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 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 commonly 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).

5.1.1 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.

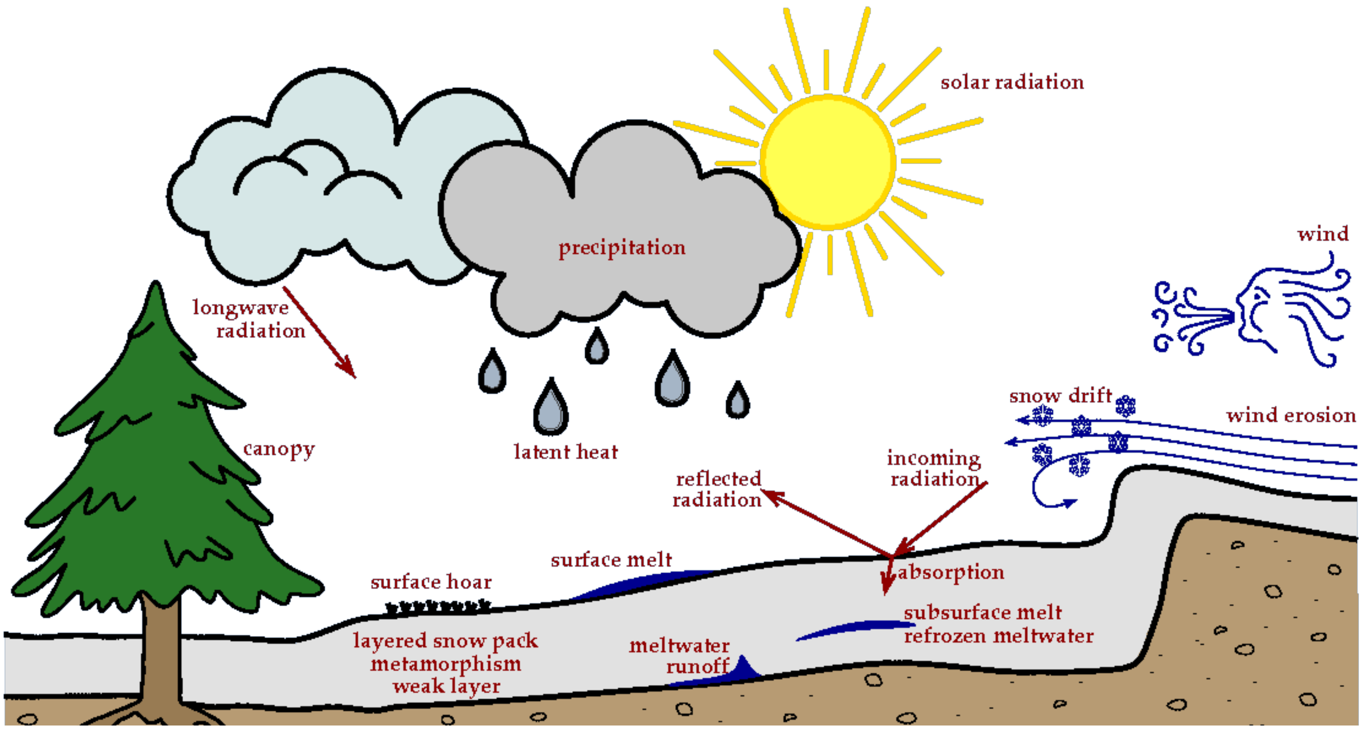

Figure 2: Infographic of the physical process of snowpacks. Source: SNOWPACK website, WSL/SLF SNOWPACK (slf.ch)

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.

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).

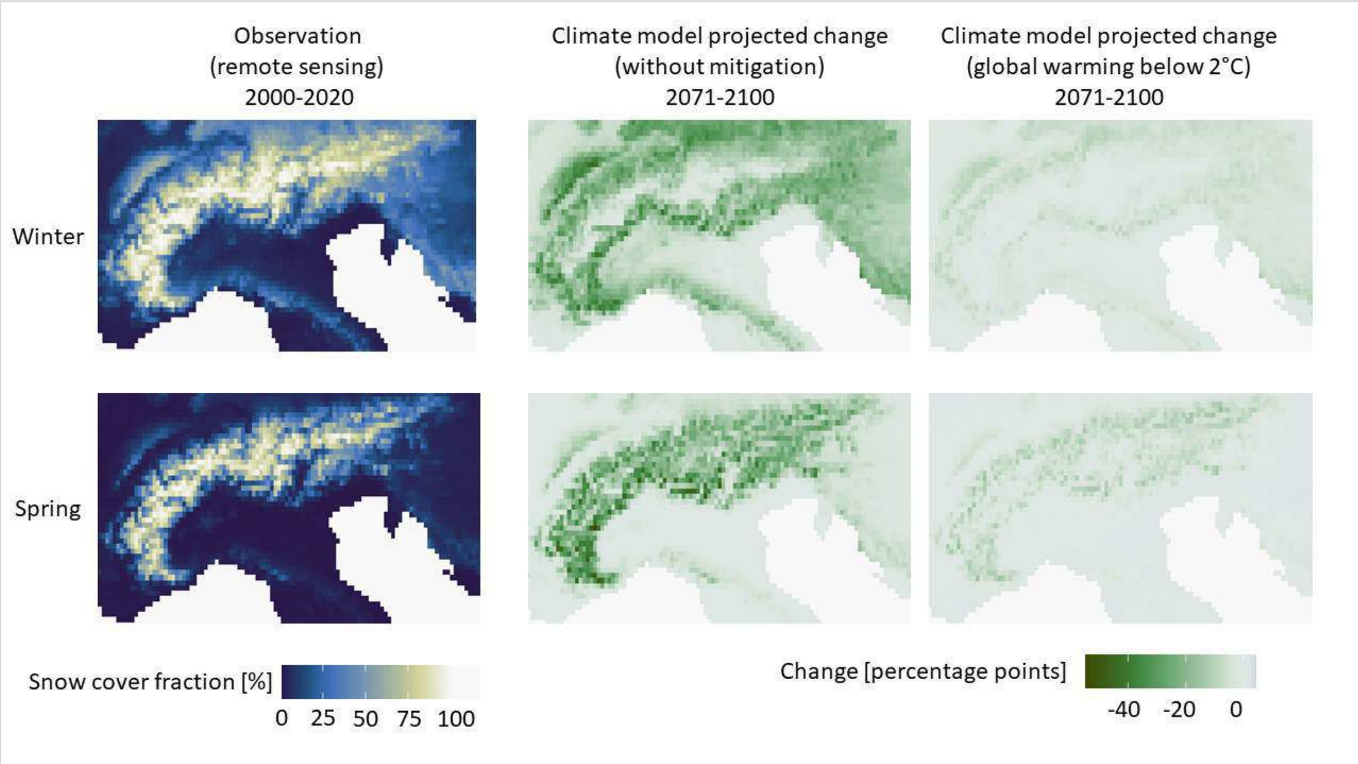

Figure 3: Snow cover in the present (2000-2020) and expected changes in the future (2071-2100): average area covered by snow in winter (December to February) and spring (March to May). Satellite images were analysed for the period 2000- 2020. The representation of future trends is based on regional climate models calibrated with satellite observations. The maps have a horizontal resolution of approximately 12 kilometres, which corresponds to the resolution of the current generation of regional climate models (Eurac Research, 2021)

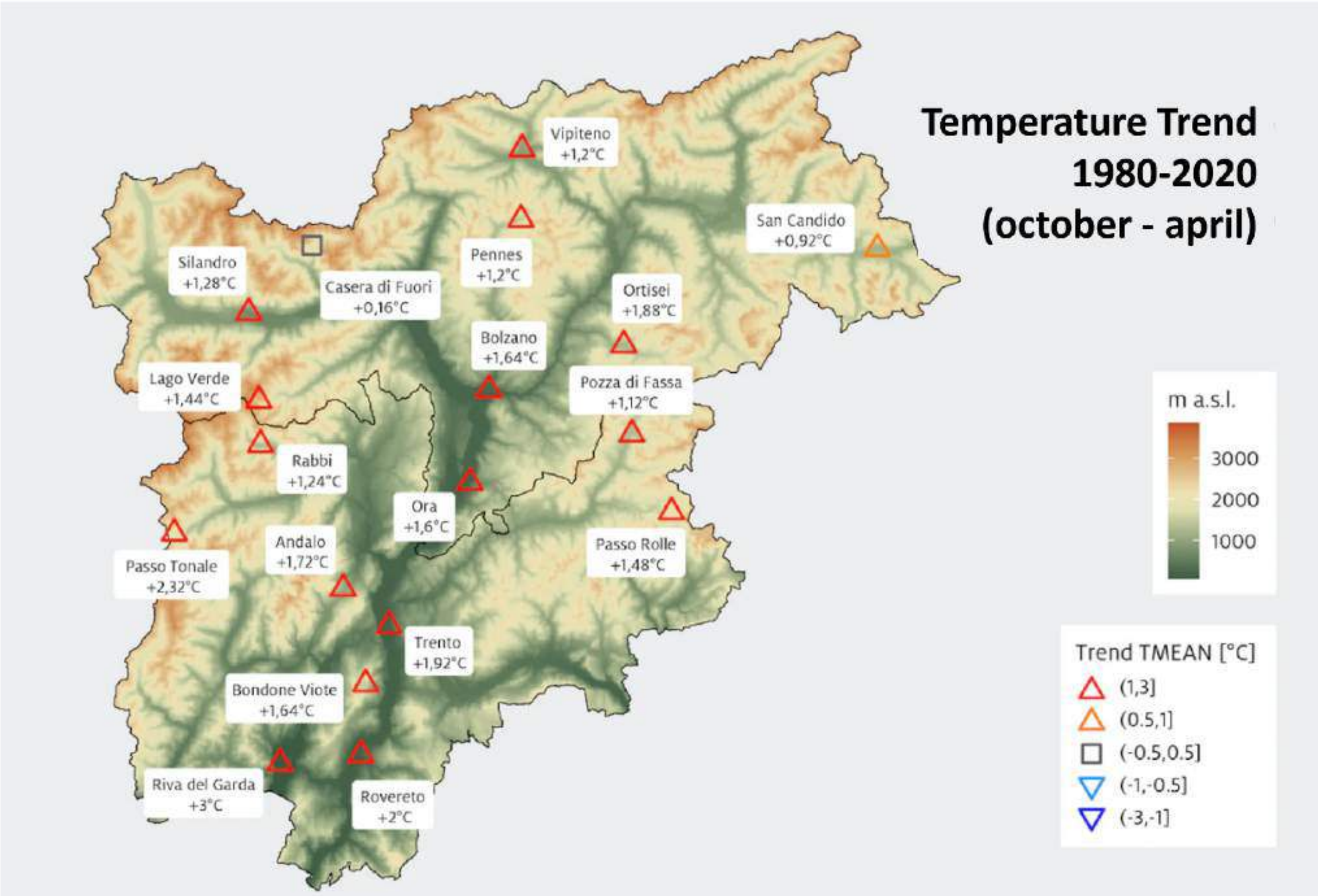

Figure 4. Example - Temperature Trend of Trentino – South Tyrol region, Italy (Bertoldi et al., 2023). Trends analysis for mean temperature shows that trends are positive for each investigated elevation, with the largest trends detected at low elevation.

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 **Errore. L'origine riferimento non è stata trovata.** an example of the spatial distribution of seasonal precipitation.

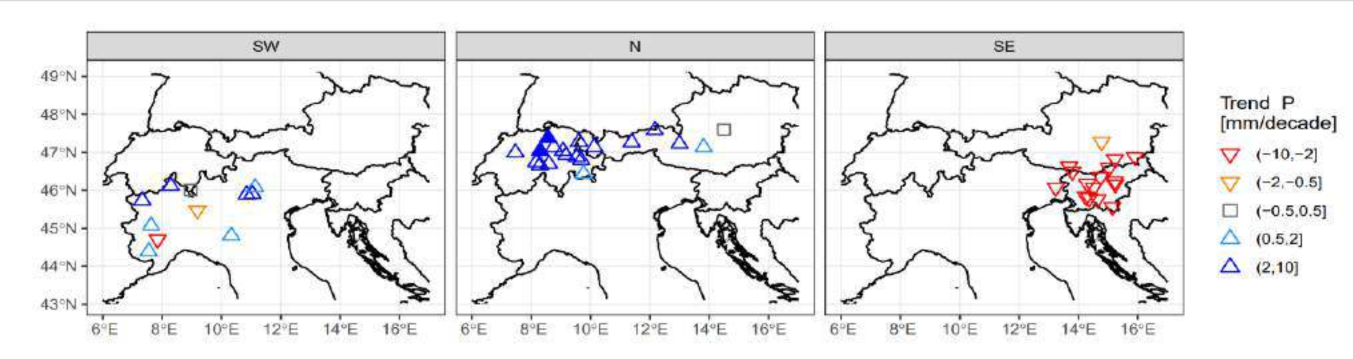

Figure 5. Spatial distribution of seasonal precipitation (P) expressed in [mm/decade] divided into 3 macro regions: South-West – North – South-East. Each point represents one station and the corresponding trend value: blue (red) triangles indicate positive (negative) trends; gray squares indicate negligible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

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 a number of 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).

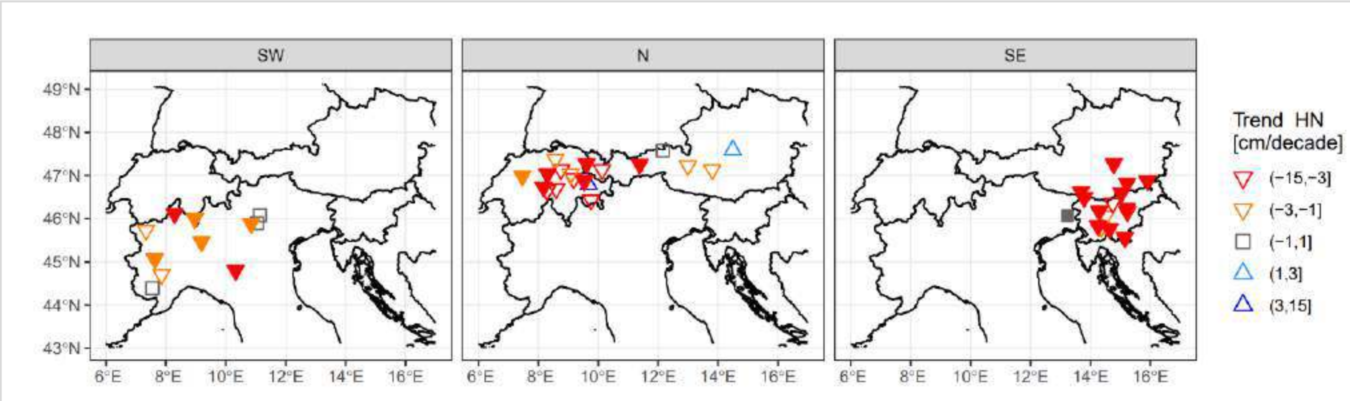

Figure 6. Spatial distribution of seasonal snowfall (HN) expressed in [cm/decade] divided into 3 macroregions: South-West – North – South-East. Each point represents one station and the corresponding trend value: blue (red) triangles indicate positive (negative) trends; gray squares indicate negligible 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 1700 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, favor 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.

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 factor for avalanche risk and also a key factor controlling snow accumulation, especially above the tree-line (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. In particular, 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.

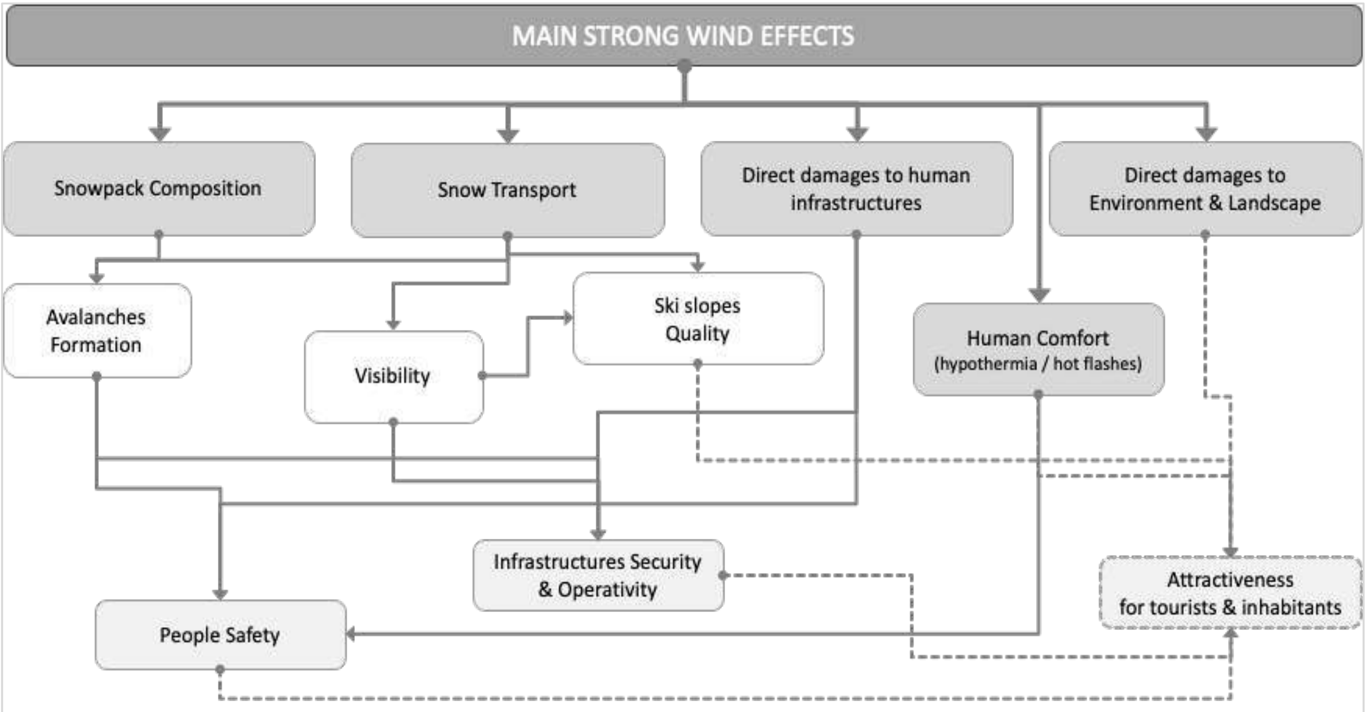

Figure 7: Diagram of the main effects of (strong) wind on STDs. Source: BeyondSnow project.

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.

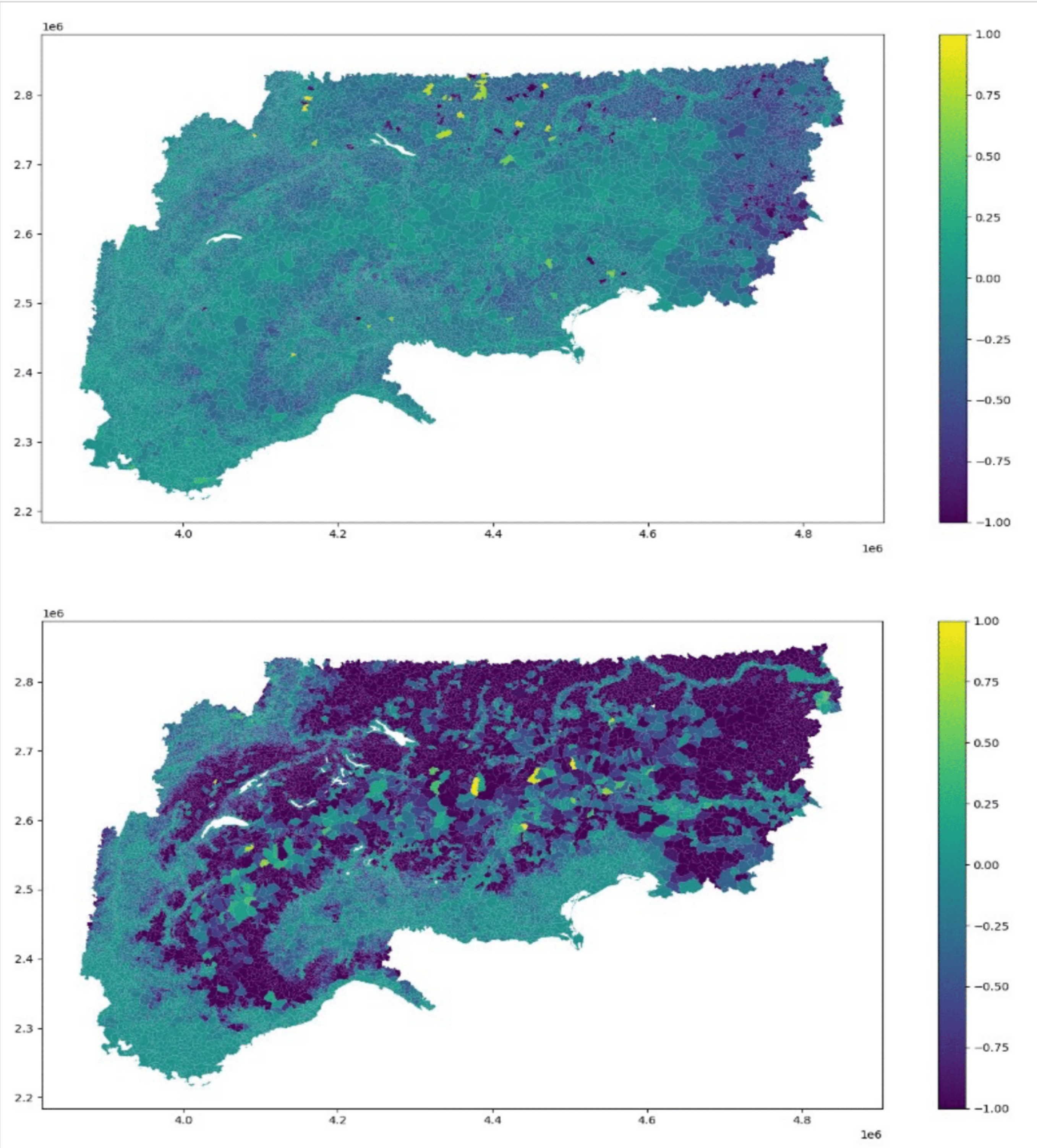

Figure 8. Theil- Sen slope values indicating positive and negative changes for the snow cover area SCA; bottom: Theil- Sen slope values indicating positive and negative changes for the snow cover duration SCD.

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.

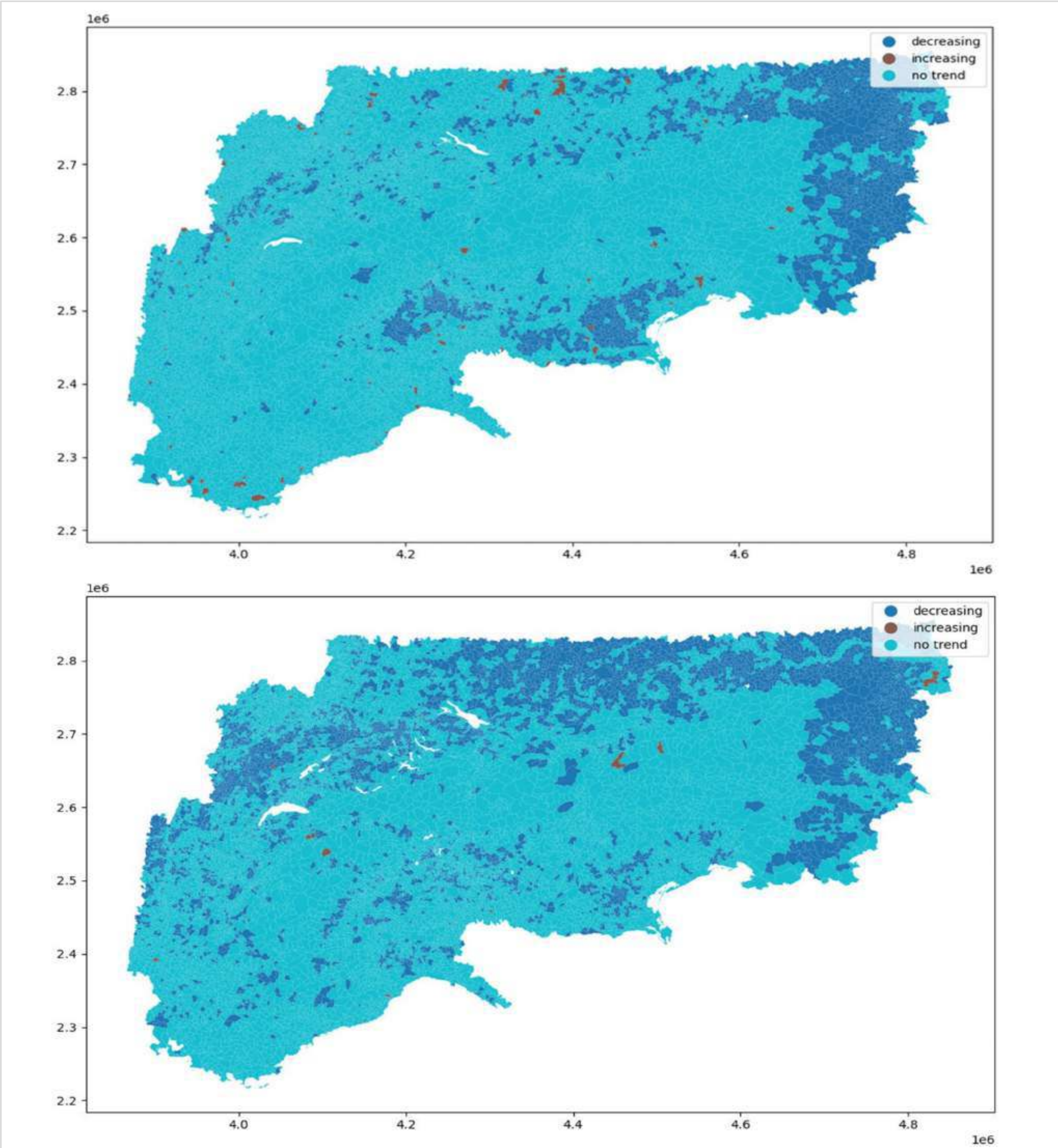

Figure 9. Top: positive and negative changes for the snow cover area SCA; bottom: positive and negative changes for the snow cover duration SCD

6 Current responses

In general, tourism destinations have to 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., 2017).

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, the 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 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 the 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.

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

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 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 such as 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.).

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, CO2 emissions and overstress of services.

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

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

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

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

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

April, 2023

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.