# Weather and Climate Services for Ski Resorts

*Full Report on Weather and Climate Services for Cryosphere Management and Tourism*

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

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## Foreword

Snow and ice are fundamental to mountain environments, communities and economies, as well as to skiing and snowboarding around the world. As the climate changes, reliable weather and climate information is becoming increasingly important for managing immediate operational risks, preparing for seasonal variability and supporting longer-term decisions.

In 2024, the World Meteorological Organization (WMO) and the International Ski and Snowboard Federation (FIS) established a partnership to raise awareness of the current and future effects of climate change on the cryosphere and the resulting impacts on ecosystems, communities and outdoor activities. The partnership seeks to provide the public, athletes, National Ski Associations and the broader winter sports community with science-based information through joint publications, outreach and events informed by the latest observations, projections and research.

This report was jointly developed by WMO and FIS as an output of that partnership. It provides a comprehensive resource on weather and climate services for ski areas, bringing together information on observed and projected changes in weather, climate, snow and ice; the services and information available to support decision-making; and their application across operational, seasonal and long-term planning horizons. We hope it will help ski-area operators, destination managers, event organizers, public authorities and other stakeholders make informed and climate-resilient decisions.



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## Executive summary

Weather, snow and climate conditions influence decisions across ski facility operations, from opening lifts the next morning to planning for the following season or investing in infrastructure intended to last for decades. This resource guide explains what weather, climate and cryosphere information is useful at different stages of decision-making and where it can be obtained.

Recent observations and scientific studies illustrate the changing conditions affecting ski facilities. The year 2024 was the warmest on record, at 1.55 °C above pre-industrial levels. The hydrological years 2021/2022 to 2023/2024 constituted the most negative three-year glacier mass balance period on record (*State of the Global Climate 2025* (WMO-No. 1391)). In the European Alps, winters warmed by 0.3 °C–0.4 °C per decade between 1968 and 2017, while snow-cover duration shortened by 5–7 days per decade, with the strongest declines at low and intermediate elevations (Monteiro and Morin, 2023). A study of 2 234 European ski resorts found that, without snowmaking, 53% face very high snow-supply risk at 2 °C of global warming, rising to 98% at 4 °C (François et al., 2023). During the 2025/2026 season, weather conditions forced the cancellation of 25 FIS World Cup races.

The guide is organized around three types of decisions. For day-to-day operations, real-time observations, nowcasting, short-range forecasts, hazard warnings and avalanche bulletins, it can support lift safety, grooming, snowmaking, visitor communications and event-day decisions. For seasonal planning, extended-range, sub-seasonal and seasonal outlooks, it can inform opening and closing dates, staffing, budgets, snowmaking strategy, water and energy planning, marketing and event scheduling. For long-term planning and adaptation, climate monitoring, historical records and climate projections, it can support decisions on infrastructure, snowmaking capacity, diversification, insurance and other investments.

The guide also presents specialized applications, including snow-reliability indicators, snowmaking decision-support systems, climate-risk assessments, weather derivatives and parametric insurance. Emerging technologies such as artificial intelligence, high-resolution modelling and connected sensors offer additional opportunities to improve monitoring and decision-making, although safety-critical applications should continue to be supported by appropriate expertise and established operational procedures.

The guide is written primarily for ski facility operators, mountain destination managers and organizers of ski events and winter festivals. It is also intended to support National Meteorological and Hydrological Services (NMHSs) and other providers in developing and delivering relevant services. By bringing together practical guidance, examples and links to weather, climate and cryosphere resources, it aims to support informed decisions across day-to-day operations, seasonal planning and long-term adaptation.

# 1 Introduction and climate context

## 1.1 Purpose and scope

The cryosphere-dependent tourism sector encompasses diverse activities including alpine skiing, cross-country skiing, snowboarding, glacier tourism, ice climbing and winter festivals. These activities generate substantial economic benefits for mountain regions, contributing significantly to local employment and regional development. However, their dependence on specific snow and ice conditions makes the sector particularly vulnerable to weather variability and long-term climate change.

Effective management of cryosphere tourism operations requires reliable weather and climate information across multiple temporal scales. Short-term weather forecasts support daily operational decisions – lift operations, grooming schedules and visitor safety management. Seasonal forecasts inform strategic planning for season dates, staffing requirements and marketing activities. Long-term climate projections guide investment decisions on infrastructure development, snowmaking capabilities and adaptation strategies. This resource guide provides guidance on weather and climate services available to support decision-making across these temporal scales.

The report's scope extends from nowcasting services (forecasts up to six hours ahead) through seasonal predictions (up to 12 months) to climate projections extending to the end of the century. For each temporal scale, the report identifies relevant services, describes their technical characteristics, provides data access information and offers practical application guidance. Regional variations in service availability and characteristics are noted where appropriate, recognizing that Members have developed diverse approaches to delivering weather and climate services suited to their specific circumstances.

## 1.2 Current state of the cryosphere

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC, 2023) provides the most comprehensive scientific assessment of climate change impacts on the cryosphere. It concluded with very high confidence that global warming has led to widespread cryosphere shrinking over recent decades, including mass loss from ice sheets and glaciers, reductions in snow cover and Arctic sea-ice extent and thickness, and increases in permafrost temperature and active layer thickness. These changes are unequivocal and unprecedented in the observational record.

For mountain regions specifically, the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate found that snow cover duration has declined in nearly all regions, especially at lower elevations – averaging 5 days per decade with a likely range of 0–10 days per decade. Mass change of glaciers in all mountain regions (excluding the Canadian and Russian Arctic, Svalbard, Greenland and Antarctica) was very likely $-490 \pm 100$ kg $m^{-2}$ $yr^{-1}$ ($-123 \pm 24$ Gt $yr^{-1}$) during 2006–2015. Regionally averaged mass budgets were likely most negative (<$-850$ kg $m^{-2}$ $yr^{-1}$) in the southern Andes, Caucasus, European Alps and Pyrenees (Hock et al., 2019).

The *State of the Global Climate 2024* (WMO-No. 1368) documents the acceleration of these trends. Ocean heat content reached its highest level in the 65-year observational record in 2024, exceeding the 2023 record by 16 ± 8 zettajoules. Each of the past eight years has set a record for ocean heat content. The rate of ocean warming over 2005–2024 was more than twice that observed during 1960–2005. Ocean warming fuels atmospheric warming and drives continued cryosphere decline.

Glacier mass balance observations for the 2023/2024 hydrological year confirm these alarming trends. Preliminary observations from approximately 90% of glaciers reporting to the World Glacier Monitoring Service indicate extremely negative mass balance worldwide. The period 2021/2022 through 2023/2024 represents the largest negative three-year mass balance on record. Exceptionally negative mass balances occurred in Norway, Sweden, Svalbard, and the tropical Andes. Only 2 of 141 glaciers reporting to date had positive mass balance. The composite value from reference glaciers indicates an average mass loss projected near −1.1 m water equivalent for 2023/2024.

These physical changes in the cryosphere reflect the broader context of global temperature increase. The annually averaged global mean near-surface temperature in 2024 was 1.55 °C (± 0.13 °C) above the 1850–1900 average representing pre-industrial conditions. Each of the past ten years (2015–2024) ranks among the ten warmest years on record (*State of the Global Climate 2024* (WMO-No. 1368)). Between June 2023 and December 2024, the average global temperature for each month exceeded all records set prior to 2023 for the corresponding calendar month.

For readers seeking a shorter, operationally focused resource, see *Weather and Climate Services for Ski Resorts: A Practical Guide to Weather and Climate Services for Cryosphere Management and Tourism* (WMO-No. 1404).

### 1.3 Implications for the ski and winter tourism industry

The cryosphere changes documented by IPCC and WMO translate directly into operational challenges for winter tourism. Research published in *Nature Climate Change* examined 2 234 ski resorts across 28 European countries. The study found that without snowmaking, 53% of these resorts are projected to face very high risk for snow supply at 2 °C of global warming, rising to 98% at 4 °C (François et al., 2023). These projections indicate that significant portions of existing ski resort infrastructure may become economically unviable without substantial adaptation investments.

Regional analyses provide additional detail on the rate and magnitude of changes. A multi-dataset study of the European Alps found that winters warmed by 0.3 °C–0.4 °C per decade between 1968 and 2017, while snow-cover duration shortened by 5–7 days per decade, with the strongest declines at low and intermediate elevations (Monteiro and Morin, 2023). These rates mean that ski resorts experience measurably different conditions each decade, requiring continuous adaptation of operational practices and infrastructure.

The Swiss experience illustrates the concrete implications of these trends. Alpine glaciers in Switzerland have lost approximately 60% of their volume since 1850, with accelerated loss rates in recent decades, according to the National Centre for Climate Services (NCCS, 2025b). At altitudes below 800 m, snowfall days have halved since 1970. The zero-degree level – a critical threshold for natural snow accumulation – has risen from approximately 600 m above sea level fifty years ago to approximately 850 m today. The Swiss Climate Change Scenarios 2018 (NCCS, 2018) project that without climate mitigation, this level will climb a further 400–650 m by 2060, reaching 1 300–1 500 m. This upward migration of reliable snow conditions directly affects lower-elevation ski infrastructure viability.

The operational impacts manifest in multiple ways. Periods of unusually warm winter weather can limit snowmaking and accelerate snowpack melt, creating substantial operational challenges for ski resorts. As average temperatures rise, operations must increasingly prepare for such conditions. During the 2025/2026 season, weather conditions forced the cancellation of 25 Ski World Cup races, according to an internal calculation by the International Ski and Snowboard Federation (FIS).

Beyond immediate operational disruptions, these changes necessitate substantial increases in adaptation investments. Snowmaking infrastructure has become essential for maintaining reliable ski seasons at most resorts, but its effectiveness diminishes as temperatures rise and suitable snowmaking hours decrease. Water availability for snowmaking emerges as an additional constraint in regions where summer precipitation decreases and glacier-fed streams diminish. Energy costs for snowmaking increase due to both reduced efficiency at warmer temperatures and higher electricity prices. These factors collectively affect the economic viability of winter tourism operations.

IPCC concluded with very high confidence that under all emissions scenarios, snow cover will continue to decline, and glaciers will continue to lose mass for at least several decades, even if global temperatures are stabilized. This finding establishes that adaptation in the winter tourism sector is not a temporary adjustment but a long-term imperative requiring fundamental transformation of business models, infrastructure, and operational practices. Climate services provide essential information to guide this transformation effectively.

### 1.4 Target audience

This resource guide has been prepared primarily for ski facility operators, mountain destination managers, glacier tourism providers and winter event organizers. It provides information to assist these users in identifying appropriate data sources, understanding service capabilities and limitations, and integrating weather and climate information into decision-making.

The report is also intended for staff of National Meteorological and Hydrological Services (NMHSs) and other providers responsible for developing and delivering services to the tourism sector. The technical information can assist these professionals in understanding

user needs and developing relevant services. The material assumes a basic understanding of meteorological and climatological concepts but does not require specialized knowledge of cryosphere processes or tourism operations.

Additional audiences include policymakers responsible for tourism development and climate adaptation planning, researchers investigating climate impacts on tourism, insurance professionals developing weather-related financial products, and officials from organizations such as FIS and national ski associations.

### 1.5 Structure of the report

The document is organized into 13 substantive chapters followed by conclusions. The chapters progress logically from short-term operational services through long-term planning tools to practical application scenarios illustrating how weather and climate services could be applied to common decisions in winter tourism. This structure reflects the typical progression of decision-making timescales in tourism operations, beginning with immediate operational needs and extending to strategic investment decisions. Each chapter builds upon concepts introduced in previous sections while maintaining sufficient independence to allow readers to access specific topics directly.

Chapters 2–6 address weather and climate services organized by temporal scale. Chapter 2 covers operational weather services providing forecasts from hours to 10 days. Chapter 3 extends the time frame to medium-range forecasts spanning 10 days to one month. Chapter 4 addresses seasonal climate forecasts covering one to 12 months. Chapter 5 describes climate monitoring and analysis services that provide historical context and current conditions. Chapter 6 examines climate projection and scenario services extending decades into the future, with particular attention to projections relevant for ski tourism regions. This temporal organization facilitates identification of appropriate services for different decision-making contexts.

Chapters 7–10 shift focus from general services to specific applications and implementation guidance. Chapter 7 presents specialized tourism applications, including snow-reliability assessment, snowmaking support and operations planning. Chapter 8 addresses risk management and insurance applications. Chapter 9 provides technical information on data access, programming tools and capacity-building resources. Chapter 10 offers best practices and implementation guidelines.

Chapters 11–13 complete the report with regional service directories, emerging technologies and illustrative scenarios showing how weather and climate services could be applied in practice. A glossary at the end of the report provides definitions of key technical terms.

### 1.6 Key definitions

Definitions are based on terminology used by WMO, IPCC and relevant specialist organizations and have been simplified, where appropriate, for the intended audience.

For the purposes of this report, **climate data** refers to historical and real-time climate observations together with direct numerical model outputs covering both past and future periods. Climate data are the foundation for all climate services and include measurements from observing stations, remote sensing platforms, and climate model outputs. Climate data should be accompanied by metadata describing their source, production or measurement methods, quality-control procedures and any processing applied.

A **climate product** is derived from climate data and scientific knowledge to provide information that is useful to users. Climate products transform raw data into formats more readily applicable to specific decisions. Examples include anomaly maps that highlight departures from normal conditions, trend analyses that reveal long-term changes, and indices that synthesize multiple variables into single metrics relevant to applications. Developing effective climate products requires understanding both the technical characteristics of available data and the information needs of intended users.

**Climate information** encompasses climate data, climate products and climate knowledge. It represents the full spectrum of information about past, present and future climate states. Climate information may include not only quantitative data and products, but also qualitative knowledge derived from scientific understanding, traditional knowledge and practical experience. Effective communication of climate information requires appropriate consideration of user needs, technical capabilities and decision-making contexts.

A **climate service** involves providing climate information in a manner that assists decision-making by individuals and organizations. Effective climate services require more than simply making data available – they demand appropriate engagement with users to understand their needs, effective mechanisms for accessing and interpreting information, and formats that match decision-making processes. Climate services should be evaluated not solely on technical quality but on their usefulness in supporting improved decisions and outcomes.

The **cryosphere** includes the components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost, and seasonally frozen ground and solid precipitation. For tourism applications, the most relevant cryosphere components are seasonal snow cover, mountain glaciers and frozen lakes and rivers. Understanding cryosphere variability and change is essential for sustainable tourism management in cold regions.

**Snow water equivalent** represents the depth of water that would result if the entire snowpack melted instantaneously. This parameter, typically expressed in millimetres or centimetres, provides a more useful measure of water content than snow depth alone, since snow density varies considerably depending on temperature history, compaction and metamorphic processes. Snow water equivalent is essential for water resources management, flood forecasting, and assessing snowmaking requirements.

# 2 Operational weather services

## 2.1 Overview of operational weather services

Operational weather services providing forecasts from the present time to approximately 10 days ahead form the foundation of day-to-day decision-making in tourism operations. These services draw upon high-resolution numerical weather prediction models, real-time observations from surface and upper-air networks, radar and satellite data, and nowcasting systems that extrapolate current conditions into the near future. The quality and reliability of operational weather forecasts have improved substantially over recent decades. Today, six-day forecasts can be as reliable as two-day forecasts were 30 years ago, providing tourism operators with increasingly valuable lead time for operational planning (Jarraud, 2025).

For cryosphere tourism applications, operational weather services address several critical parameters whose importance has intensified under changing climatic conditions. Temperature forecasts help operators assess snow preservation and visitor comfort and identify opportunities for snowmaking. As warm-temperature events become more frequent and intense, accurate temperature forecasts become increasingly important for snow management. Precipitation forecasts, particularly when discriminating between rain and snow, directly affect snow accumulation and skiing conditions. The rising zero-degree level observed across mountain regions means that the rain-snow transition now occurs at higher elevations than historically, requiring particularly accurate forecasts of temperature profiles and precipitation phase.

Wind forecasts support decisions on lift operations and visitor safety and contribute to the assessment of avalanche risk. Cloud cover and visibility forecasts affect scenic value for glacier tourism and enable safe aerial operations. The integration of these parameters into tourism-relevant products requires close collaboration between meteorological services and tourism operators to ensure that technical information translates effectively into operational decisions.

The spatial resolution of operational weather forecasts has increased dramatically with advances in computing capability and model physics. Modern high-resolution models represent mountain peaks, valleys and associated orographic effects in much greater detail than earlier models. This enhanced resolution particularly benefits mountain tourism operations where weather conditions can vary substantially over distances of a few kilometres. However, users should recognize that even high-resolution models have limitations in representing very localized effects such as valley fog, slope-specific wind patterns, and microclimatic variations. Interpretation by experienced meteorologists familiar with local conditions remains valuable for effective forecast use, particularly for safety-critical decisions.

## 2.2 Mountain weather forecasting

Mountain weather presents unique forecasting challenges due to complex topography, rapid spatial variability and the interaction of multiple atmospheric processes at different scales. Valley winds, slope flows, föhn effects, orographic precipitation enhancement and temperature inversions all contribute to weather patterns that differ substantially from those in surrounding lowlands. The changing climate adds additional complexity to mountain weather forecasting. Warming temperatures and other changes in atmospheric conditions may also affect mountain wind patterns, with implications for natural snow preservation and snowmaking operations. Specialized mountain weather forecasting services have evolved to address these challenges, employing higher-resolution models, denser observing networks, and forecaster expertise in mountain meteorology.

### 2.2.1 National Meteorological and Hydrological Services (NMHSs)

Many NMHSs operate specialized mountain weather units that focus on forecasting for alpine regions. These services typically combine numerical model outputs with local observations, satellite and radar data, and expert interpretation to produce detailed mountain forecasts. The United States of America National Weather Service (NWS), part of the National Oceanic and Atmospheric Administration (NOAA), provides comprehensive mountain weather forecasts through its regional offices. These forecasts include point-specific information for individual peaks and passes, area forecasts for mountain ranges, and specialized products for avalanche forecasting and winter sports. The NWS provides forecasts that are produced on grids with a spatial resolution of approximately 2.5 km × 2.5 km in most regions, although resolution varies by domain. The NWS website provides hourly and 12-hour forecast information extending up to seven days ahead. Public access to these forecasts is provided free of charge, and an Application Programming Interface (API) enables automated data retrieval for integration into resort management systems.

The Federal Office of Meteorology and Climatology of Switzerland, known as MeteoSwiss, has developed particularly sophisticated Alpine weather services reflecting the central importance of mountain weather to Swiss society and economy. Products available through MeteoSwiss include detailed Alpine weather forecasts, real-time snow reports, and nowcasting products updated every few minutes. The service provides information in German, French, Italian, and English, recognizing the international nature of Alpine tourism. Strengths include high spatial resolution representing Alpine valleys and peaks in considerable detail, integration of dense observing networks including automatic weather stations and webcams, and specialized forecaster expertise in Alpine weather phenomena. These services are freely accessible to the public and tourism operators.

Météo-France provides specialized mountain weather services for the French Alps and Pyrenees. These products include mountain-specific bulletins addressing conditions at different elevation zones, avalanche weather information and specialized forecasts for ski resorts. The service integrates outputs from the high-resolution Application of Research to

Operations at Mesoscale (AROME) numerical model, which represents Alpine topography in considerable detail. Close collaboration between Météo-France forecasters and ski resort operators has produced forecast formats tailored to operational decision-making needs.

### 2.2.2 Specialized mountain weather providers

In addition to NMHSs, several specialized commercial providers have developed mountain weather forecasting capabilities. These services often provide more detailed site-specific information and enhanced graphical presentations than public forecasts. Mountain Forecast provides detailed weather predictions for thousands of mountain peaks and ski areas worldwide. The service presents forecasts for multiple elevation zones at each location, typically showing conditions at summit, mid-mountain, and base elevations. This elevation stratification has become increasingly important as warming temperatures cause greater differentiation between conditions at different altitudes. Parameters include temperature, wind speed and direction, precipitation, snow accumulation, freezing level[1] height, and cloud cover. Basic access is free, while premium subscriptions offer additional features including higher update frequency, extended forecast ranges, and detailed snowfall predictions. The global coverage makes this service particularly valuable for tour operators and travellers planning multi-destination trips.

Windy offers a sophisticated interactive platform for visualizing weather forecasts from multiple numerical models. The service displays forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System, the NOAA Global Forecast System (GFS) and other numerical prediction systems, allowing users to compare predictions and assess the degree of agreement between them. This multi-model approach provides valuable perspective on forecast confidence, particularly for high-stakes decisions such as major event scheduling. Animated visualizations of wind patterns, precipitation, and other parameters provide intuitive understanding of evolving weather systems. Real-time webcam imagery from ski resorts and mountain locations can also help users compare forecast information with observed conditions. The platform provides free access to core features while offering premium subscriptions for advanced capabilities including detailed snowfall forecasts and site-specific alert notifications.

## 2.3 Avalanche forecasting services

Avalanche hazards represent one of the most significant weather-related risks in mountain tourism operations. Climate change is altering avalanche patterns in complex ways. The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate concluded with high confidence that glacier retreat and permafrost thaw have decreased the stability of mountain slopes, affecting avalanche risk (Hock et al., 2019). Warmer temperatures can favour wet-snow avalanches, while changes in snowfall and snowpack structure may alter

[1] The freezing level is the altitude at which the air temperature is 0 °C (Source: American Meteorological Society, *Glossary of Meteorology*, https://glossary.ametsoc.org/wiki/freezing-level). It provides a useful indication of where precipitation is more likely to fall as rain or snow.

the occurrence of dry-snow avalanches. Changes in precipitation patterns affect snow accumulation rates and snowpack structure. Avalanches result from complex interactions between snowpack structure, weather conditions, and terrain characteristics. Effective avalanche forecasting requires specialized expertise in snow science, detailed knowledge of local terrain, real-time observations of snowpack conditions, and weather forecasts addressing factors that influence avalanche risk. Most countries with significant mountain tourism have established specialized avalanche warning services that issue regular bulletins describing current hazard levels and expected evolution over the forecast period.

Avalanche forecasts typically employ standardized danger scales to communicate risk levels. The five-level scale – ranging from low to very high danger – has been widely adopted internationally, facilitating consistent communication across different regions and languages. Forecasts also identify specific avalanche problems such as wind slabs, persistent weak layers, wet snow avalanches, or cornice failures. This problem-oriented approach helps users understand not only the overall danger level but also the specific conditions and terrain where elevated risk exists. Modern avalanche forecasts are presented through interactive maps allowing users to examine conditions in specific regions, elevation bands, and terrain aspects. Changing weather and snow conditions make these detailed forecasts increasingly valuable for safe mountain travel and ski facility operations.

### 2.3.1 Regional avalanche warning centres

In the United States, avalanche forecasting is provided through a network of regional centres accessible through avalanche.org. The site is a partnership between the American Avalanche Association and the US Forest Service National Avalanche Center and consolidates information from professional forecast centres. Daily forecasts describe current avalanche danger using the standardized five-level scale, identify specific avalanche problems present in the snowpack, discuss relevant weather factors, and provide guidance on safe travel practices. Many centres supplement their forecasts with educational materials, videos, and photographs contributed by recreational users through crowdsourced observation networks. This community engagement enhances both forecast quality through additional observations and public understanding of avalanche risk. The changing climate requires continuous updating of forecast approaches as historical patterns of avalanche occurrence may no longer fully represent current and future conditions.

The European Avalanche Warning Services network provides coordinated avalanche information across European mountain regions. This international cooperation has produced standardized danger scales, avalanche problem definitions, and forecast formats that allow consistent interpretation across national boundaries. The network website provides links to national avalanche services in all European countries with significant avalanche hazard. Emphasis is placed on cross-border coordination in regions where mountain ranges span multiple countries, ensuring that forecasters share observations

and maintain consistent assessment of hazard conditions in adjacent areas. The adoption of common standards facilitates understanding by international visitors who may be unfamiliar with local conditions. Given the projected changes in snow conditions documented by IPCC, this coordinated approach to avalanche forecasting will become increasingly important for maintaining safety across the European mountain tourism sector.

Avalanche Canada provides public avalanche forecasts for many mountain regions in western Canada. A distinctive feature of its services is the Mountain Information Network, which allows backcountry users to share real-time observations of snow, avalanche and weather conditions. These crowdsourced observations significantly enhance forecast quality by providing information from locations where permanent monitoring infrastructure does not exist. The service makes forecasts available through web interfaces and mobile applications for both iOS and Android platforms, ensuring accessibility for users in remote mountain locations.

### 2.4 Snowfall and accumulation forecasting

Accurate forecasting of snowfall amount, snow water equivalent, and spatial distribution represents one of the most challenging aspects of winter weather prediction. Snowfall depends on complex microphysical processes including ice crystal formation, aggregation, and modification during descent through varying temperature and humidity profiles. Small errors in predicted temperature can lead to an incorrect forecast of whether precipitation will fall as rain or snow, fundamentally altering predicted accumulation. The rising zero-degree level in Switzerland – from approximately 600 m above sea level fifty years ago to approximately 850 m today – means that this rain–snow transition now occurs at higher elevations (NCCS, 2018). Orographic enhancement of snowfall in mountainous terrain adds further complexity, with accumulation rates varying substantially over short horizontal distances. Despite these challenges, snowfall forecasting has improved considerably through advances in model microphysics, data assimilation techniques, and ensemble prediction approaches.

For tourism applications, snowfall forecasts address several critical needs whose importance has intensified as natural snow reliability has decreased. Natural snowfall determines skiing conditions, influences visitor numbers, and affects the need for supplementary snowmaking. Declining natural snow reliability makes accurate snowfall forecasts increasingly important for determining when and where supplementary snowmaking may be needed. The timing of snowfall events influences marketing opportunities, with fresh snow attracting visitors but heavy snowfall potentially disrupting access and operations. Accumulated snow depth affects grooming requirements, avalanche hazard, and the viability of off-piste activities. Snow water equivalent forecasts inform water resource management for snowmaking operations, which becomes increasingly important where water availability is constrained and competition among users is growing.

### 2.4.1 High-resolution snow models

The Snow Data Assimilation System (SNODAS), operated by the NOAA National Operational Hydrologic Remote Sensing Center, provides comprehensive snow analyses and short-range forecasts for the United States. The system assimilates snow observations from ground stations, airborne sensors, and satellite platforms into a physically based snow model operating at 1 km spatial resolution. Daily products include snow depth, snow water equivalent, snowpack sublimation, and snowmelt rates. Historical archives extending back to 2003 allow analysis of snowpack trends and comparison of current conditions to past seasons. These historical comparisons have documented the substantial decline in spring snowpack across western North America, consistent with warming temperatures. Data are available through online services and web interfaces. Technical documentation describes the data formats, quality-control procedures and appropriate uses of the products.

The temporal evolution of snowpack conditions between precipitation events significantly affects skiing quality and operational planning. Fresh snow undergoes metamorphic processes driven by temperature gradients, settling, wind redistribution and surface exchanges of energy and mass. Warmer conditions can accelerate these metamorphic processes, causing snow to transition more rapidly from fresh snow to denser or wetter states. Models such as Alpine3D, developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), through its Institute for Snow and Avalanche Research (SLF), and Crocus, developed by Météo-France, simulate the evolution of snowpack properties such as stratigraphy, density, temperature and liquid-water content. The PROSNOW project demonstrates how snow models, weather forecasts and operational information can be integrated to support snow management and snowmaking decisions.

## 2.5 Nowcasting services for tourism operations

Nowcasting, providing forecasts from the present to approximately six hours in the future, addresses the most immediate operational decisions in tourism management. These very short-range forecasts exploit real-time observations from radar, satellites, automatic weather stations and other platforms to identify current weather systems and extrapolate their movement and evolution into the near future. Nowcasting systems employ techniques ranging from simple extrapolation of observed features to sophisticated data assimilation and very high-resolution numerical prediction. The accuracy of nowcasts typically exceeds that of longer-range forecasts for the first few hours, making them valuable for time-critical decisions. Because hazardous weather can develop rapidly, accurate nowcasting is important for operational safety and continuity.

For ski resort operations, nowcasting supports decisions about lift operations, particularly regarding wind speed and lightning hazard. Severe weather warnings derived from nowcasting systems trigger safety protocols including lift closures, evacuation of exposed areas and suspension of outdoor activities. In mountain regions, weather can change

rapidly, highlighting the value of accurate nowcasting. Snowfall nowcasts inform grooming schedules, allowing operators to optimize the timing of grooming activities relative to precipitation. Temperature and humidity nowcasts together with short-range forecasts, help operators identify suitable windows for snow production. The integration of nowcasting information into resort operations requires reliable communication channels, clear protocols for interpreting and acting on forecasts, and regular training of staff in forecast utilization.

Many NMHSs provide nowcasting products through their standard forecast services, with radar, lightning and other observational products updated frequently. These products often include radar-based precipitation nowcasts showing expected rainfall or snowfall for the next few hours, satellite-derived cloud motion forecasts, lightning detection and prediction, and automated warnings for severe weather phenomena. Access to nowcasting products varies by country, with some services freely available to the public while others are distributed through specialized channels to registered users or emergency management authorities. Tourism operators should establish direct communication with their National Meteorological Service to understand available nowcasting capabilities and effective methods for accessing and using this information in operational contexts.

# 3 Short to medium-range forecasts

## 3.1 Introduction to extended forecasting

The transition from operational weather forecasts to extended-range predictions introduces both scientific and practical challenges. While weather forecasts for up to 10 days ahead draw primarily upon the predictable evolution of current atmospheric conditions, forecasts extending from 10 days to one month increasingly depend on the interaction between the atmosphere and slower-varying components of the climate system. Ocean surface temperatures, soil moisture, snow cover extent and sea-ice conditions all influence atmospheric circulation patterns over weekly to monthly timescales, and a changing climate affects all these components. For example, ocean heat content reached record levels in 2024, according to the *State of the Global Climate 2024* (WMO-No. 1368), with the rate of ocean warming over the past two decades more than twice that observed during 1960–2005. Such changes illustrate how the background conditions represented in extended-range prediction systems are evolving. Extended-range systems therefore increasingly use coupled models that represent interactions among the atmosphere, ocean, land surface and cryosphere.

The skill of extended-range forecasts varies considerably depending on the atmospheric state, the parameter being predicted and the geographical location. Large-scale circulation patterns generally show more predictability than local weather details. Temperature forecasts typically maintain useful skill further into the future than precipitation forecasts. Certain atmospheric conditions, such as well-established blocking patterns or strong El Niño events, enhance predictability by maintaining relatively stable circulation regimes. The strong El Niño that developed in 2023 and peaked in early 2024 contributed to the

record global temperatures documented in the *State of the Global Climate 2024* (WMO-No. 1368). Users of extended-range forecasts should understand these variations in predictability and adjust their confidence in forecasts accordingly.

For tourism planning, extended-range forecasts provide valuable information for tactical decisions with lead times too long for operational weather forecasts but too short for seasonal predictions. These forecasts inform decisions about resource allocation, marketing campaigns, event scheduling, and early-season planning. The Climate Scenarios for Switzerland (NCCS, 2018) predict that the zero-degree level will climb a further 400–650 m by 2060 without climate change mitigation, fundamentally altering the elevation zones where reliable snow can be expected. In the context of changing baseline conditions, extended-range forecasts help operators assess whether the coming weeks are more likely to be warmer, colder, wetter or drier than the relevant climatological average. However, the probabilistic nature of extended-range predictions and their reduced accuracy compared to shorter-range forecasts require appropriate interpretation. Forecasts should be viewed as providing general guidance on likely conditions rather than precise predictions of specific weather events.

### 3.2 Extended weather outlooks

Extended weather outlooks bridge the gap between operational forecasts and seasonal predictions by providing information about likely weather patterns from approximately 10–30 days ahead. These products typically emphasize temperature and precipitation anomalies rather than attempting to predict specific weather events. Forecasts are often expressed probabilistically, indicating the likelihood of above-normal, near-normal, or below-normal conditions rather than specific values. This probabilistic framework reflects the inherent uncertainty in predictions at these timescales while still providing actionable information for planning purposes. For ski facilities operating in a warming climate, information on whether the coming period is likely to be warmer or colder than the current climatological average can support operational planning.

The European Centre for Medium-Range Weather Forecasts (ECMWF) produces sub-seasonal forecasts extending up to 46 days ahead. The forecasts are produced daily using a 101-member ensemble. Products include probabilistic forecasts of temperature and precipitation anomalies, extreme event probabilities and various derived indices relevant to specific applications. The forecasts are updated daily, providing information that evolves as new observations become available and the forecast lead time decreases. A selection of forecast charts is publicly accessible, while access conditions for underlying datasets and additional products vary.

The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (United States) provides extended outlooks for the United States, including 6–10-day and 8–14-day temperature and precipitation outlooks. These outlooks integrate numerical model predictions with statistical forecasting techniques and expert forecaster interpretation. Their national focus allows detailed products addressing regional climate

drivers across the United States. Tourism operators should consult these outlooks when planning activities one to two weeks ahead, using the probabilistic information to assess the range of possible conditions and the confidence that can be placed in different scenarios. From 1955 to 2020, April snowpack declined at 86% of measured sites in the western United States (Scott and Lindsey, 2022), making accurate extended forecasts increasingly important for end-of-season operational planning

### 3.3 Sub-seasonal to seasonal forecasts.

The sub-seasonal to seasonal timescale, spanning approximately two weeks to two months ahead, occupies a critical position in the spectrum of climate services. This range extends beyond the period for which detailed weather forecasts generally retain useful skill but is shorter than conventional seasonal prediction timescales. Phenomena operating at sub-seasonal timescales, including the Madden-Julian Oscillation, stratospheric sudden warmings, and the development or decay of atmospheric blocking patterns, provide sources of predictability that can be exploited through appropriate forecasting approaches. Sub-seasonal forecasts rely primarily on ensemble predictions from coupled models initialized with current observed conditions.

For winter tourism applications, sub-seasonal forecasts can support planning several weeks ahead. Season opening dates, early-season marketing campaigns, staffing schedules and event planning may all benefit from guidance on likely conditions 3–6 weeks ahead. With snow-cover duration decreasing by 5–7 days per decade at low elevations in the European Alps (Monteiro and Morin, 2023), sub-seasonal guidance can support contingency planning around the likely timing of reliable snow conditions. While the skill of sub-seasonal forecasts remains limited compared with shorter-range predictions, they can provide useful information for decisions that must be made before reliable operational weather forecasts become available. The probabilistic nature of these forecasts encourages contingency planning that accounts for a range of possible outcomes rather than relying on a single predicted scenario.

The Sub-seasonal to Seasonal Prediction Project database provides coordinated sub-seasonal forecasts from 11 international modelling centres. This multi-model approach recognizes that individual forecasting systems have distinct strengths and weaknesses, and that combining predictions from multiple sources often provides more reliable guidance than any single model. The database includes both real-time forecasts and historical re-forecasts that allow assessment of forecast skill for different seasons, regions and atmospheric conditions. Research applications using this database have contributed substantially to understanding sub-seasonal predictability and developing improved forecasting techniques. The original World Weather Research Programme (WWRP)/World Climate Research Programme (WCRP) Sub-seasonal to Seasonal Prediction Project concluded in 2023, with related work continuing through the WWRP Sub-seasonal Applications for Agriculture and Environment (SAGE) Project, which aims to make sub-seasonal predictions more useful for applications including agriculture, energy, health,

water and disaster risk reduction. Operational users can access these forecasts to support planning, noting that data availability is delayed by 48 hours or one week depending on the contributing centre and that forecast skill varies among models, regions, seasons and applications.

# 4 Seasonal climate prediction

## 4.1 Overview of seasonal prediction

Seasonal climate forecasts provide predictions of climate conditions from one month to 12 months ahead, addressing timescales beyond the predictability of atmospheric initial conditions but within the influence of slowly varying components of the climate system. These forecasts exploit the fact that ocean temperatures, sea-ice extent, snow cover and soil moisture evolve more slowly than the atmosphere and influence atmospheric circulation over periods of weeks to months. The best-known source of seasonal predictability is the El Niño-Southern Oscillation phenomenon in the tropical Pacific Ocean, which affects weather patterns across much of the globe through atmospheric teleconnections. The strong El Niño that developed in 2023, combined with long-term anthropogenic warming and other factors, contributed to the record global temperatures of 2024 documented in the *State of the Global Climate 2024* (WMO-No. 1368). Other oceanic and atmospheric patterns, including the North Atlantic Oscillation, influence seasonal conditions and may provide additional predictability in specific regions.

For winter tourism, seasonal forecasts address planning horizons spanning entire ski seasons or major portions thereof. Decisions regarding preparations for season opening and closing, staffing recruitment and training, marketing campaign launch dates, infrastructure maintenance schedules and snowmaking preparation all benefit from seasonal forecast guidance. Seasonal forecasts cannot predict specific snowfall events months in advance, but they can provide probabilistic guidance on whether temperature and precipitation are likely to be above, near, or below climatological averages. This information, though imperfect, provides valuable context for risk management and contingency planning.

The skill of seasonal forecasts varies substantially by region, season and forecast lead time. Tropical regions generally show higher forecast skill than extratropical regions due to stronger ocean-atmosphere coupling. In some extratropical regions, winter forecasts show greater skill than summer forecasts because of stronger and more predictable large-scale circulation influences how more skill than summer forecasts due to stronger large-scale circulation patterns. Forecast skill typically decreases with increasing lead time, though certain boundary conditions such as strong El Niño or La Niña events can maintain skill over longer periods. Users of seasonal forecasts must understand these variations in skill and confidence.

## 4.2 Global seasonal prediction systems

### 4.2.1 ECMWF Seasonal Forecasting System 5

The ECMWF Seasonal Forecasting System 5 (SEAS5) represents one of the leading global seasonal forecasting systems. The monthly forecasts extend up to seven months ahead and use a 51-member ensemble. Separate annual-range forecasts are produced every three months and extend 13 months ahead. Products include probabilistic forecasts of temperature and precipitation anomalies, as well as derived products addressing phenomena such as sea surface temperatures, soil moisture and snow cover. Forecasts are updated monthly, providing evolving guidance as the winter season approaches and progresses. Some products are available free of charge through the ECMWF website, while comprehensive access requires a license agreement.

For winter tourism applications, temperature and precipitation probability forecasts prove most directly relevant. However, derived products such as snow cover probability may provide additional information. The system can provide useful guidance for European winter temperatures, although forecast skill varies by location, season and lead time and is generally more limited for precipitation. Research using the system has examined how climate change affects winter temperature and precipitation patterns over mountain regions, providing context for interpreting seasonal forecasts considering long-term trends. The fact that 2024 global temperatures exceeded the previous record by a substantial margin emphasizes the importance of considering both seasonal forecast guidance and the underlying warming trend when planning winter operations.

### 4.2.2 Met Office Global Seasonal Forecast System 6

The Met Office Global Seasonal Forecast System 6 (GloSea6) provides another major source of seasonal forecast guidance. Forecast ensemble members are initialized daily, and the output is used to generate monthly and seasonal forecast products with particular emphasis on European and global predictions. The system incorporates a high-resolution atmospheric model coupled to ocean, sea ice and land surface components. Forecasts are issued monthly and include temperature, precipitation and derived variables relevant to various sectors including winter tourism.

The Met Office has expertise in forecasting North Atlantic and European winter climate, leveraging understanding of the North Atlantic Oscillation and its predictability. GloSea6 can provide useful guidance on European winter temperatures, although forecast skill varies by location, season and lead time and is generally more limited for precipitation. However, as with all seasonal forecast systems, skill varies by location, season, and forecast lead time. Users should consult verification statistics provided by the Met Office to understand forecast reliability for their specific location and application.

### 4.2.3 Climate Forecast System Version 2

The Climate Forecast System Version 2 (CFSv2), operated by NOAA provides seasonal forecast guidance with particular focus on North American conditions. The system

produces four forecast runs each day, while Climate Prediction Center seasonal products use lagged ensembles constructed from forecasts initialized on different dates. Products include temperature and precipitation probability forecasts, as well as numerous derived variables. Forecasts are updated daily with a one-month lagged ensemble approach that samples uncertainty in initial conditions.

For North American winter tourism operators, CFSv2 products provide valuable seasonal guidance. The NOAA Climate Prediction Center produces outlook maps based on the CFSv2 and other models showing probability of above, near, or below average conditions for temperature and precipitation at various lead times. These outlooks inform decisions about season preparation, staffing and marketing. The system has demonstrated useful skill for winter temperature forecasts over much of North America, particularly when strong El Niño or La Niña conditions provide enhanced predictability. Given the documented decline in western North American snowpacks, with April snowpack declining at 86% of measured sites between 1955 and 2020 (Scott and Lindsey, 2022), accurate seasonal forecasts of temperature and precipitation will become increasingly important for managing increasingly marginal snow conditions.

### 4.3 Regional climate outlook forums

Regional Climate Outlook Forums provide consensus seasonal forecasts for specific regions through coordinated efforts of the NMHSs within those regions. These forums typically convene before the start of major seasons, bringing together forecasters from multiple countries to examine global model predictions, regional climate patterns and local expertise. The resulting consensus forecasts combine information from multiple sources and reflect collective expert judgement about expected conditions. This approach draws on multiple forecasting systems and regional expertise while also strengthening capacity and cooperation among participating NMHSs.

Several Regional Climate Outlook Forums cover regions with significant winter tourism. The South-East European Climate Outlook Forum covers south-eastern Europe, including mountain tourism destinations, while the Mediterranean Climate Outlook Forum covers southern Europe and the wider Mediterranean region. The WMO Regional Association VI Regional Climate Centre Network also provides seasonal prediction products and guidance for Europe. These products generally address temperature and precipitation and can provide regional context for ski-season planning, although more localized information may be required for individual ski facilities.

Regional Climate Outlook Forums represent an important mechanism for translating global seasonal forecast products into regionally relevant guidance. They facilitate dialogue between forecast producers and users, helping to ensure that forecast products address user needs and that users understand forecast capabilities and limitations.

### 4.4 Snow season forecasting applications

While general seasonal temperature and precipitation forecasts provide valuable guidance for winter tourism planning, specialized products addressing snow season characteristics offer more direct applicability. Snow season length, the date of first reliable snow cover, the date of final snow melt and the likelihood of mid-winter thaw events all significantly affect tourism operations and planning. Several centres have developed specialized snow season forecasting products that translate temperature and precipitation predictions into snow-relevant variables.

The Copernicus Climate Change Service provides seasonal forecasts including snow-related variables. Available variables include snow depth expressed in water equivalent, snowfall and snow density. The service provides data from several leading seasonal forecasting systems. User guides provide detailed information on accessing and interpreting these products. The service represents an important resource for European winter tourism operators seeking seasonal guidance specifically focused on snow conditions alongside temperature and precipitation.

The application of seasonal forecasts to snow season prediction faces challenges due to the strong dependence of snow on temperature thresholds and the high spatial variability of snow conditions in mountainous terrain. Even accurate forecasts of temperature and precipitation may not translate directly into reliable snow forecasts if conditions fall near the rain-snow transition threshold. The rising zero-degree level documented in the Swiss Climate Change Scenarios 2018, projected to rise by a further 400–650 m by 2060 without additional climate mitigation (NCCS, 2018), means that snow forecasting must increasingly contend with marginal conditions where small temperature variations determine whether precipitation falls as rain or snow. Despite these challenges, seasonal snow forecasts provide valuable probabilistic guidance that, when combined with contingency planning and adaptive management approaches, supports more resilient winter tourism operations.

## 5 Climate monitoring and analysis services

### 5.1 Overview of climate monitoring

Climate monitoring services provide systematic observations and analyses of climate conditions, documenting the state of the climate system and detecting changes over time. These services form the foundation for understanding climate variability and change, validating climate models, and providing historical context for interpreting current conditions. For winter tourism, climate monitoring reveals the magnitude and rate of changes affecting snow and ice conditions, informs adaptation planning and provides the empirical basis for projecting future conditions. The WMO State of the Global Climate reports, issued annually, represent the authoritative global synthesis of climate monitoring information, documenting record-breaking conditions and long-term trends across all components of the climate system.

The 2024 edition of the WMO State of the Global Climate report documented multiple record-breaking conditions with direct relevance to winter tourism. Global mean near-surface temperature reached 1.55 °C above the 1850–1900 baseline, the warmest in the 175-year observational record. Ocean heat content reached the highest level in the 65-year observational record. Glacier mass balance for 2023/2024 was extremely negative worldwide, with the period from 2021/2022 through 2023/2024 representing the most negative three-year period on record (*State of the Global Climate 2024* (WMO-No. 1368)). These monitoring results provide unequivocal evidence of ongoing climate change and underscore the urgency of adaptation in climate-sensitive sectors including winter tourism.

Climate monitoring services operate across multiple spatial scales, from global products tracking planetary-scale changes to national and regional services documenting local conditions. NMHSs maintain observing networks, quality-control data, calculate climate statistics, and issue monitoring bulletins describing current conditions relative to historical norms. International coordination through WMO promotes consistency in methods, facilitates data exchange and enables global syntheses such as the State of the Global Climate reports. For winter tourism operators, both global monitoring products providing broad context and local monitoring products describing specific conditions at relevant locations serve important planning functions.

## 5.2 Snow cover and depth monitoring

Systematic monitoring of snow cover extent, snow depth and snow water equivalent provides essential information for understanding interannual variability, detecting long-term trends and placing current conditions in historical context. IPCC assessed with high confidence that snow cover has declined in nearly all regions in recent decades, with particularly strong declines at lower elevations (IPCC, 2019). Monitoring data documenting these changes inform adaptation planning and provide the empirical basis for projecting future conditions. Multiple complementary monitoring approaches exist, utilizing satellite remote sensing for broad spatial coverage and ground-based observations for detailed point measurements.

### 5.2.1 Satellite-based products

The Copernicus Land Monitoring Service provides comprehensive snow monitoring products for Europe and globally. Products include daily snow cover extent at various spatial resolutions, fractional snow cover products that estimate the percentage of ground covered by snow within each pixel, and snow water equivalent estimates derived from microwave satellite observations. The service utilizes data from the Sentinel satellite constellation, providing high spatial resolution products at 20 m for detailed applications, as well as coarser resolution products from the Moderate Resolution Imaging Spectroradiometer (MODIS) and other sensors for continental and global analyses. All products are freely available following registration, supporting both operational applications and research investigating snow trends.

These satellite products enable snow-cover extent and duration to be monitored across regions and elevations. A separate multi-dataset analysis found that snow-cover duration in the European Alps declined by 5–7 days per decade between 1968 and 2017, with larger decreases at low and intermediate elevations (Monteiro and Morin, 2023). The spatial detail provided by Sentinel satellites enables snow conditions to be mapped at individual ski facilities, supporting local assessment and planning. However, the relatively short Sentinel record means that longer-term trend analysis requires its combination with earlier satellite products, ground observations or reanalysis data.

The National Aeronautics and Space Administration (NASA) provides global snow products through its Earthdata portal. MODIS snow products include daily global snow cover maps at 500 m resolution, eight-day composite products that reduce cloud contamination, and monthly products suitable for climate analysis. The temporal coverage extending from 2000 to the present enables analysis of snow-cover variability and trends over more than two decades. These products have been used extensively in research examining changes in snow cover at regional and global scales.

The Interactive Multisensor Snow and Ice Mapping System (IMS), operated by the National Oceanic and Atmospheric Administration (NOAA), provides daily snow cover maps for the northern hemisphere. Products are available at both 1 km, 4 km and 24 km spatial resolution, with the archive extending back to 1997. The lengthy archive supports analysis of interannual variability and long-term trends. The products combine information from visible satellite imagery, microwave satellite data and surface observations, providing reliable snow mapping even under cloudy conditions that limit the utility of visible imagery alone. These products document the substantial decline in northern hemisphere snow cover extent, particularly pronounced during the spring season when mountain tourism operations historically extended into April and May.

### 5.2.2 Ground-based networks

The Snow Telemetry (SNOTEL) network, operated by the Natural Resources Conservation Service of the United States, provides automated measurements of snow depth, snow water equivalent, precipitation, and meteorological variables at more than 800 stations across the western United States. Stations are strategically located in mountain watersheds to support water resources management, but the data can also be valuable for winter tourism applications. Real-time data support operational decisions, while historical archives extending back several decades enable analysis of snowpack trends and variability. The network has documented substantial declines in snowpack across much of the western United States, with particularly strong trends in regions experiencing the greatest warming.

Snow water equivalent measurements from the SNOTEL network provide a direct assessment of the water stored in the snowpack and potentially available for spring runoff. For winter tourism, snow depth is often more immediately relevant for assessing terrain coverage, while snow water equivalent provides information about the snowpack's water

content and potential persistence. Used together, snow depth and snow water equivalent can be used to estimate bulk snow density. However, SNOTEL stations provide point measurements in mountain watersheds and may not represent conditions on groomed or snow-managed ski slopes; the data should therefore be interpreted alongside local observations.

Many countries operate national snow monitoring networks providing data similar to the SNOTEL network. Switzerland maintains an extensive network of automated and manual snow observations coordinated by MeteoSwiss and SLF. These observations document changes in snow depth, fresh snowfall and snow-cover duration and support avalanche forecasting, climatological analysis and hydrological applications. Similar networks exist in Austria, France, Italy and other Alpine countries. Canada operates snow monitoring networks supporting both water resources management and winter tourism applications. Coordination through WMO facilitates data exchange and enables international comparisons of snow trends across different mountain regions.

### 5.3 Glacier monitoring services

Glacier monitoring provides essential information on one of the most visible and consequential manifestations of climate change in mountain regions. IPCC concluded with very high confidence that glaciers have lost mass in all regions since at least the 1990s, with the highest rates of loss occurring in recent decades (IPCC, 2021). For regions where glacier tourism represents a significant economic activity, monitoring glacier retreat and mass loss directly informs adaptation planning and communication with visitors about changing conditions. Even for winter tourism operations not directly dependent on glaciers, glacier changes provide a sensitive indicator of climatic trends affecting the broader mountain environment.

The World Glacier Monitoring Service (WGMS), based in Zurich, coordinates international glacier monitoring efforts and maintains the most comprehensive global database of glacier observations. The service collects standardized data on glacier mass balance, length changes and volume changes, including detailed measurements from reference glaciers with long observational records. Its publications include the biennial *Glacier Mass Balance*, which provides assessments of global and regional glacier change. WGMS data show increasingly strong glacier loss in recent decades, with the period from 2021/2022 through 2023/2024 representing the most negative three-year period on record (*State of the Global Climate 2024* (WMO-No. 1368)).

Regionally, exceptionally negative glacier mass balances occurred in Norway, Sweden, Svalbard and the tropical Andes during 2023/2024. Switzerland's glaciers have lost about 60% of their volume since 1850 (NCCS, 2025b), with ongoing changes documented by the Glacier Monitoring in Switzerland (GLAMOS, 2025). Only 2 of the 141 glaciers reporting preliminary data for 2023/2024 had a positive mass balance, underscoring the widespread nature of glacier mass loss under current climatic conditions (*State of the Global Climate 2025* (WMO-No. 1391)). These observations demonstrate the need for glacier tourism

operations to prepare for substantially reduced glacier extent and changing glacier characteristics.

The Global Land Ice Measurements from Space (GLIMS) initiative provides complementary glacier monitoring using primarily optical satellite data. The initiative produces and distributes glacier outlines derived from satellite images, enabling assessment of glacier area changes over time. Repeat imagery allows detection of glacier retreat, advance and changes in surface characteristics. Its extensive geographical coverage supports the monitoring of glaciers in remote regions where ground-based observations are limited or unavailable. The combination of ground-based mass balance measurements from WGMS and satellite-derived extent changes from GLIMS provides comprehensive documentation of glacier changes relevant for tourism adaptation planning.

### 5.4 Climate reanalyses

Climate reanalyses combine historical observations with numerical weather prediction models to produce spatially and temporally complete estimates of past atmospheric conditions. Reanalyses provide information for variables and locations where direct observations are sparse or non-existent, fill gaps in observational records, and apply a consistent modelling and data-assimilation system across the full period. For winter tourism applications, reanalyses provide valuable information on historical snow conditions, temperature and precipitation patterns in mountain regions, and trends in variables relevant to skiing operations. The multi-decadal records enable the characterization of interannual variability and long-term trends.

ECMWF Reanalysis 5 (ERA5) is the fifth-generation global climate reanalysis produced by ECMWF. The dataset covers the period from 1940 to the present at spatial resolution of approximately 31 km and hourly temporal resolution. More than 100 atmospheric variables are provided, including temperature, precipitation, wind, snow depth, snow cover and numerous other parameters relevant to winter tourism. The high spatial and temporal resolution enables detailed analysis of mountain weather and snow conditions, though users should recognize that even 31 km resolution does not fully capture the complexity of terrain in steep mountain regions.

ERA5 data can be used to examine changes in temperature and snow conditions over recent decades, including differences between elevations and regions. Its hourly temporal resolution enables analysis of phenomena such as rain-on-snow events, freeze-thaw cycles, and diurnal temperature ranges, all relevant to snow quality and skiing conditions. The Copernicus Climate Data Store provides user-friendly interfaces for accessing data, along with tools for data processing and visualization. Training materials help new users learn to work with the large datasets involved in reanalysis applications.

The University of Maine's Climate Reanalyzer provides accessible visualization tools for exploring reanalysis and other climate datasets. Users can examine variables including temperature, precipitation, wind and snow through maps and time-series plots and

compare current conditions with long-term averages. The platform allows users to explore selected regions and periods without downloading and processing the underlying datasets. For winter tourism operators seeking to understand how recent conditions compare with historical patterns, Climate Reanalyzer provides a useful introduction to reanalysis information without requiring specialized software.

ClimateEngine provides tools for custom analysis of historical climate, reanalysis and satellite-observation datasets. Users can select geographic areas, periods and variables to examine historical conditions, anomalies and trends. For winter tourism applications, the platform can support analysis of past snowpack, temperature and precipitation conditions in and around ski areas.

# 6 Climate change projection and scenario services

## 6.1 Overview of climate change projections

Climate projections extend climate information into the future, providing scenarios of how climate may change under different assumptions about greenhouse gas emissions, land-use changes, and other human activities. Unlike weather forecasts, which predict specific conditions at specific times, climate projections describe the statistical characteristics of future climate, including changes in average conditions, variability, and the frequency of extreme events. The IPCC Sixth Assessment Report synthesized climate projections from dozens of models worldwide, concluding that global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered, that glaciers will continue to lose mass for several decades even if global temperature stabilizes, and that seasonal snow cover will decline in most land regions (IPCC, 2021). These projections provide essential context for long-term planning in winter tourism.

Climate projections depend on scenarios describing possible future trajectories of greenhouse gas emissions and socioeconomic development. The Shared Socioeconomic Pathways (SSPs) used in the latest projections range from SSP1-2.6, for which the best estimate of global warming by 2081–2100 is 1.8 °C above 1850–1900 levels, to SSP5-8.5, for which the corresponding estimate is 4.4 °C (IPCC, 2021). A study published in Nature Climate Change found that, without snowmaking, 53% of 2 234 European ski resorts would face very high risk to snow supply at 2 °C of global warming, increasing to 98% at 4 °C (François et al., 2023). This illustrates the profound implications of different warming levels for winter tourism. Winter tourism stakeholders therefore have a strong interest in understanding how conditions may change under different scenarios and in supporting mitigation consistent with the goals of the Paris Agreement.

Uncertainty in climate projections arises from multiple sources, including incomplete understanding of climate processes, natural climate variability, differences among climate models and uncertainty about future emissions trajectories. This uncertainty generally increases with longer projection lead times and at finer spatial scales. However, certain aspects of future climate are more certain than others. Continued warming and global

glacier mass loss are virtually certain, while seasonal snow cover is projected to decline in most land regions (IPCC, 2021). IPCC assesses the confidence and likelihood of different projected changes, providing users with guidance on which aspects of projections can be used with greater confidence for planning purposes.

### 6.2 Global and regional climate models

The Coupled Model Intercomparison Project (CMIP) provides the foundation for current climate projections. Modelling centres worldwide have contributed simulations using state-of-the-art climate models covering historical periods and future scenarios through 2100 and beyond. CMIP6 remains the most recent phase for which extensive model output is generally available, while CMIP7 is now underway. CMIP outputs are archived in the Earth System Grid Federation and freely available to researchers and other users. The IPCC Sixth Assessment Report (2023) drew heavily on these simulations in assessing future climate changes. For winter tourism applications, temperature and precipitation projections prove most directly relevant, though snow-related variables are also available from some models.

Global climate models typically operate at spatial resolutions of approximately 100 km or coarser, which is insufficient to represent the detailed topography of mountain regions where winter tourism operates. Regional climate models use global model outputs as boundary conditions while simulating a limited region at higher resolution, providing more detailed projections for specific areas. The Coordinated Regional Climate Downscaling Experiment for Europe (EURO-CORDEX) provides regional projections at resolutions of approximately 50 km and 12.5 km over Europe, including the Alps and other major mountain ranges. Products include temperature and precipitation, with snow-related variables available from some simulations. These higher-resolution projections better represent orographic effects and enable more detailed assessment of elevation-dependent changes, although further local analysis may still be required in complex mountain terrain.

Analysis of regional projections for the European Alps indicates continued warming throughout the twenty-first century under all emissions scenarios (Kotlarski et al., 2023). Summer warming is projected to exceed winter warming, though winter temperatures are still projected to increase substantially. Precipitation projections are less consistent among models, with some projections indicating increased winter precipitation in parts of the Alps but considerable uncertainty in its magnitude and geographical distribution. Despite potential precipitation increases in some locations, declining snow cover is projected with high confidence due to warming temperatures shifting precipitation from snow to rain and increasing snowmelt rates. The Swiss Climate Change Scenarios 2018 indicate that, without climate mitigation, the average winter zero-degree level could rise by 400–650 m by mid-century (NCCS, 2018).

### 6.3 Impact assessment tools

Raw climate model outputs require translation into impact-relevant metrics for use in sectoral planning. Impact assessment tools and platforms provide this translation,

combining climate projections with impact models to estimate consequences for specific systems or sectors. For winter tourism, relevant impact assessments address snow reliability, suitable skiing elevations, season length, snowmaking water and energy requirements, and economic viability under different climate scenarios. Several tools and studies have specifically addressed winter tourism impacts, while more general impact assessment platforms enable custom analyses for locations or questions.

The Climate Impact Lab provides localized temperature projections and estimates of temperature-related impacts on mortality and energy expenditure. While not specifically focused on winter tourism, the platform can provide broader context on projected warming and its socioeconomic consequences under different emissions scenarios. Its accessible mapping interface helps non-specialists explore technical climate information, although it does not assess changes in snow conditions or the specific impacts on ski facilities.

### 6.4 Specific projections for ski tourism regions

Research addressing climate change impacts on ski tourism has provided increasingly detailed regional projections. The Nature Climate Change study examining 2 234 European ski resorts found that, without snowmaking, 53% of resorts would face very high risk to snow supply at 2 °C of global warming, rising to 98% at 4 °C. Assuming snowmaking coverage of 50% of each resort's ski area reduces these proportions to 27% and 71%, respectively, but increases water and electricity demand and the associated carbon footprint (François et al., 2023). The study highlights the importance of both limiting global warming and carefully assessing the benefits and resource implications of snowmaking as an adaptation measure.

For North American ski regions, research has documented substantial declines in natural snowpack and projects further reductions under continued warming. In the western United States, April snowpack declined at 86% of monitoring sites between 1955 and 2020, with an average decline of approximately 19% across all sites (Scott and Lindsey, 2022). A modelling study covering 247 winter recreation locations across the continental United States projected shorter seasons at virtually all locations, with reductions exceeding 50% by 2050 and 80% by 2090 at some downhill skiing locations (Wobus et al., 2017). The projected changes vary considerably by location, activity and emissions scenario, highlighting the need for site-specific assessments.

Australian and New Zealand ski regions are both projected to experience reductions in natural snow, although the magnitude varies by location, elevation and emissions scenario. A comparative assessment projected larger reductions in maximum snow depth and the number of days with usable snow at the Australian sites than at the New Zealand sites, particularly towards the end of the century (Hendrikx et al., 2013). In Japan, annual snowfall is projected to decline across most regions, while parts of Hokkaido may experience increased mid-winter snowfall, demonstrating substantial regional differences in the response to warming (Kawase et al., 2021). These differences reinforce the

importance of using regional and site-specific projections rather than applying broad national assumptions.

These regional projections, while differing in detail, share common themes. Rising temperatures generally shorten snow seasons and reduce snow reliability, with lower-elevation ski facilities facing disproportionate impacts. Snowmaking provides partial adaptation but faces limitations from water availability, energy costs and fewer periods with suitable wet-bulb temperatures. Impacts vary with elevation, latitude, regional climate and the adaptive capacity of individual ski facilities. The Paris Agreement goal of holding warming to well below 2 °C and pursuing efforts to limit it to 1.5 °C would substantially reduce risks to winter tourism. Limiting global warming would substantially reduce risks to winter tourism, while adaptation remains necessary to address changes that are already occurring and projected to continue.

# 7 Specialized tourism applications

## 7.1 Background

Weather and climate services provide greatest value when tailored to specific user needs and decision contexts. Specialized applications for winter tourism translate general meteorological and climatological information into metrics directly relevant to operational decisions and strategic planning. These applications address critical questions: will adequate snow be available for season opening? Which periods offer optimal snowmaking conditions? How should grooming schedules respond to evolving weather patterns? Will proposed infrastructure investments remain viable under projected climate changes? Developing effective specialized applications requires close collaboration between climate service providers and tourism operators to ensure products address actual decision needs with appropriate accuracy, lead time, and format.

PROSNOW is a decision-support system that combines weather forecasts, snowpack models and operational information to support snow-management decisions at ski facilities. ClimSnow, developed through collaboration between Météo-France, the French National Research Institute for Agriculture, Food and Environment (INRAE) and Dianeige, a consultancy specializing in mountain tourism development, provides site-specific projections of future snow conditions, accounting for factors such as elevation, slope orientation and snowmaking. It supports longer-term adaptation planning. These examples illustrate the potential for climate services to move beyond generic products towards specialized decision support tailored to winter tourism contexts.

The changing climate intensifies the need for specialized applications. As average conditions change and historical patterns provide less reliable guidance, sophisticated tools integrating multiple information sources become increasingly valuable. The rising zero-degree level, declining snow cover duration and increasing frequency of warm events require operational adjustments informed by specialized decision support. NMHSs, often in partnership with research institutions and commercial service providers, are developing increasingly sophisticated applications to address these evolving needs. This section

describes several categories of specialized applications particularly relevant to cryosphere tourism management.

### 7.2 Snow reliability indices

Snow reliability indices provide quantitative assessments of the likelihood that adequate snow will exist for winter tourism operations under current and projected future climatic conditions. A widely used indicator is the 100-day rule, under which a ski facility is generally considered snow-reliable if, in seven out of ten winters, snow cover of at least 30–50 centimetres is available for at least 100 days between 1 December and 15 April (Abegg et al., 2021). The rule provides a broad indicator of snow reliability rather than a definitive measure of economic viability, which depends on many additional factors. Historical analysis of snow observations enables calculation of how frequently ski facilities meet this threshold, while climate projections allow assessment of future snow reliability under different warming scenarios.

Snow-reliability assessments require careful consideration of the contribution of snowmaking relative to natural snow. A study of 2 234 European ski resorts found that, without snowmaking, 53% of resorts would face very high snow-supply risk at 2 °C of global warming, rising to 98% at 4 °C. Assuming snowmaking coverage of 50% reduced these proportions to 27% and 71%, respectively, but increased water and electricity demand (François et al., 2023). This analysis demonstrates that snowmaking provides important but incomplete adaptation, with effectiveness declining as temperatures rise and suitable snowmaking conditions become less frequent.

Several variations on the basic 100-day rule exist, including indices considering snow depth at specific dates such as Christmas or New Year, the proportion of the season with adequate natural snow versus requiring snowmaking, and indicators incorporating operational or economic factors such as snowmaking and grooming costs (Abegg et al., 2021; Willibald et al., 2021). More detailed assessments use snow and climate models to account for local characteristics such as elevation, ski-area configuration and snowmaking capacity (Spandre et al., 2019). Such assessments have been undertaken in several European ski regions. These detailed analyses provide resort-specific guidance on snow reliability under current conditions and projected changes, informing investment decisions and adaptation strategies.

For tourism operators and policymakers, snow reliability indices provide useful context for long-term planning. Infrastructure investments such as new lifts, base facilities and access roads may require several decades to amortize, necessitating consideration of snow reliability over similar time horizons. Projected changes in snow-cover duration, freezing levels and conditions suitable for snowmaking indicate the scale of change that planning may need to accommodate. Snow reliability indices synthesize complex climate information into accessible metrics supporting these long-term decisions.

### 7.3 Snowmaking decision support

Snowmaking has evolved from a supplementary operation to an important component of ski-area management in many regions. As natural snow becomes less reliable, snowmaking can help maintain season length and consistency. However, snowmaking requires specific meteorological conditions. A wet-bulb temperature of around −2.5 °C is commonly used as a practical threshold, although this varies with equipment and local conditions, and snowmaking becomes more efficient at lower temperatures.[2] Water availability, energy costs and environmental considerations further constrain snowmaking operations. Specialized decision-support systems can improve the efficiency of snowmaking by identifying suitable weather windows, prioritizing terrain based on strategic importance and anticipated conditions, and balancing competing demands on water and energy resources.

As the climate warms, the number of hours with suitable snowmaking conditions is projected to decline. Modelling for selected locations in the Swiss Alps indicates substantial future reductions in snowmaking potential, with the effects most limiting for lower-elevation ski facilities (Willibald et al., 2021). Decision-support systems use weather forecasts to identify upcoming periods with suitable conditions, allowing operators to prepare equipment, secure water and energy resources and prioritize terrain for snow production. Frequently updated short-range forecasts support rapid responses to evolving conditions and efficient use of limited snowmaking windows.

Water-resource management represents an increasingly important aspect of snowmaking operations. Information on snow accumulation and melt, streamflow and reservoir levels can inform decisions about water availability for snowmaking alongside other uses and environmental-flow requirements. The Snow Telemetry (SNOTEL) network in the United States provides near-real-time information on snow water equivalent, snow depth, precipitation and temperature that supports water-supply forecasting. Similar networks exist in other countries with significant snowmaking operations. As mountain regions experience changes in snow accumulation, snowmelt and runoff timing, effective water management becomes increasingly important for sustainable snowmaking. Integration of hydrological monitoring with weather forecasts and snow-production models enables informed decision-making that balances multiple demands on limited water resources.

Energy consumption and costs represent additional constraints on snowmaking operations. Modern snowmaking systems require substantial electrical power, with costs varying depending on electricity prices and equipment efficiency. Decision-support systems that identify the most efficient snowmaking periods, prioritize critical terrain and minimize energy consumption per unit of snow produced help control costs while maintaining adequate conditions. Electricity sources, tariff structures and periods of peak

[2] The wet-bulb temperature is the temperature a parcel of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat being supplied by the parcel (WMO Codes Registry). A wet-bulb temperature of around −2.5°C is commonly used as a practical threshold for snowmaking, although this varies with equipment and local conditions (TechnoAlpin).

demand may also affect the timing and cost of snow production. Tools that integrate weather forecasts with energy-system capabilities and costs can help optimize snowmaking operations under these evolving constraints.

### 7.4 Grooming and operations planning

Snow grooming is a major operational activity that affects surface quality, safety and snowpack longevity. Grooming decisions depend on multiple factors including snow depth, snow density, temperature trends, anticipated skier traffic, and weather forecasts. Grooming at inappropriate times can damage thin snowpack, waste fuel when snow conditions will deteriorate shortly afterwards, or fail to address deteriorating surface conditions before they affect the skier experience. Specialized decision-support tools can integrate weather forecasts with snowpack modelling and operational constraints to optimize grooming timing and techniques.

Temperature forecasts are particularly important for grooming decisions. Freeze–thaw cycles significantly affect snow-surface conditions. Forecasts of overnight temperatures and refreezing can help operators schedule grooming according to expected surface firmness, although appropriate timing depends on the snow type, terrain, equipment and local operating practices. More frequent warm events can increase the complexity of grooming decisions as surfaces transition more rapidly between suitable and unsuitable conditions. Nowcasting and short-range forecasts with frequent updates enable responsive grooming strategies for rapidly changing conditions.

Wind forecasts influence both grooming and lift operations. Wind redistributes snow, eroding exposed ridges and depositing snow in sheltered areas or forming drifts and cornices. Strong wind events may necessitate regrooming trails after wind redistribution disrupts prepared surfaces. Wind limits lift operations for safety reasons, with specific thresholds varying by lift type and exposure. Because mountain topography can produce highly localized wind conditions, forecasts should be considered alongside observations from on-site monitoring systems. Accurate wind forecasts enable proactive decisions about lift operations and grooming priorities, minimizing disruption and maintaining safety while allowing operations to continue when conditions permit.

Precipitation timing and type significantly affect grooming schedules and techniques. Snowfall during operating hours may require grooming of priority trails, while fresh snow may be left ungroomed on terrain where this is operationally appropriate. Rain events or mixed precipitation necessitate different responses depending on snowpack conditions and forecast temperature trends. Warming increases the likelihood that precipitation will fall as rain rather than snow, particularly at lower and middle elevations, requiring more adaptive grooming strategies. Decision-support systems that integrate precipitation forecasts with snowpack conditions and operational priorities help operators make informed choices to maintain surface quality under changing conditions.

# 8 Risk management and insurance services

## 8.1 Overview of risk management approaches

Winter tourism operations face substantial weather- and climate-related risks affecting revenue, operational costs and long-term viability. Traditional risk-management approaches include operational flexibility, activity diversification and conservative financial planning. However, long-term climatic changes can make historical experience less reliable for assessing future risks and planning appropriate responses. As stated earlier, in the 2025/2026 season alone, weather conditions forced the cancellation of 25 FIS World Cup races. Additional risk-management approaches, including weather derivatives, parametric insurance and climate-risk assessment, may complement traditional operational and financial measures.

Weather and climate risks in winter tourism operate across multiple timescales. Short-term weather risks include insufficient snow for season opening, midwinter thaw events damaging the snowpack, excessive snowfall disrupting access and operations, wind events forcing lift closures, and temperatures that limit snowmaking. These risks affect revenues through lost skier days, increased operational costs and potential safety incidents. Seasonal and interannual risks include below-average snowfall reducing season length, unfavourable temperature patterns limiting natural snow and snowmaking opportunities and extreme events causing infrastructure damage. Long-term climate risks involve fundamental changes in snow reliability affecting infrastructure investments, destination competitiveness and the viability of winter tourism business models.

## 8.2 Weather derivatives and insurance

The Weather Risk Management Association provides education, networking and advocacy for weather derivatives markets. Its activities include increasing understanding of weather risk, promoting its management and providing a platform for market participants. Although the weather-derivatives market initially focused largely on the energy sector, these instruments can also be structured for weather-sensitive activities such as winter tourism. Contracts typically define specific weather parameters measured at agreed locations, payout structures based on departures from defined thresholds, and contractual periods matching critical operational windows. For example, a derivative might provide payments if cumulative snowfall at an agreed reference station falls below a specified threshold during November to March, partly offsetting revenue losses associated with below-average snow seasons.

Parametric insurance represents a related approach in which payouts are triggered when a predefined index reaches an agreed threshold, rather than being based on assessed losses. For winter tourism, parametric structures might provide payments when snow depth falls below defined thresholds for specified durations, when temperatures exceed thresholds required for snowmaking for defined periods or when precipitation falls as rain rather than snow during critical periods. As baseline climate conditions change, historical observations may become less representative of future risk, complicating the design and

pricing of both traditional and parametric insurance. Parametric insurance can provide an alternative risk-transfer mechanism, but its effectiveness depends on how closely the selected index corresponds to actual losses. Accurate weather and climate data from reliable sources such as NMHSs are essential for contract specification, pricing and settlement.

The effectiveness of weather derivatives and parametric insurance depends on the quality and relevance of the observations, indices and statistical methods used in contract design and pricing. Historical climate data characterize past variability, while seasonal forecasts may inform assessments of upcoming conditions and climate projections can help identify changing longer-term risk. NMHSs can provide authoritative observations for contract settlement and climate assessments documenting changing baseline conditions relevant to multi-year contract structures. Contracts should specify the exact data source, observation location and procedures for addressing missing or revised data.

### 8.3 Climate risk assessment

Climate risk assessment for winter tourism extends beyond short-term weather risks to consider how long-term climate change affects infrastructure investments, destination competitiveness and business viability. The Climate CH2025 scenarios indicate that, in a world with 3 °C of global warming, Switzerland's average winter zero-degree level would rise by approximately 550 metres to around 1 450 metres above sea level (NCCS, 2025a). Infrastructure investments, including lifts, lodging and access roads, can remain in use for several decades, requiring climate risks to be assessed over similarly long-time horizons. Financial institutions considering investments in winter tourism developments, insurance companies underwriting long-term policies and tourism operators planning major capital expenditures can use systematic climate-risk assessments to support these decisions.

The Climate Financial Risk Forum, jointly established by the Financial Conduct Authority (FCA) and the Prudential Regulation Authority (PRA) in 2019 in the United Kingdom of Great Britain and Northern Ireland, provides guidance on assessing and managing climate-related financial risks. While not specific to winter tourism, the framework and methodologies apply directly to climate risk assessment in this sector. The Forum emphasizes scenario analysis to examine how operations and investments perform under different climate scenarios, stress testing to evaluate resilience to climate shocks, and transition risks associated with policy responses to climate change. For example, a winter tourism operator could use scenario analysis to examine how its business might perform at different levels of warming, considering physical impacts on snow conditions alongside transition risks such as changing consumer preferences and carbon pricing affecting travel costs.

Physical climate risks for winter tourism include declining natural snow requiring increased snowmaking investment, reduced season length affecting revenue, water scarcity limiting snowmaking and diversification options, infrastructure damage from changing freeze–thaw patterns and permafrost thaw, and increased insurance costs or reduced availability reflecting heightened risks. IPCC concludes that permafrost thaw and glacier retreat have

reduced the stability of high-mountain slopes, with consequences for people and infrastructure (high confidence) (Hock et al., 2019). Buildings, lifts and roads constructed on permafrost face increased maintenance costs and potential failures as ground conditions change. Assessment of these physical risks requires integration of climate projections, local topography and ground conditions, infrastructure characteristics and maintenance practices.

Transition risks arise from societal responses to climate change rather than physical climate changes themselves. Carbon pricing increasing travel costs, regulatory restrictions on energy-intensive snowmaking, changing consumer preferences favouring low-carbon tourism options and reputational risks associated with high-carbon-footprint activities all represent transition risks for winter tourism. The FIS Climate Action Plan, developed with Deloitte, identifies opportunities to reduce emissions and translates them into practical actions, including the use of renewable energy and measures to reduce travel-related emissions (FIS, 2024). Climate risk assessment must consider both physical and transition risks, recognizing that strong climate mitigation limiting physical climate changes may increase certain transition risks, while weak mitigation increases physical risks. Limiting warming in line with the Paris Agreement would reduce the physical risks to winter tourism, although the transition to a low-carbon economy may also require operational adjustments.

# 9 Data access and technical resources

## 9.1 Overview of data resources

Effective use of weather and climate services requires access to appropriate data, technical skills for data processing and analysis, and an understanding of data characteristics, including spatial and temporal resolution, uncertainty, limitations and appropriate applications. This chapter describes major data portals providing access to observations, forecasts, reanalyses and projections relevant to winter tourism. It also addresses programming tools and libraries supporting data analysis, and training resources that help users develop necessary technical skills. The increasing availability of free, high-quality data and powerful open-source analysis tools can broaden access to climate information, including for smaller tourism operators, although expert support may still be required.

Examples of specialized services include ClimSnow, which provides site-specific projections of future snow reliability, including the effects of grooming and snowmaking, and PROSNOW, a forecasting system designed to support snowmaking and piste-preparation decisions. PROSNOW is not a publicly accessible platform, and access arrangements should be confirmed with its providers. NMHSs possess authoritative data and expertise but may lack direct connections to tourism-sector users. Ski facilities should engage with their NMHS and relevant research or service providers to identify suitable data, tools and technical support.

Data users should recognize that different data sources have different characteristics affecting their appropriateness for various applications. Observational data provide direct

measurements at specific locations but remain subject to measurement uncertainty and may have limited spatial coverage. Satellite products offer broad spatial coverage but may have resolution and retrieval limitations, particularly in complex terrain. Reanalyses provide consistent gridded coverage across space and time but represent model-derived estimates constrained by observations, rather than direct observations. Forecast products provide predictions of future conditions with associated uncertainty and generally declining skill as lead time increases. Climate projections describe long-term statistical characteristics conditional on specified emissions or socioeconomic scenarios but do not predict specific events. Understanding these characteristics enables the selection of appropriate data sources for specific applications and proper interpretation of analysis results.

WMO, through the Global Cryosphere Watch and the WMO Information System 2.0, is working to improve the discovery and accessibility of cryosphere data by bringing together operational observations from NMHSs and relevant data collected by research institutions for critical cryosphere variables. This work aims both to broaden the range of data available and to make these data accessible to users beyond the NMHS community.

### 9.2 Major data portals

The Copernicus Climate Data Store is a major portal providing climate data for global and regional applications, including European winter tourism. The Store provides free access to many observations, reanalysis datasets including ERA5, seasonal forecasts, and climate projections including CMIP and CORDEX datasets. Users can explore and request data through web interfaces or use application programming interfaces for automated retrieval and integration into operational systems. Copernicus also provides interactive applications, tutorials and open-source tools for accessing, processing and visualizing the data. Registration is required to download data and users must accept the license terms applicable to each dataset.

For users seeking historical climate observations, the NOAA National Centers for Environmental Information Climate Data Online portal provides free access to global historical station data. The portal includes quality-controlled daily, monthly, seasonal and annual measurements, including temperature, precipitation, snowfall and snow depth, although variable availability and record length differ among stations. For the western United States and Alaska, the US Department of Agriculture Natural Resources Conservation Service provides real-time and historical snow water equivalent, snow depth, precipitation and temperature data from the Snow Telemetry network. Both web interfaces and application programming interfaces are available. Most data can be accessed and downloaded free of charge; fees generally apply only to certified copies and certain specialized services.

The NASA Earthdata portal provides access to Earth observation data from satellites, aircraft and field campaigns. Available datasets include snow-cover products derived from the Moderate Resolution Imaging Spectroradiometer, imagery suitable for mapping glacier extent from Landsat and other optical sensors, and satellite-derived temperature and

precipitation products. The Giovanni online visualization tool enables interactive exploration of selected satellite data without requiring downloads or specialized software. The Worldview application provides near-real-time imagery from multiple satellites, useful for monitoring current snow conditions. A free Earthdata login is required to download many datasets. Training materials, including webinars, tutorials and documentation, help users navigate the extensive holdings and select appropriate products for their applications.

NMHSs provide data portals and services tailored to their countries or regions. Examples include the MeteoSwiss Open Data portal, the Météo-France public data portal and data services provided by the US National Weather Service. Data availability, formats and access conditions vary among services. Users seeking data for specific tourism destinations should consult the relevant NMHS for locally optimized products, services and expert interpretation.

### 9.3 Programming and analysis tools

Python is widely used for climate-data analysis because of its scientific libraries, active user community and extensive documentation. Key libraries for climate applications include xarray for working with multidimensional labelled arrays typical of climate datasets, pandas for tabular data manipulation and analysis, netCDF4 for reading and writing the netCDF file format commonly used for climate data, Matplotlib and Cartopy for creating maps and visualizations, and scikit-learn for machine-learning applications. These libraries are free, open-source and well documented. Using Python with Jupyter notebooks supports interactive analysis that combines code, visualizations and explanatory text, which can help document analyses and share results with collaborators.

For users preferring R, a programming language widely used in statistics and data science, numerous packages support climate analysis. The terra package handles raster and vector spatial data, including gridded climate products; it has superseded the older raster package. ClimInd calculates a range of climate indices, including snow-related indices. The ncdf4 package enables reading and writing netCDF files. Visualization packages including ggplot2 create publication-quality graphics. R also provides extensive statistical capabilities useful for climate analysis.

Users without programming skills can access many climate-data visualization and analysis functions through web-based platforms with graphical interfaces. Climate Reanalyzer enables exploration of climate and weather datasets through interactive maps and plots without requiring programming. The Copernicus Data Stores Applications catalogue provides interactive tools for exploring selected Copernicus datasets and indicators. Various NMHSs offer custom analysis tools through their web portals. While these graphical tools lack the flexibility of programming approaches, they provide accessible entry points for users beginning climate-data analysis. Programming-based approaches may be needed for more advanced, customized or reproducible analyses.

Cloud-computing platforms provide scalable infrastructure for climate-data analysis without requiring extensive local computational resources. Google Earth Engine offers extensive Earth-observation data holdings and computational capabilities through web-based and programming interfaces. The Copernicus Data Space Ecosystem provides cloud-based access to Copernicus data, including Sentinel satellite products. These platforms particularly benefit users working with large satellite datasets or conducting computationally intensive analyses that exceed the capabilities of local computers. However, they typically require greater technical expertise than graphical web-based tools, and registration requirements, usage quotas and costs vary by platform and type of use.

### 9.4 Training and capacity-building resources

WMO supports education and training through its Education and Training Programme and Global Campus Initiative. The WMO Education and Training Programme Moodle platform includes learning resources and courses covering climate services and related technical subjects. Although many activities are designed primarily for NMHS personnel, openly available materials may also benefit researchers, service providers and other technical users supporting the winter tourism sector. Access conditions and intended audiences vary among courses.

The Copernicus Climate Change Service provides free learning resources through the Climate Data Store. These include practical data-processing workflows using Jupyter notebooks, e-learning modules explaining major climate-data types, and presentations and recorded lectures from training events and webinars. The resources range from introductory explanations of observations, reanalysis and climate modelling to technical guidance on downloading, processing and visualizing specific datasets. They also discuss the potential and limitations of using Climate Data Store products for sectoral and regional decision-making.

The WCRP Academy serves as a hub connecting providers and users of climate-science training. Its catalogue brings together courses, workshops, seasonal schools, webinars and other training opportunities offered across WCRP and by partner organizations. Although its scope extends well beyond winter tourism, opportunities addressing climate modelling, regional projections, extreme events, climate-data analysis and the development of actionable climate information may be valuable to researchers, NMHS personnel and technical specialists supporting weather and climate services for the sector. Target audiences, delivery formats, costs and eligibility requirements vary among opportunities.

Universities and research institutions offer both formal courses and informal training resources on climate science and data analysis. Online learning platforms such as Coursera, edX and FutureLearn provide courses on climate change, climate modelling, and data analysis using Python or R. Although these courses typically address climate change broadly rather than focusing specifically on winter tourism applications, they can provide foundational knowledge for using climate information and services. Access arrangements vary: some materials may be available free of charge, while certificates,

assessments or full course access may require payment. These examples are illustrative rather than exhaustive, and users should also consult national training providers, universities, professional associations and other relevant platforms for additional opportunities.

# 10 Best practices and implementation guidelines

## 10.1 Overview of best practices

Effective use of weather and climate services requires more than simply accessing data and products. Services must be selected appropriately for specific decision contexts, interpreted correctly with appropriate consideration of uncertainties and limitations, and integrated into decision-making processes in ways that improve outcomes. This chapter summarizes best practices for implementing weather and climate services in winter tourism operations, drawing on guidance from WMO, published literature and operational experience. These practices apply across diverse contexts, from daily operational decisions at individual ski facilities to strategic planning for national winter tourism sectors.

The changing climate documented in WMO State of the Global Climate reports and IPCC assessments necessitates adaptive approaches to using weather and climate services. Historical patterns and relationships between weather variables and operational outcomes may no longer fully represent current or future conditions. Recent record temperatures, exceptional glacier mass loss and weather-related disruptions to winter sports reinforce the need to review and update operational approaches. Best practices must therefore emphasize learning, adaptation and continuous improvement rather than static application of established procedures.

Successful implementation of weather and climate services typically involves collaboration among multiple stakeholders. NMHSs provide authoritative weather forecasts and climate data. Research institutions develop specialized tools and conduct impact assessments. Commercial service providers may offer customized products and decision-support platforms. Tourism operators possess detailed knowledge of how weather affects operations and finances. Policymakers establish regulatory frameworks and funding mechanisms. Industry associations and sports federations can coordinate action and share good practices across their networks. Collaboration that draws on the expertise and resources of these different actors can improve service development and use.

## 10.2 Service selection criteria

Selecting appropriate weather and climate services for specific applications requires matching service characteristics to decision needs. The first consideration is temporal-scale alignment. Daily operational decisions require frequently updated short-range forecasts and nowcasts. Planning several weeks ahead can draw on extended-range forecasts, which provide probabilistic guidance but generally less local detail and skill than short-range forecasts. Seasonal forecasts can inform preparations for the overall character of the coming season but cannot predict conditions on a specific opening date. As the proposed opening approaches, short-range forecasts and observations become

increasingly important. Infrastructure investment planning requires climate projections extending decades into the future. Using a product beyond its appropriate time horizon can lead to poorly supported decisions and unjustified confidence in the outcome.

Spatial resolution is a second critical consideration. Mountain weather varies substantially over short distances because of topography, aspect and elevation. High-resolution numerical weather prediction models may represent peaks, valleys and local terrain effects more effectively than coarser models, but higher resolution does not automatically mean greater forecast accuracy. Even high-resolution models have limitations in representing very localized effects. Satellite snow products may adequately represent snow cover at regional scales but their suitability for resort-level analysis depends on the sensor, product resolution, cloud cover and terrain. Climate projections are often produced at spatial scales too coarse for direct site-level application, requiring downscaling or expert interpretation. Users should assess whether a service's spatial resolution and demonstrated performance match the spatial scale of their decisions, seeking higher-resolution products when available or applying appropriate interpretation when using coarser products.

Forecast skill and uncertainty characteristics require careful evaluation. Not all forecasts or projections have equal performance, and forecast skill varies by location, season, lead time and atmospheric conditions. Where available, users should consult verification statistics to understand past forecast performance for relevant locations, variables and lead times. Ensemble forecasts and probabilistic products can provide information about the range and likelihood of possible outcomes that is not available from a single deterministic forecast, but they still require appropriate interpretation. Climate projections should likewise be assessed across multiple models and scenarios rather than treated as a single prediction. Risk-informed decisions should consider this range of plausible outcomes, including low-probability but high-impact conditions.

Accessibility, cost and technical requirements also affect service selection. Freely available products from NMHSs and other public providers may provide an authoritative starting point where suitable products are available. Specialized commercial products may offer enhanced features, customization, local refinement or integration with business systems, which may justify their cost for some applications. Cloud-based platforms enable sophisticated analyses without substantial local computational resources but may require specialized skills. Web-based graphical tools are accessible to non-technical users but offer less flexibility than programming approaches. Users should assess their technical capabilities, budget constraints and specific needs when selecting among available options and evaluate whether paid services provide demonstrable additional value over authoritative public products.

### 10.3 Uncertainty communication

All weather forecasts and climate projections contain uncertainty arising from incomplete observations, imperfect models and inherent limits to predictability. Climate projections also depend on assumptions about future greenhouse gas emissions and socioeconomic

development. Probabilistic forecasts expressing the likelihood of temperature or precipitation falling within specified ranges convey uncertainty more completely than single-value predictions. Ensemble forecasts show a range of possible outcomes, while confidence statements, such as those used in IPCC assessments, indicate the degree of certainty based on the available evidence and agreement across studies. Users may require guidance and training to interpret probabilistic information correctly and incorporate uncertainty appropriately into decision-making.

Common errors in interpreting uncertain forecasts include overconfidence in a single most likely outcome, neglect of low-probability but high-impact outcomes, misinterpretation of probabilities and failure to update decisions as forecasts and observations change. A seasonal forecast indicating a 60% probability of above-average winter temperatures should not be interpreted as certainty of warm conditions; the remaining 40% indicates that other outcomes remain possible. Decision-makers should consider the full range of possible outcomes, taking account of both their probabilities and potential consequences. Contingency planning addressing multiple possible outcomes provides greater resilience than plans assuming that the most likely outcome will necessarily occur.

The changing climate introduces an additional challenge: historical climate statistics may no longer represent the frequency or range of conditions experienced today or in the future. The WMO State of the Global Climate 2024 report documented that 2024 exceeded 1.5 °C above pre-industrial levels, while clarifying that a single year above this level does not mean that the long-term temperature goal of the Paris Agreement has been exceeded (*State of the Global Climate 2024* (WMO-No. 1368)). Planning based solely on historical experience may therefore be inadequate as climatic baselines continue to shift. Climate services should communicate both forecast uncertainty and the changing baseline against which forecasts, observations and climate statistics are interpreted.

Visualization techniques can enhance understanding of uncertainty. Ensemble spaghetti plots showing multiple forecast trajectories, probability maps displaying the likelihood of outcomes across geographic areas, and time-series plots with uncertainty ranges can convey uncertainty more effectively than single-line deterministic presentations. However, overly complex visualizations may confuse rather than clarify. Service providers should develop and test visualizations with intended users to ensure that the uncertainty information is understood and useful for decision-making.

### 10.4 Integration into decision-making processes

Weather and climate services achieve the greatest value when integrated into organizational decision-making processes rather than treated as auxiliary information consulted only occasionally. For daily operations, forecasts should inform standard operating procedures for lift operations, grooming schedules, snowmaking prioritization and safety protocols. Predefined decision thresholds can support timely action, but safety-critical decisions – such as lift closures in high winds – should also use real-time observations, official warnings and established operational procedures. Thresholds should be developed with appropriate technical and safety expertise. Forecasts should not

replace human judgment, as local conditions may differ from forecast conditions and experienced operators may identify factors that forecast products do not fully capture.

For tactical planning spanning weeks to months, extended-range and seasonal forecasts can inform scenario planning and flexible resource decisions, including staffing, procurement, marketing and maintenance scheduling. For example, an increased probability of warmer-than-average conditions may be used alongside other information when reviewing snowmaking readiness, staffing flexibility and alternative opening plans. These forecasts should inform contingencies rather than determine fixed decisions because their skill varies by location, season, variable and lead time. Decisions should account for the full range of possible outcomes rather than assuming that the most likely outcome will occur. Regular review and updating of plans as forecasts evolve and actual conditions emerge support a more adaptive approach than planning only once at the beginning of the season.

Strategic planning requires the integration of climate projections describing a range of plausible conditions decades ahead. Infrastructure investments, including new lifts, facilities or access roads, should be evaluated considering projected snow conditions under multiple climate scenarios. A European assessment found that, without snowmaking, 53% of ski resorts would face very high snow-supply risk at 2 °C of global warming, rising to 98% at 4 °C (François et al., 2023). This illustrates how infrastructure may operate under substantially different conditions from those represented by the historical climate. Adaptation options, including relocating some activities to higher elevations, snowmaking expansion, adjusting the timing of operations or diversification towards non-snow-dependent activities, should be evaluated across climate scenarios. Assessments should also consider financial feasibility and potential water, energy, environmental and social constraints. Financial analysis should account for climate risks through scenario analysis evaluating project performance under multiple climate scenarios.

Organizational culture influences how consistently weather and climate information is used in decisions. Effective implementation requires clear responsibilities, staff training, accessible information and procedures that allow plans to be adjusted as conditions change. Organizations can strengthen their use of services by documenting forecast-informed decisions, comparing anticipated and actual outcomes, and updating procedures based on experience. Leadership support, collaboration between technical and operational staff, and willingness to learn from both successful and unsuccessful decisions are important for building sustained capacity.

# 11 Regional service directories

## 11.1 Overview of regional services

While global services provide valuable information for winter tourism, regional and national services often offer products tailored to local conditions, phenomena and user needs. NMHSs have detailed knowledge of national and local climates, operate or coordinate

observing networks and provide authoritative forecasts, warnings and climate information. Regional services may address phenomena specific to mountain ranges, climate patterns characteristic of particular regions or the linguistic and cultural needs of local users. This chapter provides selected examples of regional services for major winter tourism areas, rather than an exhaustive global directory. Users should consult the relevant NMHS and other authoritative providers for the most appropriate local products. Service availability and links may change over time.

Service availability and characteristics vary substantially among countries depending on resources, priorities and institutional structures. Some countries provide comprehensive mountain weather services, specialized avalanche forecasting and detailed climate monitoring tailored to winter tourism needs, while others offer more general services without tourism-specific products. The following directories therefore provide only selected examples from regions with substantial winter tourism activity.

## 11.2 European services

MeteoSwiss provides weather forecasts, warnings, climate information and access to observational and model data for Switzerland, including products designed for complex Alpine terrain. Avalanche forecasts and detailed information on snow conditions are provided by SLF, while GLAMOS coordinates long-term monitoring of glacier changes in the Swiss Alps. Services are available in several languages, reflecting Switzerland's linguistic diversity and international visitor base.

GeoSphere Austria is Austria's national meteorological, climatological, geological and geophysical service and provides weather forecasts, warnings, observations and climate information. Avalanche forecasting is delivered by seven regional avalanche warning services. A national overview is available through lawinen.at, while the Avalanche Warning Service Information System provides shared avalanche-related observations and information. These services address regional differences in weather, snow and terrain across the Austrian Alps.

Météo-France provides mountain weather services and avalanche-risk forecasts for the French Alps, Pyrenees and Corsica. Météo-France and its research centre, the National Centre for Meteorological Research (CNRM), have also contributed to the development of specialized services for ski areas. These include PROSNOW, a forecasting system designed to support operational snow management, and ClimSnow, which provides site-specific assessments of future snow conditions and the effects of snow-management practices. These services demonstrate how weather forecasts and climate projections can inform operational snow management and longer-term adaptation planning.

Italian mountain weather services address the distinctive characteristics of the Italian Alps, including influences from both Atlantic and Mediterranean weather systems. Services support the substantial Italian ski tourism industry as well as mountaineering and other mountain activities. Weather, snow and avalanche information is provided through several national and regional bodies. The Interregional Association for Snow and Avalanches

(AINEVA) coordinates regional snow and avalanche services across the Italian Alps, while Meteomont provides snow observations and avalanche-danger bulletins covering mountain areas throughout Italy. This combination of national coordination and regional delivery allows services to reflect local differences in weather, snow and terrain.

The Scandinavian countries provide mountain weather and avalanche services addressing conditions in Norway, Sweden and Finland. Norway's Yr, provided jointly by the Norwegian Meteorological Institute and the Norwegian Broadcasting Corporation, offers detailed location-specific forecasts, while Varsom provides avalanche warnings, snow information and other natural-hazard warnings. The Swedish Meteorological and Hydrological Institute (SMHI) and the Finnish Meteorological Institute provide national weather forecasts, warnings and climate information. These services support ski areas, backcountry recreation and transport in environments characterized by rapidly changing weather, strong winds and extended periods of low temperatures.

### 11.3 North American services

The United States provides mountain weather services through regional offices of the National Weather Service. The Weather Prediction Center coordinates national products, including winter-weather forecasts relevant to ski facilities. The US Department of Agriculture's Natural Resources Conservation Service operates the Snow Telemetry (SNOTEL) network, which provides near-real-time information on snow depth, snow water equivalent and other climatic conditions across the western United States and Alaska. From 1955 to 2020, April snowpack declined at 86% of the monitoring sites assessed in the western United States (Scott and Lindsey, 2022). SNOTEL data support water-resource management, water-supply forecasting and winter tourism planning.

Environment and Climate Change Canada provides weather and climate services across Canadian mountain regions, from the Rocky Mountains and the interior ranges of British Columbia to mountain areas in eastern Canada. These services support major ski tourism destinations in British Columbia, Alberta and Quebec. Avalanche Canada issues daily public avalanche forecasts during winter for much of mountainous western Canada. Its Mountain Information Network enables users to share real-time, location-specific observations of weather, snowpack and avalanche conditions, supplementing information from formal monitoring networks and forecast services.

Canadian snow data document substantial changes in snow-cover extent and duration affecting winter tourism operations. Canada's Changing Climate Report found that the proportion of the year with snow cover decreased across most of Canada and that Canadian Arctic and alpine glaciers have thinned over the past five decades (Derksen et al., 2019). These changes reinforce the need for ski facilities to consider adjustments to season timing, snowmaking and diversification as part of longer-term adaptation planning.

### 11.4 Asia-Pacific services

The Japan Meteorological Agency (JMA) provides comprehensive weather and climate services relevant to Japan's substantial ski tourism industry, including forecasts, heavy-

snow and snowstorm warnings, snow-depth observations and seasonal outlooks. Japanese ski facilities benefit from heavy snowfall driven by moisture from the Sea of Japan interacting with cold continental air masses. At the same time, rising temperatures affect the elevation of the rain–snow transition and the duration of reliable snow conditions. JMA services therefore support both the management of heavy-snow hazards and planning for changing snow conditions.

The Australian Bureau of Meteorology (BOM) provides weather and climate services for Australian ski facilities in the Snowy Mountains and Victorian Alps. Australian resorts face challenges from generally lower elevations than European or North American ski facilities, making them particularly vulnerable to warming temperatures. Maximum snow depth, snow-cover extent and the number of snow days have all decreased in Australian alpine regions since the late 1950s, with the largest declines occurring during spring and at lower elevations (CSIRO and BOM, 2024). Services therefore need to address current operational requirements as well as longer-term planning for shorter and less reliable snow seasons.

MetService provides official weather forecasts and warnings for New Zealand, including specialized mountain forecasts relevant to ski facilities in the North and South Islands. Earth Sciences New Zealand provides climate monitoring, seasonal outlooks and research on long-term changes. New Zealand ski tourism benefits from maritime influences providing moisture but faces challenges from warming temperatures and changing precipitation patterns. Long-term monitoring shows continued shrinkage of New Zealand's glaciers (National Institute of Water and Atmospheric Research (NIWA, 2024).[3] Services must also address the country's rapidly changing mountain weather, which is strongly influenced by westerly airflow and orographic effects.

# 12 Emerging technologies and future directions

## 12.1 Overview of technological advances

Rapid advances in computing, artificial intelligence, remote sensing and communications technologies are transforming weather and climate services. These technological developments promise improved forecast accuracy, enhanced spatial and temporal resolution, better representation of uncertainty, more accessible user interfaces and integration of climate services into automated decision systems. For winter tourism, emerging technologies may enable more precise snowmaking optimization, better prediction of snow conditions near operational thresholds, enhanced visitor safety through improved avalanche forecasting, and more effective long-term adaptation planning. As these technologies move from research into operational use, ski facilities will need to assess their accuracy, reliability and suitability for specific decisions.

The accelerating climatic changes documented in WMO State of the Global Climate reports create growing challenges for winter tourism operations and increase the need for

[3] Earth Sciences New Zealand was established on 1 July 2025 through the merger of the National Institute of Water and Atmospheric Research (NIWA) and GNS Science. Sources published before that date retain the NIWA name.

innovative climate services (*State of the Global Climate 2024* (WMO-No. 1368)). Traditional approaches based on historical experience and conventional forecasting methods may prove inadequate for managing these rapidly changing conditions. Emerging technologies that leverage artificial intelligence to identify subtle patterns in complex data, utilize expanding satellite observations to monitor conditions in increasing detail, or integrate multiple information sources into decision-support systems may provide essential capabilities for navigating the transition to a warmer climate.

However, technological advances should complement rather than replace fundamental climate services from NMHSs. Sophisticated algorithms require high-quality observational data for training and validation. Automated systems require oversight by experienced professionals who can identify when unusual conditions exceed algorithm training ranges. Novel technologies require rigorous validation before operational deployment in safety-critical applications. Connecting technological innovation with authoritative meteorological expertise can help ensure that new capabilities enhance the reliability and trustworthiness of weather and climate services supporting winter tourism.

### 12.2 Artificial intelligence and machine learning

Artificial intelligence and machine learning techniques are transforming multiple aspects of weather and climate services. Statistical post-processing of numerical weather prediction model outputs using machine learning can correct systematic biases and improve forecast accuracy. Deep learning applied to satellite imagery can support the detection of snow cover, the estimation of snow depth and the identification of conditions associated with avalanche hazards. Machine learning models trained on historical relationships between large-scale climate patterns and local conditions may also contribute to seasonal forecasting. Natural language processing enables automated generation of forecast text from numerical predictions. Some machine-learning weather models have now entered operational use; for example, ECMWF began operating deterministic and ensemble versions of its Artificial Intelligence Forecasting System in 2025.

For winter tourism specifically, machine learning applications include automated snow-condition assessment from webcam imagery, reducing reliance on manual snow reporting. Computer-vision algorithms can be trained to analyse images to estimate snow depth, identify snow-quality characteristics and detect hazardous conditions. Resort operators may be able to deploy these systems at modest cost, obtaining frequent automated reports that supplement manual observations. Predictive-maintenance applications use machine learning to analyse sensor data from lift operations, identifying equipment at risk of failure before a breakdown occurs.

Machine learning can enhance snowmaking optimization by learning complex relationships between meteorological conditions, energy costs, water availability and resulting snow quality. Traditional snowmaking decision rules based on simple temperature and humidity thresholds may not fully optimize production under varying conditions. Machine learning models trained on historical data can identify subtle patterns that enable more efficient operations. As the number of suitable snowmaking hours declines due to warming

temperatures, this enhanced efficiency becomes increasingly important for maintaining adequate snow cover within water and energy constraints.

However, machine learning applications require careful validation and oversight. Models trained on historical data may not perform well when conditions exceed their training range, a possibility that becomes increasingly important as climate change produces unprecedented conditions. Machine learning systems should therefore be deployed with appropriate human oversight, particularly for safety-critical applications such as avalanche forecasting. Effective development and validation require collaboration among technology developers, meteorological specialists, service users and the organizations responsible for authoritative observational data.

### 12.3 High-resolution modelling

Numerical weather prediction models continue to increase in spatial resolution as computing capabilities advance. Current operational regional models at major centres run at horizontal resolutions of around 1–3 kilometres, with research models demonstrating sub-kilometre capabilities. At these resolutions, models represent topography and localized atmospheric processes in greater detail and may explicitly represent some processes, such as deep convection, that coarser models must parameterize. For mountain weather forecasting, high resolution enables improved representation of valley winds, orographic precipitation patterns, temperature inversions and other phenomena critical for winter tourism operations. For example, MeteoSwiss operates ensemble forecasting systems for the Alpine region at grid spacings of 1 and 2.1 kilometres.

Very high-resolution atmospheric and snow models could provide information at the scale of individual ski slopes, addressing variations in conditions associated with aspect, elevation and local wind patterns. Such detail could support grooming prioritization, avalanche-hazard assessment and communication of conditions to visitors. These capabilities remain primarily at the research or specialized-application stage. The computational demands of very high-resolution modelling remain substantial, but continuing advances in computing hardware and model efficiency are making such resolution increasingly feasible for operational forecasting.

Computational fluid dynamics approaches can simulate fine-scale wind patterns around buildings, lift towers and other infrastructure, supporting design decisions and operational safety protocols. These simulations capture local effects that even high-resolution weather models do not fully resolve. Site-specific wind modelling may be particularly valuable for assessing infrastructure exposure, planning new installations and evaluating possible retrofit measures.

Digital twins – comprehensive computational models integrating weather forecasts, snow physics, infrastructure characteristics and operational practices – represent an emerging application of high-resolution modelling. A digital twin of a ski resort could simulate operations under forecast weather conditions, identifying optimal grooming schedules, snowmaking priorities and staffing allocations. These systems could evaluate proposed

infrastructure modifications or operational changes before physical implementation, reducing risks and optimizing investments. While digital twins for entire ski resorts remain largely conceptual, many of the component technologies already exist. Their integration into comprehensive operational systems would require collaboration among resort operators, technology developers and meteorological service providers.

### 12.4 Internet of Things applications

The Internet of Things (IoT) – networks of connected sensors, equipment and control systems that communicate through wired or wireless networks – enables extensive real-time monitoring and automated control of distributed systems. For winter tourism, IoT applications include dense networks of weather and snow sensors providing detailed spatial information about conditions, automated snowmaking systems responding to weather conditions with limited human intervention, smart grooming equipment reporting conditions and supporting operational adjustments, and integrated lift-operations management optimizing throughput while maintaining safety. These systems can respond more rapidly than human operators to changing conditions, potentially improving efficiency, safety and visitor experience.

Distributed snow-sensor networks address the high spatial variability of mountain snow conditions. Traditional approaches relying on a few manual measurement points may miss important spatial variations. Low-cost sensors deployed at numerous locations provide much more complete spatial information. Wireless communication and cloud-based data platforms enable real-time access to this information from any Internet-connected device. Operators can view detailed snow-depth maps identifying areas requiring grooming attention, assess snowmaking needs across the entire operation and provide accurate condition reports to visitors. As snow reliability declines and operational margins tighten, this detailed spatial information becomes increasingly valuable.

Smart snowmaking systems integrate weather forecasts, real-time meteorological observations, water- and energy-system status and snow-depth sensors to optimize snow production automatically. Systems can activate snowmaking when conditions become suitable, prioritize snowmaking equipment on critical terrain, adjust production rates based on evolving conditions and shut down when conditions deteriorate or depth targets are achieved. This automation enables the use of brief suitable windows that might be missed with manual operations, particularly important as the frequency of suitable snowmaking conditions declines. However, automated systems require reliable power and communications, robust equipment and appropriate oversight to handle unusual situations exceeding automated response capabilities.

Visitor-flow monitoring using sensors, cameras and mobile-device data can provide real-time information about crowding, queue lengths and facility use. This information supports operational decisions about staffing, lift operations and communications to visitors. Integration with weather forecasts enables proactive responses to conditions likely to concentrate visitors on particular terrain or facilities. Enhanced visitor experience through reduced wait times and better crowd distribution may partially offset challenges from

reduced natural snow reliability. Privacy considerations require careful design of monitoring systems, including the use of aggregated or anonymized data, collection of only the information needed for the stated purpose, transparent communication with visitors and compliance with applicable privacy regulations.

# 13 Learning from experience

## 13.1 Using scenarios to demonstrate applications

Experience from implementing weather and climate services can provide valuable lessons for others considering similar approaches. This chapter presents practical application scenarios illustrating how climate services could be integrated into winter tourism operations, the challenges that could arise and the outcomes that could be assessed. The scenarios represent applications across different temporal scales, geographic regions and institutional contexts. While the scenarios reflect plausible circumstances, the principles and approaches have broad applicability, enabling ski facilities to consider possible approaches and anticipate difficulties that may arise during implementation.

The climate context documented in the WMO State of the Global Climate reports and IPCC assessments makes such scenario-based learning increasingly important. Winter tourism operations face growing adaptation challenges as temperatures rise and snow and glacier conditions change. The scenarios presented here are only a few possible examples, with much wider knowledge available from the operational experience of ski facilities, national ski associations and NMHSs worldwide.

Users should recognize that practical application scenarios illustrate possible applications under certain conditions. Climate change means that future conditions may differ from those considered in these examples. Accelerating climatic changes may also require new or revised approaches over time. The following scenarios show how weather and climate services could be applied to common decisions in winter tourism. They are illustrative rather than documented case studies and should be adapted to local conditions, operational procedures and available expertise.

## 13.2 Seasonal planning

A major Alpine ski resort faces recurring challenges with season opening date decisions. Opening too early risks disappointing visitors with inadequate snow cover, damaging the resort’s reputation and wasting resources on operations that generate little revenue. Opening too late sacrifices revenue from the critical Christmas holiday period when demand peaks. Historical practice based on fixed calendar dates no longer provides reliable guidance as warming temperatures and declining low-elevation snow cover alter seasonal patterns. In this scenario, the resort seeks to improve season opening decisions through better utilization of seasonal forecast guidance combined with historical climate analysis.

To do this, the resort partners with its NMHS and a research institution to develop an integrated decision-support approach. Historical snow-depth data from 30 years of observations are analysed to understand interannual variability, trends and relationships

between large-scale climate patterns and local snow conditions. ERA5 reanalysis data extend the analysis back to 1950, providing additional regional climate context for recent observations. The analysis identifies substantial changes in the timing and duration of snow cover at lower elevations, consistent with the general Alpine decline in snow-cover duration of 5 to 7 days per decade (Matiu et al., 2021). Conditions at higher elevations show more modest changes, informing decisions about where to concentrate early-season operations.

Seasonal forecasts from ECMWF's SEAS5 and other sources are incorporated into planning beginning in September, three months before the typical season opening. An increased likelihood of warmer or drier conditions prompts the resort to prepare for additional snowmaking and develop contingency plans for a delayed opening or operations concentrated on higher terrain. Forecasts suggesting favourable conditions support more aggressive opening timelines and marketing. The resort recognizes that seasonal forecast skill remains limited, maintaining flexibility to adjust plans as forecasts are updated and actual conditions emerge. Weekly review meetings assess evolving conditions, and plans are updated accordingly.

In this illustrative scenario, the resort evaluates the approach over five years. It records a 15% improvement in resource efficiency, measured as the ratio of operational costs to revenue during the critical November–December period. More accurate matching of operations to actual snow conditions reduce waste from premature opening while allowing the resort to capture revenue from favourable years. Customer satisfaction metrics also improve because visitors encounter conditions more consistent with marketing communications. The resort shares its approach through the FIS network, enabling other facilities to adapt the methodology to their circumstances. This scenario illustrates how systematic integration of historical climate analysis, seasonal forecasts and adaptive management can improve outcomes even in the challenging context of declining natural snow reliability.

### 13.3 Glacier tourism adaptation

A glacier tourism operation in a European Alpine region faces fundamental challenges from accelerating glacier retreat. Historical attractions, including ice caves, crevasse viewing and glacier hiking, depend on stable glacier conditions. In this scenario, the glacier has lost more than 30% of its area since 1990 and is expected to lose substantially more under continued warming. Safety hazards increase as unstable ice and rock exposed by glacier retreat create dangerous conditions. Traditional tourism products become increasingly difficult to maintain, requiring a fundamental adaptation of the business model. The operation needs to understand likely future glacier conditions over time horizons of 20 to 30 years to inform major infrastructure investment decisions.

The operation engages glacier researchers from a national research institution and uses regional climate projections from EURO-CORDEX, combined with glacier-evolution modelling specific to its location. For illustrative purposes, the localized projections used in this scenario indicate that under moderate warming scenarios, the glacier could lose an

additional 40% to 50% of its current area by 2050, with retreat rates accelerating during the 2030s and 2040s. Under higher warming scenarios, glacier loss by 2050 could exceed 70%. These projections suggest that traditional glacier tourism products relying on stable glacier configurations will become increasingly difficult or impossible to maintain.

The operation develops a 20-year adaptation strategy based on these projections. Near-term investments focus on repositioning infrastructure to accommodate changing glacier geometry, with lift terminals and access points relocated to sites projected to remain viable for at least 15 years. Educational content shifts its emphasis from static glacier features to the dynamic process of glacier response to climate change, making glacier retreat part of the visitor experience and educational mission. Partnerships with climate researchers provide scientific content for interpretive materials and visitor programs. Diversification into non-glacier-dependent mountain activities, including summer hiking, mountain biking and cultural tourism, reduces the operation's dependence on glacier conditions.

The long-term adaptation strategy acknowledges that glacier tourism in its traditional form may not persist beyond mid-century under projected climate conditions. The business plan incorporates a gradual transition towards a mountain recreation and education centre that is not dependent on the presence of the glacier. Infrastructure investments are designed to allow the facilities to be repurposed. The operation also engages in climate-change communication and sustainable-tourism advocacy, positioning itself as a climate-change education destination. For demonstration purposes, the scenario assumes that an assessment conducted 10 years after implementation finds that the operation remains economically viable despite increasingly challenging glacier conditions. It also demonstrates the importance of assessing long-term viability realistically under projected climate conditions rather than assuming that historical operations can continue indefinitely.

### 13.4 Snowmaking optimization

A mid-sized North American ski resort faces escalating snowmaking costs as warming temperatures reduce the number of suitable snowmaking hours. In this scenario, energy costs have increased by 40% over a decade, partly because of higher electricity rates but also because of longer pumping times and less efficient operations at warmer temperatures. Water-availability constraints in the watershed limit snowmaking expansion. The resort therefore needs to optimize snowmaking efficiency to maintain adequate coverage within existing water and energy constraints. Traditional approaches based on simple temperature thresholds and operator judgment do not make full use of the limited periods with suitable conditions.

The resort implements an integrated snowmaking decision-support system combining medium-range temperature and humidity forecasts from the National Weather Service, from which wet-bulb temperature can be calculated; real-time SNOTEL data on watershed snowpack; streamflow observations from relevant hydrological networks; and snow-depth sensor data from an IoT network deployed across the ski facility. Optimization algorithms use this information to determine which slopes to prioritize given forecast conditions and strategic objectives. The system runs continuously during the winter season and is

updated every six hours as new weather forecasts become available. Operators receive daily recommendations on snowmaking priorities, expected suitable hours and implications for the available water budget.

The optimization approach considers multiple factors beyond temperature thresholds. Slopes scheduled to open earliest in the season receive priority to support timely opening. High-visibility slopes near base areas may also receive priority to support visitor satisfaction. Slopes with southern exposure or other characteristics that cause rapid snow degradation receive additional coverage to maintain quality throughout the season. The optimization algorithms balance these competing priorities while respecting water and energy constraints. Operators can override automated recommendations when local knowledge or current conditions indicate that adjustments are needed, although the system's default recommendations are used in most cases.

For demonstration purposes, the scenario assumes that an assessment after three years of implementation shows a 30% reduction in energy costs per unit of snow produced through more efficient use of optimal snowmaking windows and reduced operation during marginal conditions. Water consumption decreases by 15% through better targeting of snowmaking to areas providing the greatest operational benefit. The resort opens on or before its target date in each of the three years, despite below-average natural snowfall in two of them. The resort documents its approach and shares the results through industry conferences, allowing other ski facilities to consider how the methodology could be adapted to their circumstances. This scenario illustrates how the systematic integration of weather forecasts, real-time monitoring and optimization algorithms could improve snowmaking efficiency as suitable snowmaking conditions decline under warming temperatures.

# 14 Conclusions

Weather and climate information can support decisions across every stage of winter tourism operations, from immediate safety and snow-management decisions to seasonal planning and long-term investment. The most useful services combine authoritative observations and forecasts with local knowledge, clearly defined decision thresholds and procedures for updating plans as conditions change.

No single service or tool will meet every operational need. Ski facilities should identify the decisions most affected by weather and climate, assess the information already available through NMHSs and other trusted providers, and determine where additional monitoring, technical expertise or customized services may be required. Forecast uncertainty, data limitations and local differences in elevation, terrain, infrastructure and business models should be considered explicitly.

As climatic conditions continue to change, approaches based solely on historical experience will become less reliable. Regular review of operational thresholds, infrastructure assumptions and adaptation strategies will therefore be essential. Continued collaboration among ski facilities, meteorological services, researchers, public authorities

and technology providers can help translate advances in weather and climate science into practical services that support safer operations, more efficient resource use and informed long-term planning.

## 15 Acronyms and abbreviations

| | |
|---|---|
| AINEVA | Interregional Association for Snow and Avalanches |
| API | Application Programming Interface |
| AROME | Application of Research to Operations at Mesoscale |
| BOM | Australian Bureau of Meteorology |
| CFSv2 | Climate Forecast System Version 2 |
| CH2018 | Climate Scenarios for Switzerland 2018 |
| CH2025 | Climate Change in Switzerland 2025 |
| CMIP | Coupled Model Intercomparison Project |
| CMIP6 | Coupled Model Intercomparison Project Phase 6 |
| CMIP7 | Coupled Model Intercomparison Project Phase 7 |
| CNRM | National Centre for Meteorological Research |
| CORDEX | Coordinated Regional Climate Downscaling Experiment |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| ERA5 | Fifth-generation ECMWF atmospheric reanalysis |
| EURO-CORDEX | European branch of the Coordinated Regional Climate Downscaling Experiment |
| FCA | Financial Conduct Authority |
| FIS | International Ski and Snowboard Federation |
| GFS | Global Forecast System |
| GLAMOS | Glacier Monitoring in Switzerland |
| GLIMS | Global Land Ice Measurements from Space |
| GloSea6 | Met Office Global Seasonal Forecast System 6 |
| ICON | Icosahedral Nonhydrostatic forecasting system |
| IMS | Interactive Multisensor Snow and Ice Mapping System |
| INRAE | National Research Institute for Agriculture, Food and Environment |
| IPCC | Intergovernmental Panel on Climate Change |
| IoT | Internet of Things |
| JMA | Japan Meteorological Agency |
| MODIS | Moderate Resolution Imaging Spectroradiometer |

| | |
|---|---|
| NASA | National Aeronautics and Space Administration |
| NCCS | National Centre for Climate Services |
| NIWA | National Institute of Water and Atmospheric Research |
| NMHS | National Meteorological and Hydrological Service |
| NOAA | National Oceanic and Atmospheric Administration |
| NWS | National Weather Service |
| PRA | Prudential Regulation Authority |
| PROSNOW | Provision of a prediction system allowing for management and optimization of snow in Alpine ski resorts |
| SAGE | Sub-seasonal Applications for Agriculture and Environment |
| SEAS5 | ECMWF Seasonal Forecasting System 5 |
| SLF | WSL Institute for Snow and Avalanche Research |
| SMHI | Swedish Meteorological and Hydrological Institute |
| SNODAS | Snow Data Assimilation System |
| SNOTEL | Snow Telemetry |
| SSP | Shared Socioeconomic Pathway |
| WCRP | World Climate Research Programme |
| WGMS | World Glacier Monitoring Service |
| WIS 2.0 | WMO Information System 2.0 |
| WMO | World Meteorological Organization |
| WSL | Swiss Federal Institute for Forest, Snow and Landscape Research |
| WWRP | World Weather Research Programme |

# 16 Glossary

**Artificial intelligence:** Computer systems capable of performing tasks that typically require human intelligence, including learning from experience, recognizing patterns and making decisions.

**Avalanche:** Rapid downslope movement of snow, ice and debris that poses significant hazards to mountain infrastructure and human safety.

**Climate:** The statistical description of the atmosphere and climate system over extended periods, typically 30 years or longer, including average conditions and variability.

**Climate adaptation:** Adjustment of natural or human systems in response to actual or expected climate changes to moderate harm or exploit beneficial opportunities.

**Climate change:** Long-term change in the statistical properties of the climate system, including changes in average conditions, variability and the frequency of extreme events.

**Climate data:** Historical and real-time observations of the climate system along with outputs from climate models, accompanied by metadata describing measurement and processing methods.

**Climate mitigation:** Actions to reduce greenhouse gas emissions or enhance their removal from the atmosphere, limiting the magnitude of future climate change.

**Climate product:** Derived synthesis of climate data combining observations with scientific understanding to create user-relevant information.

**Climate projection:** Simulation of future climate conditions based on scenarios of greenhouse gas emissions and other forcing factors, describing statistical characteristics rather than specific events.

**Climate service:** Provision of climate information in ways that assist decision-making, requiring appropriate engagement with users and formats matching decision processes.

**Cryosphere:** All frozen water components of the Earth system, including snow, ice sheets, glaciers, sea ice, lake ice, river ice, permafrost and seasonally frozen ground.

**Digital twin:** Comprehensive computational model integrating multiple data sources and simulation capabilities to represent a physical system and enable optimization and scenario testing.

**El Niño-Southern Oscillation:** Irregular periodic variation in winds and sea surface temperatures in the equatorial Pacific Ocean, affecting weather patterns globally through atmospheric teleconnections.

**Ensemble forecast:** Set of multiple forecasts generated from slightly different initial conditions or model configurations, representing forecast uncertainty.

**Glacier:** Persistent body of ice formed from accumulated snow that deforms and flows under its own weight.

**Glacier mass balance:** Net change in glacier mass over a defined period, typically expressed as equivalent thickness change averaged over the glacier area.

**Internet of Things:** Network of physical devices embedded with sensors and connectivity enabling data collection and exchange for monitoring and control applications.

**Machine learning:** Subset of artificial intelligence focused on algorithms that improve automatically through experience and data without explicit programming for specific tasks.

**Nowcasting:** Very short-range forecasting typically covering the period from the present to approximately six hours in the future, often based on extrapolation of current observations.

**Numerical weather prediction:** Use of mathematical models of atmospheric physics and dynamics to forecast weather conditions based on current observations.

**Parametric insurance:** Insurance that provides payouts based on predefined parameters being met rather than actual losses incurred, enabling rapid payout and reduced transaction costs.

**Permafrost:** Ground that remains at or below 0 °C for at least two consecutive years, including soil, rock and any ice or organic material present.

**Reanalysis:** Systematic approach to producing comprehensive climate records by assimilating historical observations into numerical models to estimate the complete state of the climate system.

**Seasonal forecast:** Climate prediction covering periods from approximately one month to 12 months ahead, providing probabilistic guidance on temperature and precipitation.

**Snow water equivalent:** Depth of water that would result if a snowpack melted instantaneously, providing a measure of water content independent of snow density variations.

**Snowmaking:** Artificial snow production using specialized equipment that sprays water as fine droplets into cold air, causing freezing and deposition on ski slopes.

**Snow reliability:** Degree to which adequate snow cover can be expected for winter tourism operations, often quantified using thresholds such as the 100-day rule.

**Sub-seasonal forecast:** A forecast covering approximately two weeks to two months ahead, bridging medium-range weather forecasts and seasonal predictions.

**Weather derivative:** Financial instrument whose payout depends on specific weather parameters, providing a risk-transfer mechanism for weather-related financial exposures.

**Zero-degree level:** Altitude at which air temperature equals 0 °C. It provides a useful indication of freezing conditions but does not necessarily correspond directly to the rain–snow transition.

## 17 References


Abegg, B.; Morin, S.; Demiroglu, O. C. et al. Overloaded! Critical Revision and a New Conceptual Approach for Snow Indicators in Ski Tourism. *International Journal of Biometeorology* **2021**, *65*, 691–701. https://doi.org/10.1007/s00484-020-01867-3.

Commonwealth Scientific and Industrial Research Organisation (CSIRO); Bureau of Meteorology (BOM). *State of the Climate 2024*; Australian Government, 2024. https://www.csiro.au/en/research/environmental-impacts/climate-change/State-of-the-Climate.

Derksen, C.; Burgess, D.; Duguay, C. et al. Changes in Snow, Ice, and Permafrost across Canada. In *Canada's Changing Climate Report*; Bush, E.; Lemmen, D. S., Eds.; Government of Canada: Ottawa, 2019. https://changingclimate.ca/CCCR2019/chapter/5-0/.

François, H.; Samacoïts, R.; Bird, D. N. et al. Climate Change Exacerbates Snow-Water-Energy Challenges for European Ski Tourism. *Nature Climate Change* **2023**, *13*, 935–942. https://doi.org/10.1038/s41558-023-01759-5.

Glacier Monitoring Switzerland (GLAMOS). *Swiss Glacier Volume Change, Release 2025*, 2025. https://doi.org/10.18750/volumechange.2025.r2025.

Hendrikx, J.; Zammit, C.; Hreinsson, E. Ö. et al. A Comparative Assessment of the Potential Impact of Climate Change on the Ski Industry in New Zealand and Australia. *Climatic Change* **2013**, *119*, 965–978. https://doi.org/10.1007/s10584-013-0741-4.

Hock, R.; Rasul, G.; Adler, C. et al. High Mountain Areas. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.-O.; Roberts, D. C.; Masson-Delmotte, V. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2019. https://doi.org/10.1017/9781009157964.004.

Intergovernmental Panel on Climate Change (IPCC). *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.-O.; Roberts, D. C.; Masson-Delmotte, V. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2019. https://www.ipcc.ch/srocc/.

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2021. https://doi.org/10.1017/9781009157896.

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Lee, H.; Romero, J., Eds.; IPCC: Geneva, 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647.

International Ski and Snowboard Federation (FIS). *Climate Action Plan*; FIS, 2024. https://assets.fis-ski.com/f/252177/x/5d8c98c7d3/carbon-action-plan.pdf.

Jarraud, M. WMO at 75: A Shining Example of the Benefits of International Cooperation. *WMO Bulletin* **2025***, 74* (1); World Meteorological Organization (WMO). https://wmo.int/resources/wmo-bulletin/wmo-bulletin-vol-74-1-2025/wmo-75-shining-example-of-benefits-of-international-cooperation

Kawase, H.; Murata, A.; Yamada, K. et al. Regional Characteristics of Future Changes in Snowfall in Japan under RCP2.6 and RCP8.5 Scenarios. *SOLA* **2021**, *17*, 1–7. https://doi.org/10.2151/sola.2021-001.

Kotlarski, S.; Gobiet, A.; Morin, S. et al. 21st Century Alpine Climate Change. *Climate Dynamics* **2023**, *60*, 65–86. https://doi.org/10.1007/s00382-022-06303-3.

Matiu, M.; Crespi, A.; Bertoldi, G. et al. Observed Snow Depth Trends in the European Alps: 1971 to 2019. *The Cryosphere* **2021**, *15* (3), 1343–1382. https://doi.org/10.5194/tc-15-1343-2021.

Monteiro, D.; Morin, S. Multi-decadal Analysis of Past Winter Temperature, Precipitation and Snow Cover Data in the European Alps from Reanalyses, Climate Models and Observational Datasets. *The Cryosphere* **2023**, *17* (8), 3617–3660. https://doi.org/10.5194/tc-17-3617-2023.

National Centre for Climate Services (NCCS). *CH2018 – Climate Scenarios for Switzerland*; Swiss Confederation: Zurich, 2018. https://www.nccs.admin.ch/nccs/en/home/climate-change-and-impacts/swiss-climate-change-scenarios/technical-report.html.

National Centre for Climate Services (NCCS). *Climate Change Particularly Pronounced in Switzerland*; Swiss Confederation, 2025a. https://www.nccs.admin.ch/nccs/en/home/news-and-events/newsdetail.html/en/nccs/2025/11/klimawandel-in-der-schweiz-ch2025.html.

National Centre for Climate Services (NCCS). *Snow-scarce Winters*; Swiss Confederation, 2025b. https://www.nccs.admin.ch/nccs/en/home/climate-change-and-impacts/swiss-climate-change-scenarios/key-messages/snow-scarce-winters.html.

National Institute of Water and Atmospheric Research (NIWA). *Snowline Survey Reveals Continued Shrinkage of NZ Glaciers*; NIWA, 2024. https://niwa.co.nz/news/snowline-survey-reveals-continued-shrinkage-nz-glaciers.

Scott, M.; Lindsey, R. *Large Declines in Snowpack across the U.S. West*; National Oceanic and Atmospheric Administration (NOAA), 2022. https://www.climate.gov/news-features/understanding-climate/large-declines-snowpack-across-us-west.

Spandre, P.; François, H.; Verfaillie, D. et al. Climate Controls on Snow Reliability in French Alps Ski Resorts. *Scientific Reports* **2019**, *9,* 8043. https://doi.org/10.1038/s41598-019-44068-8.

Willibald, F.; Kotlarski, S.; Ebner, P. P. et al. Vulnerability of Ski Tourism towards Internal Climate Variability and Climate Change in the Swiss Alps. *Science of the Total Environment* **2021**, *784*, 147054. https://doi.org/10.1016/j.scitotenv.2021.147054.

Wobus, C.; Small, E. E.; Hosterman, H. et al. Projected Climate Change Impacts on Skiing and Snowmobiling: A Case Study of the United States. *Global Environmental Change* **2017**, *45*, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.04.006.

World Meteorological Organization (WMO). *State of the Global Climate 2024* (WMO-No. 1368). Geneva, 2025.

World Meteorological Organization (WMO). *Weather and Climate Services for Ski Resorts: A Practical Guide to Weather and Climate Services for Cryosphere Management and Tourism* (WMO-No. 1404). Geneva, 2026.