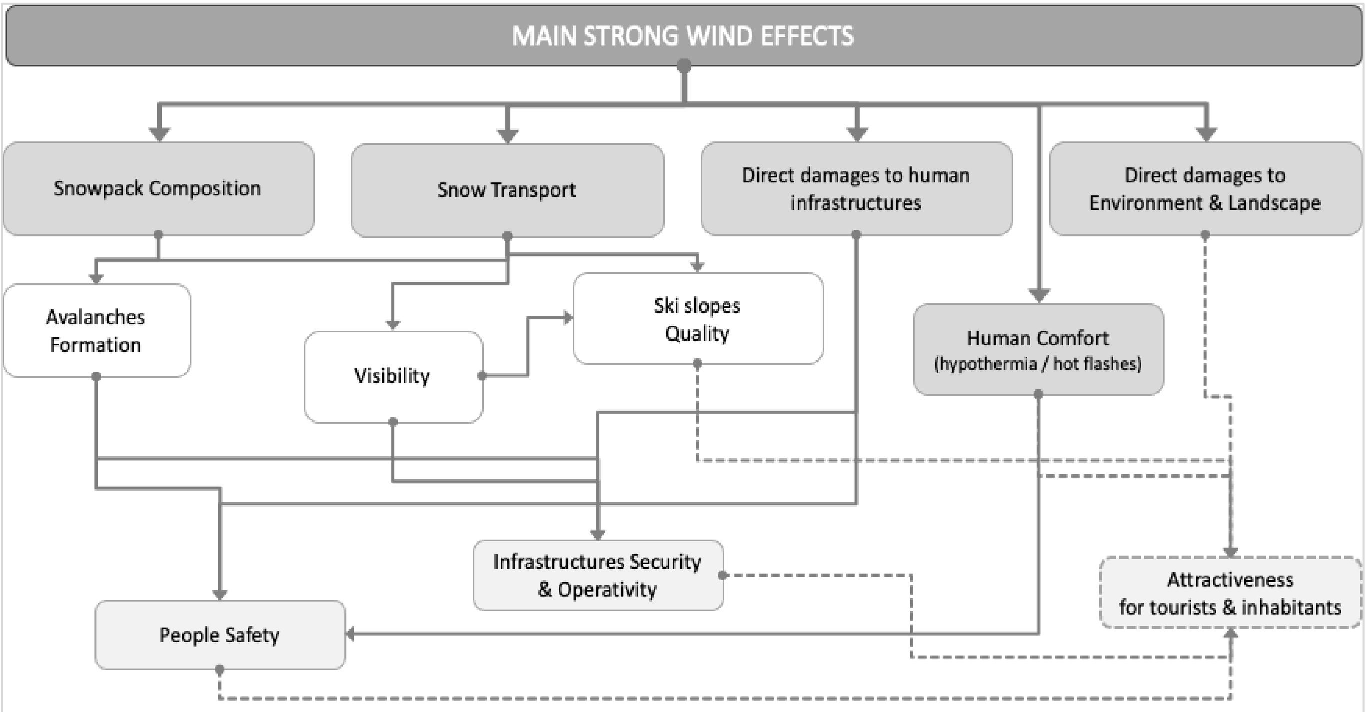

Figure 7: Diagram of the main effects of (strong) wind on STDs. Source: BeyondSnow project.

5.5 Snow cover duration and snow depth

Changes in snow cover and duration have a critical role in mountain environment as they are interlinked to water availability in downstream areas. In fact, changes in water regimes derived from snow melt variability can affect several sectors such as agriculture, tourism, and hydropower production (Huss et al., 2017; Bormann et al., 2018). In this context, two main indicators derived from time series of satellite images such as changes in snow cover duration (SCD) and snow cover area (SCA) can be of utmost importance to understand the current situation and the impact on STDs. More specifically the availability of around 20 years of data allows detecting the trends at the level of single municipalities.

To perform the trend analysis, snow cover maps produced by Eurac Research through the algorithm of Notarnicola et al (2013) are exploited. The algorithm makes use of the MODIS product at a spatial resolution of 250 m for snow detection. The algorithm allows a binary classification (snow/snow free) at 250 m spatial resolution, representing an improvement with reference to other standard MODIS products at 500 m. The maps cover a period of more than 20 years, with a daily image from 2002 up to now.

Cloud presence represents a relevant issue, particularly in regions like the Alps, where persistent cloud coverage notably impacts the area, especially during the winter, for approximately half of the time (Parajka & Blöschl, 2006). For this reason, a cloud reduction algorithm that generates a cloud filtered map is firstly applied. The algorithm considers a time window of +- 2 days. Only pixels having snow (or no snow) in the images inside this window before and after the date to be corrected is cleared from cloud presence.

After this step, two snow presence indicators for each of the municipalities that are present in the study area in the Alps are computed. For computing the following metrics, the information about snow presence at the level of the polygons representing the municipalities is aggregated. When referring to a period of 1 year, the hydrological year starting from the 1st of October to the 30th of September is considered. The first indicator is the snow cover area (SCA), i.e., the percentage of pixels inside each polygon that is covered by snow. The second indicator is the snow cover duration (SCD), i.e., the number of days that show presence for the considered area. In this case, the cloud presence putting a threshold of 50% in terms of SCA for the considered polygon is discriminated. Also in this case, annual means are computed.

Based on these maps available for a long record of data (about 20 years), a trend analysis can be performed to understand whether there are positive (increase of snow cover area or snow cover duration) or negative (decrease of snow cover area or snow cover duration) changes. The presence of a monotonic increasing or decreasing trend in time in the analysed variables for a given area is assessed with the non-parametric Mann-Kendall (MK) test. The Theil-Sen slope is reported for both SCA and SCD in Figure 8.

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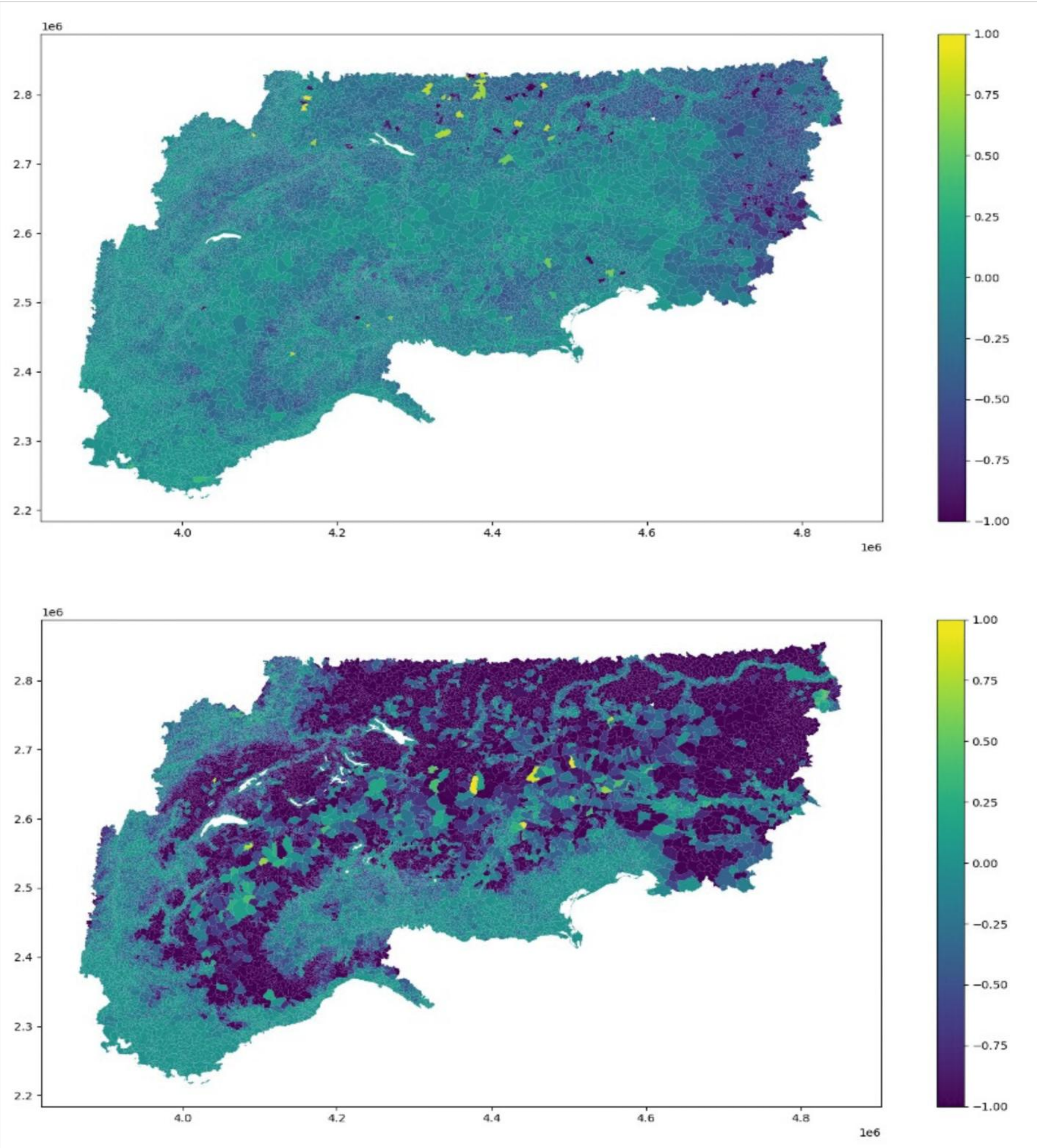

Figure 8. Theil- Sen slope values indicating positive and negative changes for the snow cover area SCA; bottom: Theil- Sen slope values indicating positive and negative changes for the snow cover duration SCD.

For a clearer interpretation, we also plot the results of the test as a classification of the municipalities with places with decreasing, increasing and no trend areas for both SCA and SCD.

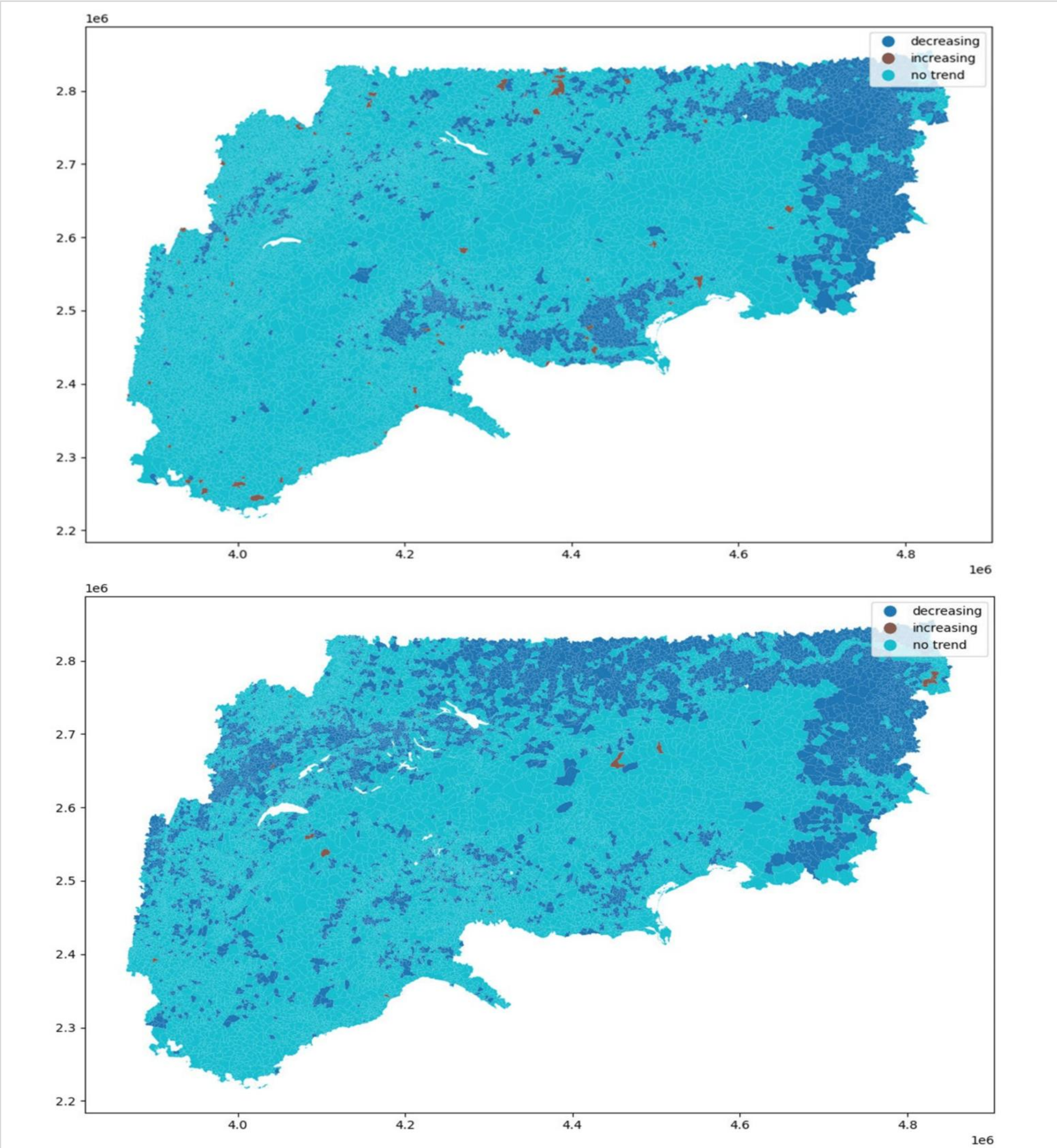

Figure 9. Top: positive and negative changes for the snow cover area SCA; bottom: positive and negative changes for the snow cover duration SCD

6 Current responses

In general, tourist destinations must consider the seasonal fluctuations of their tourism flows. While city and cultural destinations exhibit minor variations of tourism flows throughout the year, and sun-&-beach destinations concentrate their efforts on the summer mono-season, mountain tourism destinations are usually shaped by a bi-seasonal distribution of tourist influx, displaying tourist arrival and overnights peaks in winter as well as in summer. Within these two high seasons, further "micro-seasonalities" are present, which translate into peak days or weeks within the overall winter and summer high seasons, being influenced by the difference between weekdays and weekends, events and, most of all, fixed (e.g., Christmas) as well as moving (e.g., Easter, Carnival) holidays (Candela & Figini, 2012). Being the tourism experience an intangible product (one bed not sold one night, cannot be stored, and sold the next day - The revenue of that bed is inevitably lost), tourism destinations, for being economically viable, are required to ensure the best conditions to attract and retain the most adequate number of guests within an optimal time period, independently of their size (Moreno-Gené et al., 2018, 2020).

6.1 Skiable days

SWT destinations, especially those concentrating on skiing, are highly dependent on the (optimal) external weather conditions throughout the winter season. In terms of CC effects on ski operations of SWT destinations, an initial assessment can be undertaken by following the 100-day rule, first suggested by Witmer (1986). It states that in order to successfully operate and being defined as snow-reliable, a ski area necessitates of a snow cover sufficient for skiing (snow depth ≥ 30 cm), lasting at least 100 days per season in seven of ten winters (Abegg, 1996). Although not an imperative rule, it has been widely accepted among ski area operators in Europe, North America and New Zealand (Abegg et al., 2007; Hendrikx et al., 2012; Scott et al., 2008). In order to ensure these optimal parameters, the percentage of slope areas, on which technical snow is employed, amounted to 25% in Germany, 39% in France, 54% in Switzerland, 70% in Austria and 90% in Italy (Province of South Tyrol) (Seilbahnen Schweiz, 2022). The provision of adequate skiing conditions becomes even more imperative during the (economically) important Christmas, New Years Eve and Carnival holidays (Demiroglu et al., 2016).

Next to snow depth, additional climatic conditions, which contribute to an optimal ski day (OSD), are precipitation, temperature, snow depth, sunshine duration, and wind speed (Berghammer & Schmude, 2014). Compared to the 2010s, until the 2050s in the German Alps OSDs are expected to decline between −35% and −91% (Steiger et al., 2019).

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6.2 Night & sunrise skiing

Skiing or snowboarding after sundown, has been offered in some Alpine ski areas since the 1950s. Within them, two or three times a week, a few slopes are prepared and illuminated with specific floodlights for nocturnal visibility. It typically begins after the end of the daily skiing (normally at sunset) and ends between 8:00 PM and 10:30 PM, permitting last runs for daily skiers and offering the possibility to experience the activity during nighttime. In some other cases, such as in the ski areas of the Italian Dolomites, night skiing is allowed after the slopes have been re-prepared after 7:00 PM, enabling the skiers to safely ski on packed snow also due to the temperature decrease during nightfall. In recent years, the portfolio of night winter activities of some ski areas has been expanded with night sledding, snowshoe night-excursions on prepared and floodlit trails and night-time freestyle park openings, activities which are gaining in popularity and are growing rapidly.

Other ski areas are also piloting early morning openings of some ski facilities and slopes. They are offered as new and exciting experiences for mountain skiers: Skiing in the silence of mountain peaks during the early hours of the day, while the sun starts illuminating the freshly groomed slopes. This is often accompanied by particular breakfast offers. In some cases, these sites feature early closures of facilities in the afternoon.

6.3 Snow manufacturing

6.3.1 Technical snow & artificial snow

The correct term for snow which has been produced with the aid of snow guns is "technical snow". This is often referred to colloquially as “artificial snow”. It consists solely of water and air and differs from natural snow only in that it is produced by a machine. In the true sense of the term, artificial snow refers to snow used for theater and film and made from plastic or polystyrene (TechnoAlpin AG, 2023).

6.3.2 Technical snow

Technical snowmaking provides nowadays the basis for winter tourism. Without snowmaking systems, ski resorts would oftentimes no longer be able to meet today's increased demands. According to TechnoAlpin AG (2023), one of the world's leading companies in the production of ski facilities, snow reliability is the number one criterion when it comes to choosing a SWT destination. As stated by this company, some studies (not verified) also show that just 20% of visitors will accept extras or hotel services by way of compensation for insufficient snow. Especially when planning a skiing holiday well in advance, winter

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holidaymakers will choose the destination which has the facilities to offer guaranteed snow for the dates in question. Guaranteed snow is also a deciding factor for potential investors. Besides the direct added value for ski resorts by way of cable cars or ski schools, technical snow also forms the basis for indirect added value for entire regions and has an impact on the hotels and restaurants in the surrounding area.

6.3.3 Technical snow / natural snow

Like natural snow, technical snow consists exclusively of water and air. The only difference lies in the production method. Technical snow is produced by replicating the natural snow formation. Natural snow is formed when the finest water droplets accumulate in the clouds on crystallization nuclei (e.g., dust particles) and freeze there. The resulting ice crystal lattices (less than 0.1 mm in size) fall downwards due to the increasing mass. On the way to earth, the water vapor in the air accumulates, causing the crystals to continue growing. The size of the snowflakes deposited as new snow depends on the temperature. If it is warmer than -5° C, large snowflakes form. At cooler temperatures, the air becomes drier, and the flakes are smaller. The principle of formation is the same for technical snow. The only difference is that the snow core is produced by a mixture of water and compressed air through the snow gun. Due to the lower overall drop height, however, technical snow has a slightly different crystal structure than natural snow and is harder because the snowflakes are smaller (TechnoAlpin AG, 2023).

6.3.4 Fan guns

Fan guns are often also called snow guns. For a long time, mobile fan guns were the only models which were used. As snowmaking technology developed, however, the stationary installations also became popular for surface coverage in order to avoid set-up times. Fan guns are characterized by a wide projection range, high snow output, low wind sensitivity and flexible use. Therefore, they are mainly used on wide slopes, in areas with a high demand for snow or in open areas exposed to wind (TechnoAlpin AG, 2023).

6.3.5 Snow lances

Snow lances basically generate snow in the same way as fan guns. A greater height is required, however, to crystallize the snowflakes because they lack the propeller, or turbine, fitted in the fan guns. Snow lances therefore have a lower projection range and greater wind sensitivity, but they are more accurate in terms of where the snow lands. The quantity of snow produced by a lance is similar to that of a small fan gun. Ideal fields of application are, for instance, narrow slope sections without particular exposure to wind, connecting slopes or ski trails (TechnoAlpin AG, 2023).

6.3.6 Snow factory

The snow factory is a snow generator which can also be used in warm temperatures. The snow factory is designed to add to the possible applications of snowmaking technology and is therefore mainly used on lower slope sections or at events in large towns. The snow factory produces snow by means of an innovative cooling technology without any chemical additives. No complicated building work or fittings are necessary to install it which is why it is also suitable for temporary applications (TechnoAlpin AG, 2023).

6.3.7 About the use of ecological and economic resources

Most skiing events at the 2018 Winter Olympics in Pyeongchang took place on technical snow. This is a striking example of how important is for the ski industry to invest greater and greater reliance on technical snow to secure ski activities and the winter tourist season. Small communities almost always lack such resources to invest and rely on national or regional public funding where available. It is still a topic of study and discussion what is the environmental and the economic impact of the replacement of the natural snow with technical snow.

The first consideration is the resource cost. Having to create snow, illuminating the slopes at night, operating the lifts for longer hours and resurfacing some slopes for extraordinary openings, etc. increases the STDs expenses, limiting profitability. Warmer weather means reduced snowmaking efficiency, so a greater number of snow fan guns will be required to make the same amount of snow. A recent study by Pickering & Buckley (2010) determined that the efficiency drop is especially true at lower altitude resorts where a warming climate will be felt first.

It is empirically clear that more snow guns mean more water pipes, compressors, and other technical and digital infrastructure necessary to operate them. Thanks to technological innovations less and less (about 80% compared to a few years ago, with some instruments running on zero electricity), but fan guns / lances and their support equipment still run on electricity. Except for a few cases of the use of very locally produced renewable energy (solar panels, mini wind turbines, locally compatible mini hydroelectric power plants, etc.), these tools tend to increase GHG emissions and the related negative externalities on climate. Illuminating the slopes at night and operating the lifts at night or early in the morning also have some negative environmental impacts (e.g. disturbance to wildlife, light and noise pollution, etc.). Another central topic in today's debate is the depletion of the good-resource water for snow production. Even water for snowmaking is now mainly taken from specially created reservoirs, the question remains open as to its priority use in areas and periods when this resource is in limited supply.

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6.4 Snow farming

It is a snow accumulation and management technique, already tested and used in past years to safeguard glaciers from melting. According to (Grünewald et al., 2018), large amounts of snow are collected, also at lower elevations, at the end of the winter or produced by snow machines and conserved over the summer months in a so-called snow depot. Given that a ski slope needs approx. 20-40 thousand cubic metres of snow to be prepared for winter, and a thickness of at least 30-40 centimetres for skiing, snow farming may be considered a practice that is not always economical and more appropriate for cross-country ski runs, or only for certain sections of downhill slopes, or for special circumstances such as the preparation of slopes for important events.

Figure 10. Livigno Snowfarm. Source: APT Livigno, 2023. https://www.livigno.eu/en/livigno-snowfarm

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6.5 Non-snow-dependent activities

6.5.1 Not only snow. Towards multifaceted territories and tourism destinations

In several documents of the European Union, e.g., the Green Paper on Territorial Cohesion (European Commission, 2008), the concept of a “different” territory emerges, pointing towards a strategic approach in the view of a more sustainable development, based on its economic, environmental, energy and cultural potential. This led to the introduction of reflections about re-orientation policies regarding mountain territories focused on the mass tourism industrial policies and the policies on economic assistance for technical snowmaking.

Studies conducted on socio-economic and human sciences have highlighted an array of distinctive features of the mountains, deriving both from co-evolutionary relations between local communities and the natural environment, as well as from the relationship with the rest of the world. These relations have influenced the mountain territories in the use of the soil, agricultural and farming practices, settlements, landscapes, culture, social organisations and, more generally, the territorial practices such as sport activities, usually taking place above 1,000 m, and especially winter sports. In the last ten years, while certain mountain development trends saw a gradual decline, new trends and approaches have gradually become the main factor of economic growth in the mountain areas more affected by CC. This development is quite limited to a restricted number of areas, in crisis due to limited snow cover, depopulation, and economic decline.

In these mountain areas, some resources have a strong positive impact. These resources encompass the large allocation of water, hydro-electric resources and forest biomass, biodiversity, the provision of "eco-systemic services", typical local products, cultural diversity with its rich material and symbolic heritage, the know-how connected to the numerous activities and multi-functionality of the territory, cooperative practices and community organisations for the management of collective properties, and the simplification of cross-border relations. The difficulties to consider are hydro-geological risks, a higher vulnerability to climatic change, the reduction of agricultural production, the obstacles represented by morphology and climate, the weak institutional structures, and the subsequent lack of political autonomy of many territories, which oftentimes are considered mere appendices of strong centralized areas.

Considering these aspects, for many mountain areas this means to restart the interrupted evolutionary path, which is oftentimes connected to a contamination of the tangible and intangible heritage with innovative solutions, but suitable to the natural, social and cultural environment, which needs to keep its peculiarity also in the context of CC. As stated by Bonomi (2013), p. 67) “resilience is the opposite of rigidity, you endure to move forward, not to withdraw into sadness and desperation again. You do it to open up to hope, as a conscious aspiration to a new future".

Initiatives carried out in this framework regard new forms of tourism, within which the re-interpretation of local resources has now become the trigger for development combining local and supra-local networks (Fourny, 2014). These initiatives are targeting specific touristic niche markets, interested in nature, agritourism etc. In order to create processes of territorial regeneration enhancing the underestimated local potential considering strongly declined or absence of snow cover, two factors are key elements to implement innovation: the objective presence of specific territorial resources (natural and cultural) and the subjective perception of the potential customers. The latter is the one that has changed the most in recent years, generating a new demand for new forms of tourism, for example, eco-tourism or culinary tourism. Social and cultural changes have resulted in several challenges for alpine tourism, which are encouraging the search for innovation.

In the winter, tourists frequently visit mountains to perform common snow-related sport activities, such as downhill and cross-country skiing, ski mountaineering, Nordic skiing as well as snowshoe hiking. Further, often underlying motives can also comprise seeking nature, culture, and relaxation. Particularly affected by this new trend are ski resorts, which are no longer just identified as ski destinations, but become a tourism destination where the various additional experiences can be enjoyed holistically. In the scientific literature, various models have attempted to respond to the mature phase of the development life cycle reached by many of these resorts (Buhalis, 2000). Among these, one of the mentionable models is the 4L model (landscape, leisure, learning and limit) defined by authors as "4L tourism" (Franch et al., 2008), which could provide mature destinations with the means to innovate their tourism products in a sustainable way. Currently, only a few ski resorts have attempted to intercept the 4L demand.

In recent years, the effects of CC led to the necessity to reconsider some of the essential elements of SWT destinations. Shorter and milder winters are likely to cause challenges to tourism businesses, not only in the Alps (Sievänen et al., 2005). The tourism industry should therefore be prepared to develop and implement other activities and products alongside snow-based recreation and to offer mitigation options for this economic sector (Steiger et al., 2020). Decreasing as well as irregular snowfall compelled many ski resorts to differentiate their offerings, ideally utilizing the territorial resources already present in the area and new establishing networks with other local and regional players (Dissart, 2012). While the main attraction factor of a ski resort remains skiing, the differentiation of the tourist offer allows the destination to be attractive while decreasing its dependence on favourable weather conditions.

Figure 11. Outline of the main ski-related and other possible winter activities in mountain area. Source: BeyondSnow Project, 2023

Concerning this matter, two strategies encompass the creation of opportunities for non-snow related tourism products while still matching the expectations of non-skiers. On the one side, ski resorts have started to propose different offers linked to cultural, gastronomic, as well as sports possibilities based on short networks, with sportspersons from the territory, or on long networks, with sportspersons from other territories (Figure 11). On the other hand, many SWT destinations which focused their main efforts solely on the winter season, have begun to develop products and activities also for summer tourism. They converted their image on the tourism market to outdoor venues *tout court* by enlarging their activity portfolio with new sports opportunities as well as cultural initiatives (festivals, book fairs, film festivals, food

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and wine events etc.). Due to increasingly mild autumns and springs, this strategy is also propaedeutic to the extension of the summer season and the de-seasonalisation of flows by enabling the guests to pursue summer activities such as hiking, biking, and canoeing also during these shoulder and low seasons.

How ski resorts cope with the lack of snow (strategies and networking)[1]	
Short networks	**Long networks**
Collaboration with the local historical-architectural heritage system (local museums, eco-museums, historical-artistic buildings)	Collaboration with the historical-architectural heritage system of the surrounding foothill, lowland or towns (e.g., Alpine towns, capital cities)
Collaboration with local farms regarding *zero-km*-products Proposal for a starred cuisine in local restaurants Farm visits for families	Collaboration with other regional tourism systems (e.g., wine landscapes, product routes, etc.).
Organisation of events and shows related to the culture of the area and/or region (theme evenings with nature parks, local associations, enogastronomic evenings, visits to local artisans)	Organisation of day trips: city tours, shopping in shopping centres, theme parks
Integrated outdoor offer including other activities, e.g., hiking, cycling, golf, paragliding, canoeing, fishing but also different ways to enjoy traditional paths (hiking with animals, full moon hiking, thematic paths). Integrated indoor activities, e.g. climbing, swimming, tennis.	Organisation of on-site events related to regional specificities (e.g., wine tasting evenings including wines and products from the valley floor/ plain)
Wellness offers both within accommodation infrastructures as well as in Spa centres.	

Table 1: Strategies to overcome the snow-based winter tourism.

[1] Methodological note: the table is derived from the analysis of the websites related to four ski resorts in France (Serre Chevalier Vallée Briançon), Western Italy (Praliskiarea), Eastern Italy (Alpe Cimbra Folgaria-Lavarone), and Switzerland (Pays du Grand Saint-Bernard). Two of them are small ski resorts with less than 50 km of slopes. The others are medium-large ski resorts with more than 100 km. All the four ski resorts are located at medium altitude (1,100-1,200 meters a.s.l.) although if the lifts could reach higher altitudes (2,800 meters a.s.l.).

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7 Community perception of Climate Change

CC can generate the necessity of physical, environmental, social and/or economic changes/transformations of Alpine SWT destinations. Their local communities are increasingly called to give a response to change through initiatives leading to adaptation and new ways of resource management due to extreme climate phenomena. Progressively significant changes increase the relevance of attitudes in response to new situations that depend on the perception of the climate problem, and consequently the means that are made available.

An all-encompassing understanding of CC by local populations and communities is not obvious (Jurt et al., 2015) and indeed there are many difficulties to comprehend a global phenomenon and translate it to a local scale, resulting in one of the key issues being "the social construction of the climate problem is still largely to be done at local level" (Brédif et al., 2015). The theme of the perception of CC in Alpine SWT destinations by local stakeholders has been the subject of research since the late 90s, about 10 years after the research of impact and vulnerabilities assessments (Abegg, 1996). Today in field research the relevance of the CC perception of stakeholders has a limited role.

The ability to adapt the ski and tourism systems to the new challenges inevitably needs to be built upon the sensitivity and capabilities of whom can highly relate to the complex world of snow. The reference contexts of CC perception are those most exposed to its effects such as the areas traditionally depending on the skiing and SWT economy (e.g., Switzerland, Bavaria, Tyrol) but also mountain areas directly connected to CC phenomena, such as melting glaciers (Clivaz & Savioz, 2020). Perception must be understood as the first situation of awareness followed by responsible actions and projects to implement CC adaptation strategies. Often CC is considered solely a global phenomenon and the awareness regarding its potential and specific consequences at local level has not yet been unfolded, hindering, therefore, the possible development of adaptation strategies and individual initiatives (Trawöger, 2014).

Generally, the perception of the communities regarding CC in Alpine ski and SWT contexts has been mainly examined based on two different categories of stakeholders, who represent mainly the dynamics and economies of SWT destinations: ski industry and tourists. The representatives of these two categories are directly affected as well as concerned by the effects caused by CC.

The perception of CC of many ski and SWT industry stakeholders, including ski resort operators, hospitality and services sector professionals as well as local and regional government officials, is varied and depends on individual sensitivity and knowledge. But oftentimes it is perceived as an incremental and temporally distanced threat (Steiger et al., 2019). Furthermore, the industry's faith in snowmaking technology and high fear of business damage can cause a distortion of the perception on effects of CC. Despite most reviews of the impact of CC on the ski industry has used CC scenarios for estimating future changes in snow conditions (especially snow depth and duration) (Gilaberte-Búrdalo et al., 2014), there is skepticism to introduce CC adaptation and mitigation actions by stakeholders and decision-makers. One of the potentially most influential drivers of CC perception is the transfer of scientific knowledge in practices.

Tourists' perception of CC is closely linked to their activities while being present within the ski and SWT destination. Their behavior and habits change based on the snow conditions and the increase of anomalously warm seasons, leading them to change their travel patterns oftentimes significantly, for instance by considering alternative holiday plans, and/or their activity patterns, for e.g., by undertaking new sport activities. Furthermore, tourists can also simply choose an alternative ski and SWT destination (Witting & Schmude, 2019). Another way of tourist CC adaptation is to reduce their travel frequency or concentrate the number of skiing days in the most favorable snow season. This increase of demand peaks can generate adverse consequences for transport patterns and volumes, CO_2 emissions and overstress of services.

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Box:

Mountain territories: testimonies about critical situations experienced and related emotions, identified obstacles and levers

Fabrique des Transitions (PP13 - FABTRA)

The experience of la Fabrique des Transitions (PP13 FABTRA) has given rise to a strong conviction: ***Transition*** *is not an adjustment variable for existing public policies or a purely technical issue, but a more complex and systemic challenge, which calls for a change of model and imagination.*

Considering the need to radically change our systems of thought, our economic models, our institutions and our development trajectories, "territories", in the sense of communities woven from human relationships, and thought of as multi-actor ecosystems, are key players to be led in the transition.

This is why it is crucial to take an interest in how the inhabitants of these territories (citizens, elected officials, local authority agents, social and economic stakeholders, and State representatives) are being influenced by climate change: how are they experiencing these upheavals? How are their functions being transformed in a time of transition? What are the challenges and obstacles they face and what levers can they use to act?

On the occasion of a collective intelligence workshop as part of the "Avenir Montagne Ingénierie" support program conducted with 62 French mountain territories with the ANCT (Agence Nationale de Cohésion des Territoires), la Fabrique des Transitions gathered the testimonies of 56 mountain territory actors and stakeholders (elected officials, agents of local authorities, associations and companies) on critical situations they experience related to climate change, emotions they arouse and the obstacles and levers for action identified by them.

The exercise aimed at concretely and locally illustrating the consequences of overstepping planetary limits. This was achieved, not by technically and scientifically analysing the effects of the degradation of the major biogeochemical cycles, but by observing the way in which the **territorial actors, experienced and perceived these disruptions individually and collectively.**

Hereinafter the synthesis of the results (For the full version, please refer to Annex 1)

Fabrique des Transitions (PP13 - FABTRA) – 1/4

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Critical situations, causes and consequences

A **critical situation** can be defined as the disappearance of a resource and/or of an asset (ecological, economic, social), which most likely results in tensions, and has the potential to jeopardise the continuation of the socio-economic system as well as the overall future of the territory.

- A shorter and more discontinuous snow period:
  - Lack of snow;
  - Need for an alternative and diversified economic and tourism model.
- Drought:
  - Lower energy capacity;
  - Restrictions in water usage;
  - Risk to the drinking water supply;
  - Impossibility to practice certain recreational activities (swimming, rafting, canyoning, etc.).
- Loss of biodiversity:
  - Reduction or disappearance of forest stands;
  - Fragmentation of biotopes;
  - High mortality of bees.
- Overtourism:
  - Car park saturation;
  - Traffic jams;
  - Paths widening;
  - Inappropriate behaviours;
  - Challenging coexistence between locals and tourists, often resulting in conflicts.
- Decrease of the living standard of inhabitants:
  - Lack of housing;
  - High housing costs (buying and renting);
  - Few accommodation possibilities for seasonal workers;
  - Closure of local shops;
  - Emigration of full-year service providers.
- Other critical situations:
  - Conspicuous change in local fauna (emergence of new predators, displacement of traditional species);
  - Extreme geological events;
  - Extreme weather events.

Fabrique des Transitions (PP13 - FABTRA) – 2/4

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Emotions

- **Fear and anxiety**

Faced with the numerous critical situations mentioned by the territorial actors and stakeholders, the dominating emotions encompass **fear** and **concern**. Faced with the disappearance of natural elements and with the emergence of abrupt changes, further emotions encompass **shock** and **stupefaction**. These emotions are expressed through a range of words and nuances that reveal both a sharing of similar affects as well as the expression of individual feelings. The concepts of eco-anxiety and solastalgia[1] were widely expressed.

- **Anger**

Also, many mention a strong feeling of **anger**, with even **forms of hostility** and **animosity** towards certain populations or categories of actors (towards the State or those who finance infrastructures that reproduce the same model, from the local population towards tourists).

- **Sadness, helplessness and denial**

Alongside these affects, two reactions emerged from the discussions. Some actors and stakeholders see in these rapid changes a form of **fatality** as well as feeling **powerless and helpless**, not being able to act to deal with what is happening on their territory.

- **Hope**

On the other hand, those situations produce **hope** and **desire** to be able to finally change things and to do things differently and better. The awareness imposed by these events and critical situations is then experienced as an "***unhealthy satisfaction***", which is quite paradoxical, as it gives rise to both unpleasant emotions such as anxiety, but also a drive towards positive dynamics. Also regarding this, the workshop was able to shed light on the role of emotions, and the associated sense of empowerment or helplessness, in engaging in actions that require transformative change.

Fabrique des Transitions (PP13 - FABTRA) – 3/4

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Obstacles and levers

The actors and stakeholders of the territories present at the workshop agreed on the fact that the critical situations mentioned and the context of climate change more generally, call for **necessary changes that are both plural, global and local**. The notions of change and **adaptation of territories** were omnipresent. The **need** for these changes thus seems to be consensual, witnessing a **shared awareness** of the different actors and a desire to move beyond the existing (economic) model.

Global changes

- Getting out of abundance and excess, building
- Thinking about new (economic) models
- Rethinking the link between man and nature

Specific changes

- Diversifying tourism activities,
- Proposing mobility solutions adapted to the tourism flows
- Adapting water management
- Adapting pastoralism

Levers

- Extending the cooperation between actors and territory
- Recovering a sense of common interest
- Acquiring new knowledge

Although they are mentioned as levers for implementing the necessary changes, these elements can also function as **weaknesses** within the concerned territories. Thus, from the group discussions emerged that this dimension of cooperation and even citizen participation is complex and difficult to manage, **as it requires time, resources and expertise** (training) that local authorities and other players oftentimes don't have. Thus, from the group discussions emerged that this dimension of cooperation and even citizen participation is complex and difficult to manage, **as it requires time, resources and expertise** (training) that local authorities and other players oftentimes don't have.

Fabrique des Transitions (PP13 - FABTRA) – 4/4

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8 First overview regarding snow and climate conditions within Alpine Space

The data and information in this report highlight the impacts of human-caused CC accruing in the Alpine Space cooperation area. More precisely, they underline the main negative effects of the diminishing snow cover, particularly in low- and medium-altitude mountain areas of the Alps.

On one hand, large STDs (and the respective resorts) at medium and high altitudes could still rely on natural or technical snow as well as resort to adequate economic resources and personnel to cope with the effects in order to plan and manage change. On the other hand, smaller and lower altitude STDs will face difficult challenges. Maintaining and renewing the necessary ski infrastructures, producing technical snow, and managing increasingly short and/or fluctuating tourist seasons requires substantial resources and investments that are not always at the disposal of the small and medium-sized communities that host them and whose livelihoods depend on. Hence, this has become a pressing issue for those mountain tourism destinations that have been excessively committed to snow activities and skiing over the past years.

These are not only economic hardships, but also political and social issues, in particular related to the understanding of the current and future situation by local administrators and destination managers, as well as the comprehension of the effects of CC on the territory by the local population.

Altogether, these physical, social, and economic factors contribute extensively to the vulnerability of low and medium altitude STDs to CC. Therefore, this vulnerability should be understood and explored at a local level, so that the related risk for the economy and the society can be partially mitigated through collaborative actions that enhance their resilience and ensure the sustainability and viability of the tourism sector.

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10 Annexes

10.1 Mountain territories: Testimonies about critical situations experienced and related emotions, identified obstacles and levers

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BeyondSnow is an Interreg - Alpine Space project co-funded by the European Union. It aims at decreasing the snow-dependency of Alpine Space snow tourism destinations, strengthen their resilience to climate change and retain/increase the viability for residents and their attractiveness for tourists.