Chapter 9
Actionable Science for Snow Monitoring and Response

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1 Introduction

Snow is essential for the sustainability and survival of human society, and abnormal snow conditions can have catastrophic consequences (Alldredge and Silver 1988). Snow serves as a natural reservoir of water, particularly in mountainous and polar regions. It accumulates during winter and melts gradually in spring, releasing water into rivers and streams. For instance, in the Western United States, the Sierra Nevada snowpack provides vital water resources for millions of people and extensive agricultural operations in California's Central Valley (Serreze et al. 1999). Snow also serves as a catalyst for winter tourism and recreational activities, attracting visitors and supporting local economies in snow-dependent regions. In addition to its economic importance, snow information also helps regulate water runoff and mitigate flood risks during snowmelt. By gradually releasing water, snow also acts as a natural buffer, reducing the likelihood of sudden and overwhelming flooding events. From a broader perspective, snow can profoundly influence ecosystem dynamics and agricultural productivity (Rasmussen et al. 2012), because its insulating properties shield vegetation, crops, and soil from extreme cold temperatures during winter, allowing for their survival and providing crucial moisture when the snow gradually melts.

Despite its importance, the knowledge and research surrounding snow science have not always translated into actionable solutions for people having their livelihoods relying on snow. While scientific research provides invaluable insights into aspects of snow and its impacts, there is often a gap between scientific findings and their practical application. Challenges like limited resources, technological limitations, and communication barriers can impede the practical application of snow science. This chapter aims to explore the reasons behind this gap and shed light on the potential for making snow science more actionable. Scientific research and NOAA snow monitoring are indispensable in comprehending the aspects of snow and its impacts. The translation of scientific research into actionable information often requires simplification and practical adaptation. It involves distilling the complex findings into practical guidelines and recommendations that can be easily understood and implemented by stakeholders, such as policymakers, land managers, and the general public.

This chapter aims to highlight the importance of making snow science more actionable. It will introduce the advancements in research methods, technological innovations, and communication strategies that can facilitate the practical application of snow science findings. Eventually, we hope the chapter could inspire researchers, policymakers, and practitioners to collaborate and develop more actionable solutions that leverage the immense value of snow science for the benefit of society and the environment.

2 Current Practice in Snow Monitoring and Decision Making

Snow monitoring relies on advanced tools and techniques that employ a range of innovative approaches to gather detailed information about snowpack characteristics. One such technique is LiDAR (Light Detection and Ranging), which employs laser pulses to measure distances and create highly precise three-dimensional maps of the snowpack (Deems et al. 2013). LiDAR systems usually consist of a laser emitter, a scanning mechanism, and a receiver. The emitter releases short pulses of laser light that travel toward the ground surface. When these pulses encounter an object, such as a snowflake or the ground, they bounce back and are detected by the receiver. By measuring the time it takes for the laser pulse to travel to the object and return, LiDAR systems can calculate the distance and create a detailed representation of the snowpack's surface. LiDAR technology is particularly valuable in snow monitoring due to its ability to capture detailed snow depth measurements across vast areas. By flying an aircraft equipped with LiDAR sensors over a snow-covered region, researchers can collect data on the snowpack's thickness and its vertical and horizontal distribution. This data is essential for assessing snow accumulation, understanding snow water equivalent (SWE) (Jonas et al. 2009), and determining potential risks associated with snowmelt and avalanches. The high-resolution three-dimensional maps generated by LiDAR enable researchers to identify and analyze complex snow structures and features. These structures include cornices, snowdrifts, and layers within the snowpack, which are important factors in determining avalanche hazards and slope stability. LiDAR also allows for the estimation of parameters such as snow density, which is essential for hydrological modeling and assessing water resources associated with snowmelt (Deems et al. 2013).

Satellite-based sensors provide high-resolution images of snow-covered areas, enabling researchers to analyze spatial patterns and changes in snow extent over time. By integrating satellite observations with ground-based measurements and weather data, comprehensive snow monitoring systems such as the Snow Data Assimilation System (SNODAS) (Barrett 2003) have been developed. SNODAS incorporates satellite observations from sensors like Moderate Resolution Imaging Spectroradiometer (MODIS), which capture high-resolution images of snow-covered areas. These images provide valuable information about the extent and distribution of snow cover (Fig. 9.1). SNODAS also utilizes ground-based measurements collected from weather stations and snow telemetry (SNOTEL) sites (Serreze et al. 1999), which provide vital data on snow depth, snow water equivalent (SWE) (Jonas et al. 2009), and other snowpack properties. Weather data, including temperature, humidity, wind speed, and precipitation, are also integrated into the system. The assimilation process within SNODAS involves integrating these diverse data sources into a unified model framework. This involves accounting for various factors such as elevation, aspect, slope, vegetation, and land cover characteristics, which can influence snow accumulation and melt patterns. Through sophisticated algorithms and data assimilation techniques, SNODAS combines the observed and modeled

data to generate accurate snow cover and snowmelt information at high spatial and temporal resolutions.

Decision making in response to snowstorms involves multiple stakeholders, such as meteorologists, emergency management agencies, transportation authorities, and local governments. The process typically includes meteorologists using weather models and satellite data to predict the occurrence and severity of snowstorms. These forecasts help in alerting relevant authorities and preparing for potential impacts. Once a snowstorm is forecasted, authorities assess the potential risks and impacts, such as road closures, power outages, and disruptions to transportation and infrastructure. Based on the risk assessment, emergency management agencies and local governments develop response plans, mobilize resources, and communicate with the public to ensure preparedness. During a snowstorm, decision makers coordinate response efforts, such as snow removal, prioritizing critical services, and ensuring public safety. After the storm, recovery operations take place, including damage assessment, infrastructure repairs, and restoration of services (Fuchs and Bründl 2005). Compared to snow monitoring, snowstorm forecasting is a more complex task, and forecast accuracy can vary depending on various factors such as atmospheric conditions, topography, and storm dynamics (Mitchell et al. 1998). Effective coordination among multiple stakeholders is crucial for a timely response. Delays can occur if there is a lack of communication or coordination between meteorological agencies, emergency management organizations, and local governments. Developing robust early warning systems that can detect the onset of a snowstorm with greater precision can help in initiating response actions earlier, reducing the
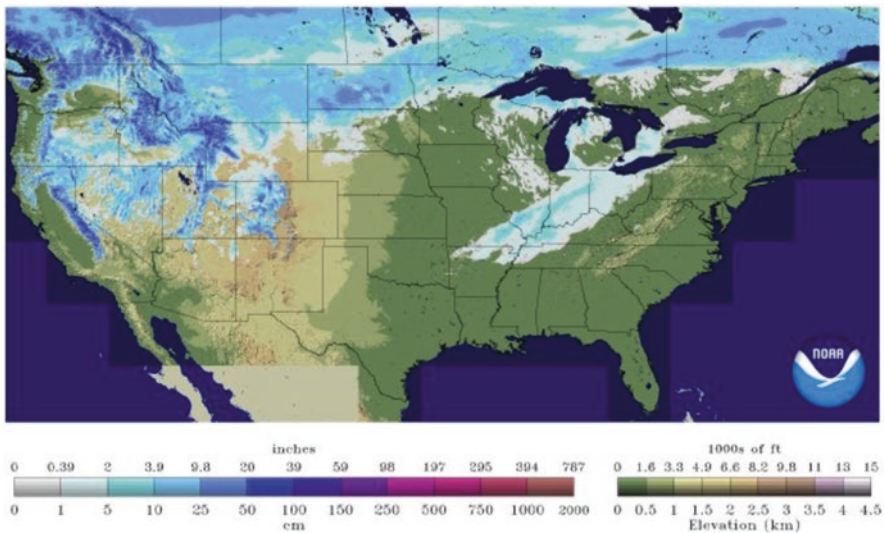

Fig. 9.1 Sample Snow Depth Output from SNODAS for January 15, 2015, United States, in addition to extending well into Canada as well as outlines the coast and contains parts of Mexico. (Image courtesy: NOHRSC)

time lag. Current snowstorm warning systems rely on a combination of weather radar, satellite imagery, weather stations, and meteorological models. Radar systems measure precipitation characteristics, while satellites provide valuable data on cloud cover and temperature (Zrnic et al. 2007). Ground-based weather stations offer real-time observations of temperature, humidity, and wind (Karabatić et al. 2011). These data sources are integrated into meteorological models to generate forecasts. To enhance these systems, radar technology can be improved by increasing resolution and incorporating dual-polarization capabilities to better identify precipitation types and estimate snowfall rates. Other potential upgrades include phased array radar which can enable rapid scanning of larger areas, and multi-frequency radar which can mitigate attenuation issues (Zrnic et al. 2007).

2.1 How Is Snow Monitored in Operation?

One of the primary methods used in snow monitoring is remote sensing. Satellites capture data in different spectral bands, enabling scientists to detect and analyze snow cover presence, extent, and changes. Several open-accessible satellites can fulfill this task, like MODIS and Visible Infrared Imaging Radiometer Suite (VIIRS) on terra and aqua. These images, combined with data from ground-based observations and weather stations, form the basis for monitoring and understanding snow dynamics. There are many scientific ground-based observation station networks such as SNOTEL which deploy sensors such as snow pillows and snow depth sensors to gather data (Yang et al. 2023). Located in various mountainous regions, these stations provide real-time measurements of snowpack characteristics. In Colorado, the SNOTEL network encompasses over 100 stations distributed throughout the state's Rocky Mountain region (Henn et al. 2017; Doesken & Schaefer 1987). Similarly, in the state of Utah, the SNOTEL network includes approximately 60 stations positioned across the Wasatch Range and other mountainous areas (Henn et al. 2017). These stations provide valuable real-time data on snowpack conditions, helping researchers, water managers, and avalanche forecasters make informed decisions. These measurements are essential for accurately assessing snow depth, snow water equivalent, and other critical parameters. The data collected by these ground-based networks, combined with satellite imagery, enhances the accuracy and reliability of snow monitoring efforts.

In addition to satellite remote sensing and ground-based observations, scientists also employ technology such as LiDAR to monitor snow. LiDAR technology measures the distance between the sensor and the snow surface, providing highly accurate and detailed information about snow depth, surface roughness, and snowpack structure. By conducting airborne LiDAR surveys across snow-covered areas, scientists can create high-resolution maps that depict variations in snow distribution and properties. These maps are invaluable for understanding snow dynamics, identifying avalanche-prone areas, and supporting land management decisions. The integration of satellite remote sensing, ground-based observations, and technologies

like LiDAR has made it possible to monitor snow more accurately, enabling scientists to obtain a comprehensive and detailed understanding of snowpack conditions, including its spatial variability, temporal changes, and underlying processes. This information enables more accurate avalanche forecasting, better water resource management, and improved decision-making.

2.2   What Does a Day of a Water Manager Look Like?

Snow melt is a significant source of water for downstream regions, particularly during the spring and early summer when snowpacks melt (Barnett et al. 2005). A water manager is responsible for ensuring a reliable water supply for various uses, including agriculture, industry, and domestic consumption (Seeger 1960). They monitor the snowpack, track snow melt rates, and allocate water resources to meet the demands of different stakeholders. A water manager's day typically begins with a thorough review of various data and reports related to water management, like analyzing weather forecasts, streamflow measurements, reservoir levels, and snowpack data (Seeger 1960). They closely work with meteorologists, hydrologists, engineers, and other experts to understand the complex factors influencing water availability (Seeger 1960). Regular meetings and discussions occur to exchange insights, share data, and develop strategies for effective water management. They also engage with stakeholders, including government agencies, local communities, and industry partners, to gather input and incorporate diverse perspectives into decision-making processes.

They often conduct site visits to reservoirs, dams, and water treatment plants to oversee their operation and ensure optimal performance (Gomes et al. 2020). Rigorous inspections, maintenance activities, and adherence to safety protocols are part of their duties. For instance, they may coordinate the controlled release of water from reservoirs to strike a balance between storage capacity, flood control, and downstream water requirements (Seeger 1960). They also monitor snow accumulation and snowpack conditions in mountainous regions prone to spring or rapid snowmelt floods, taking proactive measures to manage water levels in reservoirs and control water releases. By analyzing historical data, real-time observations, and climate projections, they evaluate the reliability and sustainability of water resources, helping develop strategies for water allocation, managing water rights, and planning for potential water shortages or drought conditions.

2.3   How Does the Snow Sport and Tourism Industry Operate?

Snow sports and tourism are very popular in recreation and are a major component in the tourism industry, especially in regions with favorable winter climates and mountainous landscapes. This industry encompasses various activities, including

skiing (Fig. 9.2), snowboarding, snowmobiling, ice climbing, snowshoeing, and more. The operation of snow sports and tourism involves several key aspects, including snow condition monitoring, ski resort management, safety measures, environmental considerations, and marketing strategies. These elements work together to create enjoyable and sustainable experiences for visitors while minimizing environmental impacts.

Snow condition monitoring is required by the operation of snow sports and tourism (Ross et al. 2020). Ski resorts and snow sports facilities have to closely monitor snowfall, snow depth, snow quality, and weather conditions to ensure optimal skiing and snowboarding conditions. Automated weather stations provide real-time information on snowpack, helping ski resort operators make decisions regarding trail maintenance, snow grooming, and avalanche control. Snow surveys and field observations are also conducted to assess snow conditions, including snowpack stability and avalanche risk. Trained personnel perform snowpack tests, analyze snow layers, and monitor weather patterns to ensure visitor safety (MacGillivray et al. 2006).

Safety is a top priority in snow sports and tourism (Bentley et al. 2004). Ski resorts normally implement measures to minimize risks and ensure the well-being of visitors. Trained ski patrol teams monitor the slopes, respond to accidents, and provide first aid when necessary. They also conduct avalanche control measures to reduce the risk of avalanches and maintain safe skiing conditions. For example, Whistler Blackcomb is one of the largest and most popular ski resorts in North America. It offers over 8171 acres of skiable terrain, world-class facilities, and hosted the alpine skiing events during the 2010 Winter Olympics. Ski resorts operate through effective management systems encompassing various aspects, including lift operations, slope maintenance, guest services, and accommodations. Modern ski resorts feature well-designed lift systems, including chairlifts, gondolas, and aerial tramways, to transport visitors efficiently across the mountain. Lift operators ensure the safe operation of lifts, monitor capacity, and maintain equipment. Meanwhile, slope maintenance involves snow grooming, trail marking, and signage to provide a safe and enjoyable skiing experience.

Environmental sustainability is an essential consideration in snow sports and tourism operations nowadays (Flagestad and Hope 2001). Ski resorts recognize the importance of preserving the natural environment and strive to minimize their ecological footprint. They implement practices such as water conservation, energy-efficient infrastructure, waste management, and environmental education programs. Some resorts have even adopted renewable energy sources, such as solar or wind energy, to reduce their reliance on non-renewable resources and lower greenhouse gas emissions. By prioritizing sustainability, ski resorts aim to protect the surrounding ecosystems and ensure the longevity of snow sports activities.

Research and innovation can definitely help in advancing snow sports and tourism, enhancing safety within the snow sports and tourism industry (Unbehaun et al. 2008). Scientists continuously study snow hydrology, climate change impacts, slope stability, and snowpack dynamics to understand better and manage snow resources (Steiger et al. 2019). This knowledge contributes to improved snow management techniques, safety protocols, and sustainable practices within the

industry (Blackburn 2004). Collaboration between scientists, industry stakeholders, and policymakers fosters the development of effective strategies for snow sports and tourism that balance environmental conservation, visitor safety, and economic growth.

2.4 How Does the Government Make Policies and Decisions About Snow?

Governments formulate policies and make decisions related to snow management. The government recognizes the need to address issues related to snow, such as snow removal, road maintenance, and safety concerns. This may arise from public demand, expert recommendations, or an analysis of past experiences and challenges faced during snowy seasons and then research and collect relevant data to understand the specific snow-related issues comprehensively. This involves studying snowfall patterns, analyzing road conditions, assessing the impact on transportation, and considering the economic and social implications. They engage with various stakeholders, including transportation departments, meteorological agencies, snow removal service providers, local communities, and experts in relevant fields

Fig. 9.2 Ski Lift of Winter Park Resort in Colorado. (Image courtesy: Dr. Ziheng Sun)

(Engelhard et al. 2007). This collaboration ensures the policy development process incorporates diverse perspectives, expertise, and practical considerations. The government establishes clear goals and objectives for snow-related policies based on research and stakeholder input. These goals include ensuring safe and efficient transportation, minimizing disruptions, reducing accidents, promoting environmental sustainability, and supporting economic activities like tourism and trade (Kuemmel and Kuemmel 1994). The government designs the policy framework that outlines the specific measures, guidelines, and regulations to address the identified issues. This may include provisions for snow removal strategies, road maintenance standards, allocation of resources, coordination mechanisms, and safety protocols (Miller 2020). The formulated policies are shared with relevant stakeholders and the public for feedback and consultation. This allows for further refinement, consideration of alternative perspectives, and identification of potential challenges or unintended consequences. Once the policies are finalized, the government begins implementing them. This involves allocating resources, establishing coordination mechanisms, and disseminating guidelines and regulations to the relevant departments, agencies, and service providers responsible for snow removal, road maintenance, and safety management. Governments continuously monitor the implementation of snow-related policies to assess their effectiveness and make necessary adjustments. They collect data on key performance indicators, such as accident rates, road conditions, transportation efficiency, and environmental impact, to evaluate the policy outcomes and identify areas for improvement.

For example, the Snow and Ice Control Policy implemented by the City of Toronto in Ontario, Canada, was created to address the challenges posed by snow and ice on city roads during winter and ensure safe and efficient transportation for residents (Audit of Winter Road Maintenance Program – Toronto 2023). The policy is developed and implemented by the Transportation Services division of the city government. The government took a comprehensive approach to snow removal, road salting, and maintenance activities. The policy is based on extensive research, analysis of weather patterns, and consultation with various stakeholders, including transportation experts, city officials, and community representatives. The policy outlines specific procedures and guidelines for snow removal and ice control operations. It includes criteria for prioritizing roads based on traffic volume, transit routes, emergency access, and school zones. The policy also establishes performance standards for snow clearing, specifying the maximum time allowed for snow removal after a snowfall event. To implement the policy effectively, the City of Toronto has a dedicated fleet of snowplows, salt spreaders, and other equipment. When a snow event occurs, the Transportation Services division activates its snow response teams and deploys resources strategically across the city. Snow Plows are first dispatched to clear major arterial roads, bus routes, and priority areas, followed by residential streets. The policy also emphasizes communication and public awareness. The city utilizes various channels, such as its website, social media platforms, and traditional media, to provide timely updates on snow removal operations, road conditions, and any necessary travel advisories. Residents are encouraged to stay informed and cooperate by following parking regulations during snow-clearing operations. In

addition, the policy includes provisions for continuous monitoring and evaluation. The Transportation Services division regularly assesses the effectiveness of snow and ice control operations, gathers feedback from residents, and identifies areas for improvement. This feedback loop helps to refine the policy and make necessary adjustments to enhance snow management practices.

The government's decision-making process involves several steps. Usually the initial thing done by meteorological agencies is to closely monitor weather patterns and collect data from various sources such as satellites and weather stations, analyzing this data to forecast snowstorms and their potential impacts (Mitchell et al. 1998). Based on the forecast, relevant government agencies, including transportation departments, public works departments, and emergency services, collaborate to assess the risks and impacts of snow on critical infrastructure and public safety. They exchange information, develop contingency plans, and coordinate resources. Once the assessment is complete, the government activates snow response operations, mobilizing snow removal teams, equipment, and resources to clear roads and public spaces. Snowplows, salt spreaders, and personnel are deployed based on predetermined criteria such as snow accumulation thresholds and visibility conditions (Campbell and Langevin 1995). Throughout the snow event, government agencies continuously monitor weather conditions and snowfall accumulation, updating their strategies and operations accordingly. After the snowstorm subsides, post-storm assessments are conducted to evaluate the effectiveness of the response, gathering feedback, assessing performance, and identifying areas for improvement. An example of effective government decision-making about snow can be seen in the case of the Massachusetts Department of Transportation (MassDOT). They have a comprehensive snow and ice control program in place, which includes pre-treating roads, deploying a large fleet of snowplows, and utilizing innovative technologies such as real-time weather and road condition monitoring. MassDOT's decision-making process ensures a proactive and efficient response to snow events, facilitating safe and reliable transportation for residents and visitors.

2.5   How Does the Snow Community Work and Live? What Science Knowledge Do They Use Every Day?

The snow community encompasses diverse examples of organizations dedicated to studying and living in snow-dominated environments. Take the Sami people for example. They are the indigenous inhabitants of Sápmi, a region that spans across northern parts of Norway, Sweden, Finland, and Russia (Kiniry 2020). The Sami have a deep connection with the snow and ice, relying on traditional knowledge and scientific understanding to navigate and adapt to their snow-covered surroundings. Their expertise in reindeer herding is vital for sustaining their way of life in harsh winter conditions. The Sami community's knowledge of snow and its ecological significance, passed down through generations, showcases the integration of

traditional knowledge and scientific insights in snow-related practices. IceCube Neutrino Observatory located at the South Pole is an example of a state-of-art research facility that uses a cubic kilometer of Antarctic ice as a detector to capture high-energy neutrinos from outer space (Deiana et al. 2022). By studying these neutrinos, scientists gain insights into astrophysical phenomena such as supernovae, and gamma-ray bursts. The observatory utilizes an array of optical sensors buried deep within the ice, taking advantage of the exceptional clarity and stability of the polar ice sheet. This project represents the intersection of snow and ice science with astrophysics, showcasing the interdisciplinary nature of the snow community.

In snowy mountainous regions, local communities have developed specific skills and knowledge related to snow and its management. Take, for instance, the mountain farmers in the Swiss Alps who practice traditional snow farming techniques. They understand the importance of water availability during drier months and employ ingenious methods to ensure a controlled supply. By managing snow accumulation, they can control the timing and rate of snowmelt, allowing for a steady release of water when it is most needed for agricultural purposes. This traditional practice demonstrates their deep understanding of snowpack properties and the local climate. Moreover, the architectural techniques employed by snow communities reflect their intimate knowledge of snow. Houses are constructed with steep roofs, often layered with insulating materials such as thatch or snow blankets, which prevent excessive snow buildup and minimize the risk of structural damage. Houses are strategically positioned to leverage natural slopes and wind patterns, allowing snow to slide off more easily (Valle 2023). These traditional building methods showcase the integration of local wisdom and scientific principles in creating resilient structures that withstand the harsh snowy conditions. Beyond these practical aspects, local snow communities rely on their observational skills and traditional indicators to navigate their surroundings safely. Through generations of experience, they have learned to interpret visual cues provided by the snow and the environment. By observing snow surface patterns, wind direction, and temperature gradients, they can discern variations in snowpack stability and potential avalanche risk (Riseth et al. 2011). This knowledge, combined with their understanding of local weather patterns and the behavior of different snow layers, enables them to make informed decisions about travel, hunting, and other outdoor activities. While they may not employ sophisticated scientific instruments, their day-to-day reliance on observation and interpretation exemplifies the practical science embedded in their way of life.

Across different snow-covered regions, diverse communities integrate scientific knowledge with their traditional practices to thrive in snow-dependent environments. For instance, Andes Mountains, communities like the Quechua and Aymara have devised sophisticated irrigation systems called "qanats" or "acequias" (Neuwirth 2021). These systems harness the power of snowmelt, precisely managing water resources through canals to sustain agriculture in arid high-altitude regions. By incorporating scientific insights on snow accumulation and the timing of meltwater release, these communities optimize water usage for crop cultivation,

showcasing the synergistic relationship between traditional knowledge and scientific principles in snow management (Eira et al. 2018).

In general, local snow mountainous communities face a range of hardships that require them to apply scientific knowledge and innovative techniques to overcome them. One significant challenge is the risk of avalanches, which is a constant concern for communities residing in avalanche-prone areas (Jamieson and Stethem 2002). In Alaska's Arctic communities, extreme cold temperatures, heavy snowfall, and frozen ground pose difficulties in maintaining essential services and infrastructure (Pastick et al. 2015). The Alaska Department of Transportation and Public Facilities (DOT&PF) constructs ice bridges on frozen rivers to create temporary roadways, allowing transportation of essential goods and services despite freezing temperatures. The impact of climate change on snow availability and quality presents significant challenges for snow communities. Indigenous communities like the Inuit in northern Canada utilize scientific principles in their traditional snow house, the igloo (Tremblay et al. 2006). The domed shape and insulating properties of igloos enable efficient heat retention, offering warmth in extremely cold conditions. By combining traditional wisdom with scientific approaches, they ensure their safety, adapt to changing environmental conditions, and develop innovative solutions for transportation, energy supply, and climate resilience. Through their resilience and resourcefulness, these communities showcase the successful integration of science and local knowledge in navigating the unique challenges of living in snowy environments.

3   Current Research in Snow Monitoring and Prediction

Current research in snow monitoring and prediction encompasses a range of cutting-edge topics that contribute to our understanding of snow processes, improve forecasting capabilities, and enhance snow-related decision-making. Scientists and researchers are continually pushing the boundaries of knowledge in this field, utilizing advanced technologies, innovative methodologies, and interdisciplinary approaches. In this section, we will explore some of the latest hot research topics in snow monitoring and prediction.

3.1   Rocky Mountains

This mountain range spans across western North America, including the United States and Canada. The Rocky Mountains provide a diverse range of snow conditions and are an important source of freshwater for downstream regions (Fig. 9.3). Pelto et al. (2019) focused on evaluating the feasibility of using remotely sensed methods to assess seasonal glacier mass balance. Tandem airborne laser scanning (ALS) surveys and field-based measurements were conducted over a 4-year period

on six alpine glaciers in British Columbia, Canada. Geodetic balance, winter balance, and summer balance were calculated using digital elevation models (DEMs) and density estimates based on surface classification. The study found that geodetic estimates of winter, summer, and annual balance were slightly different from glaciological measurements, with surface classification playing a significant role in geodetic annual mass change. The results demonstrate the potential of ALS and geodetic methods for accurately assessing seasonal mass change in multiple glaciers. Another study that highlights the challenges in accurately estimating snow water storage is conducted by Wrzesien et al. (2019), due to limited observational networks and satellite sensing limitations. Four global data sets showed moderate agreement in estimating global SWS, but when compared to high-resolution regional models, they differed significantly, with biases up to 66% and potential underestimation of SWS by 1500 km^3 (Wrzesien et al. 2019) globally. This emphasizes the need for further research to improve water resource characterization in snow-dominated regions, particularly in mountains. Machine-learning techniques have been widely used in monitoring and forecasting snow in the Rockies (Sun et al. 2022b). Cannistra et al. (2021) highlight the importance of optical remote sensing techniques in measuring snow-covered area (SCA) and their impact on physical, ecological, and societal systems. The development of a convolutional neural network-based method using high-resolution satellite imagery shows promise in accurately observing SCA at fine-scale spatial and temporal resolutions, offering potential applications in ecological and water resource research. Sun et al. (2022a) used Geoweaver to construct the full-stack SWE forecasting workflow to make the snow AI more FAIRable (findable, accessible, interoperable, and reusable) (Alnaim and Sun 2022; da Silva et al. 2023) (Fig. 9.3).

3.2 Himalayas

In the realm of monitoring and forecasting, Sood et al. (2020) examined snow cover variability over the North Indian Himalayas, including the Western Himalayas and Karakoram mountain ranges, using MODIS data (Jain et al. 2008). The findings reveal changes in snow cover area, with a one-month shift in snow accumulation and melt over the past decade, providing valuable information for climatology, hydrology, cryosphere, and glaciology studies. This research contributes to our understanding of snow processes and enhances snow monitoring and prediction capabilities in the North Indian Himalayas. Kirkham et al. (2019) present the use of a passive gamma ray sensor and complementary meteorological instruments at high altitude in the Nepal Himalayas to measure snow water equivalent (SWE) and snow depth. The findings highlight the accuracy and limitations of the instrument setup, emphasizing the importance of continuous monitoring for developing snow models and improving understanding of the high-altitude water cycle in data scarce regions. This information enhances our understanding of snow processes and contributes to improved climatology, hydrology, cryosphere, and glaciology studies in the region.

Fig. 9.3 Snow cover on Rocky Mountain. (Image courtesy: Dr. Ziheng Sun)

Using MODIS Terr and Aqua snow cover products, Sahu and Gupta (2020) focus on estimating the annual and seasonal snow cover area (SCA) in the Chandra basin, Western Himalayas. The study reveals that the average SCA observed during the study period was 84.94% of the basin area, with the highest and lowest values in 2009 and 2016, respectively. A strong correlation is observed between SCA and temperature, indicating the high sensitivity of SCA variability to temperature changes.

3.3 Alps

Alps have extensive snow cover and have significant impact on various aspects of life in the region, they stretch across several countries including France, Switzerland, Italy, Austria, Germany, Slovenia, and Liechtenstein. The mountain range runs approximately 1200 km (750 miles) in a crescent shape, from the Mediterranean Sea in the south to the Danube River in the north. Alps are known for their landscapes, high peaks, and diverse ecosystems, making them a popular destination for outdoor activities, tourism, and winter sports.

Poussin et al. (2019) focused on monitoring snow cover in the Gran Paradiso National Park in the western Italian Alps using Landsat satellite observations stored

in an Open Data Cube. The methodology includes temporal filtering and multi-sensor analysis to improve the estimation of snow cover area. However, the challenge of cloud cover still affects the accuracy of snow mapping from satellite data. Another study conducted by Lievens et al. (2022) explores the potential of the Sentinel-1 mission to monitor snow depth in the European Alps at sub-kilometer resolutions. The Sentinel-1 backscatter observations, particularly in cross-polarization, exhibit a strong correlation with regional model simulations of snow depth. An empirical change detection algorithm using radar backscatter changes is employed to retrieve snow depth, showing promising results with a spatiotemporal correlation of 0.89 compared to in situ measurements. The findings highlight the capability of Sentinel-1 to provide valuable snow estimates in mountainous regions, aiding applications such as water resource management, flood forecasting, and numerical weather prediction. Further research is needed to understand the underlying physical mechanisms of Sentinel-1's sensitivity to snow accumulation.

3.4 Other Regions and Global Study

Notarnicola (2020) used MODIS products from 2000 to 2018 revealing that approximately 78% of global mountain areas are experiencing a decline in snow cover, characterized by shorter snow cover duration and smaller snow cover area. Changes in snow cover are influenced by air temperature and precipitation, with implications for water resources, ecosystems, tourism, and energy production. However, the analysis is limited by the relatively short time period and uncertainties in snow cover estimates, particularly in complex terrain. In the domain of remote sensing, Tsai et al. (2019) use spaceborne remote sensing, particularly synthetic aperture radar (SAR), offer a valuable means of monitoring snow cover continuously, overcoming limitations such as cloud cover and polar darkness. This review discusses the advancements in SAR-based techniques, including interferometric SAR and polarimetric SAR, along with the integration of auxiliary data to improve snow cover analysis. The summary highlights the importance of monitoring snow cover and the potential of SAR for providing valuable insights into the cryosphere. Furthermore, studies conducted by Aves et al. (2022) in the Ross Island region of Antarctica collected snow samples and found microplastics present in all samples, with fibers and polyethylene terephthalate (PET) being the most common types. The research suggests that microplastics can be transported over long distances and may originate from both distant and local sources, including nearby research stations, highlighting the widespread presence of airborne microplastic pollution in Antarctica. Another interesting study by Zhang et al. (2019), based on long-term observational data, has found that the previously observed inverse relationship between central Eurasian spring snow cover and Indian summer monsoon rainfall has disappeared since 1990. This change is attributed to the altered regulation of mid-tropospheric temperature and land-ocean thermal contrast due to declining spring snow cover, indicating that Eurasian spring snow cover may no longer serve

as a reliable predictor of Indian summer monsoon rainfall in a changing climate. In the domain of monitoring and forecasting, Largeron et al. (2020) reviewed the challenges in monitoring and forecasting snow cover characteristics in mountainous regions and discussed the use of data assimilation techniques to improve estimates of snow water equivalent (SWE). It highlights the suitability of different data assimilation methods based on snow model complexity and available observations, providing recommendations for enhancing snow hydrology monitoring and prediction systems in mountainous areas.

4 Why Are These Studies Difficult to Be Used in Reality?

Not all the mentioned studies achieve this desired level of actionability. This inability to bridge the gap between knowledge and action poses a significant challenge, as it hinders the effective utilization of research findings and diminishes their potential impact. By unraveling the reasons behind non-actionability, we can gain a deeper understanding of how to enhance the relevance and practicality of scientific research, ultimately striving for research outcomes that make a tangible difference in addressing societal challenges.

Most snow cover variation studies currently emphasizes the scientific endeavors rather than providing practical guidance on addressing the observed concerning changes. Without clear and specific recommendations, stakeholders such as policymakers, resource managers, and local communities face difficulties in translating the Himalaya study's results into actionable measures and interventions tailored to their unique circumstances. First of all, the technology has limitations considering snow conditions can vary significantly within relatively small regions. The data generated by these snow studies might not offer the local specificity that snow communities require. Actionable decisions often need data at finer spatial resolutions to address localized challenges accurately (Yang et al. 2013). For instance, datasets from the MODIS or Synthetic Aperture Radar (SAR) sensors are typically collected on predefined schedules, and their availability might not align with the real-time or near-real-time decision-making needs of snow communities. For managing issues like avalanche risk, water resource planning, or emergency response during snow events, stakeholders require timely and up-to-date information. In addition, remote sensing data alone may not provide the contextual insights needed for actionable decision-making. While these data can indicate the presence or absence of snow cover, they may not offer information about factors like snowpack density, water content, or local terrain conditions, which are critical for various applications, including water resource management and avalanche forecasting (Vickers et al. 2020; Tsai et al. 2019; Hedrick et al. 2018). Meanwhile, the adoption of snow research outcomes for actionable decision-making can be operationally challenging as it usually requires integrating these result datasets into existing decision-support systems, ensuring data continuity, and maintaining technical infrastructure, all of which demand resources and expertise that may not be readily

available to snow communities. Last but not least, many snow covered regions, e.g., Himalayas, span multiple countries or jurisdictions. Geopolitical tensions, disputes over boundaries, resources, and differing national priorities can hinder collaborative efforts to address shared snow-related challenges. Lack of cooperation among countries and local communities with various culture can prevent the development of regionally coordinated strategies for collective snow management and effective climate adaptation.

Therefore, the absence of stakeholder involvement significantly hampers the study's actionability (Greenwood 2007). Failure to mention the engagement of relevant stakeholders and end-users limits the study's potential impact. Engaging stakeholders, including local communities residing in the snow-impacted region, policymakers, environmental agencies, scientific organizations, and non-governmental organizations (NGOs) working on climate change and natural resource management, is crucial to enhancing the study's actionability. Collaborating with these stakeholders allows researchers to gain valuable insights, validate findings, and develop specific actions and policies based on the study's outcomes. By incorporating diverse perspectives, knowledge, and expertise, the research can be aligned with the real-world needs and priorities of the stakeholders, increasing the likelihood of its findings being effectively utilized.

On the other hand, researchers should offer practical and tailored recommendations that go beyond presenting the analysis and findings. These recommendations may involve implementing improved snow monitoring systems given local available resources to enhance data collection and analysis capabilities. Additionally, suggesting community-based adaptation strategies can empower local communities to respond to changes in snow cover by utilizing their traditional knowledge and practices. Policy interventions, such as the development of sustainable land and water resource management policies, can also be proposed to mitigate the impacts of snow cover changes.

For example, Poussin et al. (2019) discussed the use of remotely sensed data to monitor and understand climate and environmental changes in mountain regions, with a focus on snow cover as a key variable. While the study provides valuable insights into the methodology for snow cover detection and its application to a case study in the western Italian Alps, it may have low actionableness in terms of public adaptability and scientific acceptance. The paper's highly technical nature is evident through the utilization of advanced remote sensing techniques, statistical analyses, and complex algorithms for snow cover detection. These methods may involve intricate image processing algorithms, spatiotemporal techniques, probability of snow approaches, and multi-sensor data fusion. Furthermore, scientists may employ specialized terminology related to remote sensing, such as Landsat data, Worldwide Reference System-2 paths and rows notation system, Collection 1 Level 1 data, green and shortwave Infrared (SWIR1) bands, and the snow observation from space (SOfS) algorithm (Frau et al. 2018). These technical aspects and specialized terminology can create barriers in understanding the intricacies of the study and its implications for climate change research and environmental management. Another factor that may limit the actionableness of the study is the lack of clear recommendations

or actionable steps for policymakers, resource managers, or other stakeholders. While the study highlights the importance of monitoring and understanding snow cover changes in mountain regions, it does not provide specific guidance on how to use this information to inform decision-making or take action to mitigate the impacts of climate change.

To increase the actionableness of the mentioned studies above, the researchers could take one step further to provide more specific recommendations. For instance, they could identify key areas or regions within mountainous environments where the methodology for snow cover detection could be applied effectively. By highlighting these specific areas, policymakers, resource managers, and stakeholders can better understand the relevance of the study's findings and how they can be translated into actionable steps. They could suggest prioritizing conservation efforts or implementing targeted adaptation measures in areas where snow cover changes pose significant ecological or socio-economic risks. Collaboration with local resource managers and policymakers is essential to translate the study's findings into practical management strategies. They can work closely with these stakeholders to identify specific areas where the methodology for snow cover detection can be integrated into decision-making processes. By demonstrating how remotely sensed data can complement sparse in situ observations and provide valuable insights into snow cover dynamics, the researchers can help inform land-use planning, conservation efforts, and climate change adaptation strategies in mountainous regions. They could also provide more specific guidance on how to use the information generated by the study to inform decision-making or take action to mitigate the impacts of climate change. For instance, they could suggest specific measures that could be taken to reduce the vulnerability of mountain communities to the impacts of snow cover changes, such as investing in water storage infrastructure or promoting alternative livelihoods that are less dependent on snow cover. By providing clear and actionable recommendations, the authors can help ensure that their research has a tangible impact on the ground.

5   Playbook to Advance Actionable Science in Snow

To maximize the impact of snow research, it is essential to bridge the gap between knowledge generation and practical action. This section provides detailed suggestions for snow scientists and stakeholders, targeting those already familiar with the field. By focusing on specific areas such as methodology advancements, stakeholder engagement, and actionable recommendations, we aim to enhance the relevance and application of snow research findings.

5.1 Suggestions for Snow Scientists

Understanding the needs, concerns, and constraints of stakeholders such as policy-makers, land managers, and local communities is vital for aligning research objectives with real-world problems. In addition to considering end-users, snow scientists must also take into account the actual costs associated with their research. While advanced technologies like Unmanned Aerial Vehicles (UAVs) with Light Detection and Ranging (LiDAR) may offer exciting possibilities, their financial feasibility should be carefully evaluated. Instead of relying solely on expensive and complex technologies, scientists should explore cost-effective alternatives that can still yield reliable and actionable results. Realistic barriers faced by people in snow-covered areas should also be acknowledged and factored into research design. Accessibility, equipment availability, and manpower limitations are all practical constraints that need to be considered. By developing research methodologies that can be implemented within these constraints, scientists can ensure that their findings are feasible and can be readily applied in real-world scenarios.

Time constraints are an important consideration for snow scientists conducting research in snow-covered areas (Bates 2021). Efficiently managing research activities within limited time frames is essential to ensure the collection of high-quality data and maximize the impact of the research (Durre et al. 2010). Scientists need to carefully plan research activities, taking into account the seasonal variations and weather patterns specific to the study area. Understanding the optimal timing for data collection, such as peak snowfall periods or stable snow conditions, enables scientists to capitalize on favorable weather and snow conditions, ultimately maximizing the opportunities for data acquisition. Streamlining fieldwork logistics can maximize efficiency, such as careful planning of transportation routes, minimizing travel time between sampling sites, and optimizing data collection workflows. Using efficient data collection techniques and equipment that require minimal setup time can also help maximize the productivity of fieldwork. To achieve these objectives, scientists can explore partnerships with equipment manufacturers, research institutions, or governmental agencies that may provide access to necessary equipment (Etzkowitz 1983). Adapting or developing low-cost alternatives or open-source solutions for measuring snow properties can help mitigate equipment availability challenges. Finding qualified personnel or local expertise in snow research can be difficult, particularly in remote areas. Scientists should invest in capacity building and knowledge transfer by organizing training programs or workshops for local communities, students, or researchers. By building local capacity, scientists can create a network of individuals with the necessary skills and expertise to assist in data collection and analysis. To manage costs effectively, scientists can seek funding opportunities specifically designed for snow-related research, such as grants or fellowships. National and international research funding agencies often provide grants, fellowships, and research funding opportunities for various scientific disciplines, including snow science. Examples of such organizations include the National Science Foundation (NSF), European Commission's Horizon Europe

program, Natural Sciences and Engineering Research Council of Canada (NSERC), and Japan Society for the Promotion of Science (JSPS). Collaborative research projects between different countries or institutions can be a valuable avenue for sharing financial burdens and accessing resources. International programs and initiatives like World Climate Research Programme (WCRP) may offer funding opportunities or facilitate collaborations among snow scientists (Schiffer and Rossow 1983).

5.2   Suggestions for Decision Makers

For decision makers involved in funding allocation and policy making for snow monitoring, establishing a robust connection between scientific research and the decision making process is essential. Adopting advanced snow monitoring drones and leveraging their accurate and real-time data enables decision-makers to make informed assessments of risks, allocate resources effectively, and make timely decisions.

Decision-makers should prioritize key monitoring needs based on the significance and urgency of monitoring specific variables. For example, allocating resources for monitoring snowpack stability in high-risk avalanche-prone areas helps identify hazards and mitigate risks. Neglecting to prioritize these needs can lead to inadequate data collection, increased vulnerability to disasters, and potential loss of life and property. Collaborating with funding agencies is instrumental in securing financial support for snow monitoring programs. By effectively communicating the value of actionable science in snow monitoring, decision-makers can increase the likelihood of receiving the necessary funding. This collaboration empowers decision-makers to leverage additional resources, enabling them to enhance data collection capabilities, upgrade equipment, and improve response capabilities. Adequate financial support ensures accurate assessment of snow conditions, facilitates accurate avalanche forecasting, and empowers decision-makers to implement timely and effective mitigation measures to safeguard communities and critical infrastructure. Allocating a portion of the budget to technological advancements is essential for elevating the accuracy and efficiency of snow monitoring. By investing in cutting-edge technologies, sensor systems, and data processing tools, decision-makers can enhance their capabilities in assessing snow conditions. Utilizing advanced equipment enables decision-makers to accurately determine snow cover extent, predict snowmelt runoff, and effectively manage water resources. This strategic allocation of funds supports informed decision-making, aids in resource planning, and improves overall snow monitoring capabilities.

5.3 Suggestions for Snow-Impacted Communities

Snow-impacted communities face unique challenges when it comes to water availability and resource management for both high- and low-altitude areas (Jerez 2021). High-altitude regions experience heavy snowfall and prolonged snow cover characteristic of these areas necessitate careful consideration when implementing snow harvesting and storage practices. The design and construction of storage facilities should account for the potentially larger snow accumulation and the need for increased storage capacity to accommodate the substantial snow loads (Meløysund et al. 2006). Science-based techniques, such as snow density profiling and water content measurements, can aid in accurately estimating the amount of water stored in the snowpack and optimizing the capacity calculations (Proksch et al. 2016). Given the significant temperature fluctuations in high-altitude regions, which can lead to freeze-thaw cycles, insulation materials and storage designs must be tailored to minimize snowmelt and preserve the water resource effectively (Hamada et al. 2007). Meanwhile, the challenging accessibility of high-altitude regions during winter necessitates careful planning of infrastructure development and transportation logistics to ensure efficient snow collection, storage, and distribution.

To ensure the quality and safety of the harvested water, common water treatment methods such as filtration, sedimentation, and disinfection are commonly employed in snow-impacted communities (Harper et al. 2011). High-altitude regions can benefit from advanced water treatment technologies like UV disinfection or reverse osmosis, providing additional layers of protection if necessary. It is equally important to focus on the design and optimization of water distribution systems and infrastructure to efficiently deliver the stored water to the community. Considerations such as pressure, flow rate, and water demand should be taken into account to ensure a reliable and sufficient water supply that meets the needs of the community.

In contrast, some arid regions face distinct considerations in snow harvesting and storage due to lower snowfall variability and shorter snow cover periods. These areas often experience less snowfall, making it important to optimize snow collection efficiency during periods of intense snowfall. Techniques such as snow fences or catchment structures can be employed to enhance the effectiveness of snow collection. In low-altitude regions where snowmelt is relied upon for drinking water supply, careful attention must be given to water quality and the risks of contamination. Robust water treatment processes, including filtration and disinfection, should be implemented to address potential pollutants or impurities associated with low-altitude snowmelt. Moreover, the higher evaporation and sublimation rates in low-altitude regions require careful monitoring and modeling to estimate water losses and optimize storage capacities accordingly. In addition to these standard methods, low-altitude regions may also need to address specific contamination risks associated with pollutants commonly found in urban or agricultural environments. Water treatment technologies, such as activated carbon filters or ion exchange systems, can be employed to address these specific challenges.

In regions with varying altitudes, the incorporation of snow-sensitive designs into buildings and infrastructure can bring significant advantages. In high-altitude snow regions, where heavy snowfall and prolonged snow cover are common, it is essential to prioritize building designs that can safely withstand snow loads. Sloped roofs with adequate load-bearing capacity are crucial in preventing excessive snow accumulation and reducing the risk of roof collapse. By providing a steeper angle for snow to slide off, sloped roofs help alleviate the weight burden on structures (O'Rourke et al. 1982). Furthermore, incorporating materials such as steel or reinforced timber trusses enhances the structural integrity and resilience of buildings in the face of heavy snow loads. High-altitude communities can also consider utilizing snow sheds or snow fences strategically placed to create windbreaks and minimize snow accumulation in critical areas, such as access roads or pedestrian pathways. These measures, combined with regular monitoring and snow removal efforts, contribute to safer and more resilient built environments in high-altitude snow regions. During periods of abundant snowfall, communities can strategically stockpile excess snow in designated storage areas. Insulating materials or cooling systems can then be employed to preserve the stored snow, protecting it from external factors such as sunlight, temperature fluctuations, and wind erosion. By carefully managing the distribution of the stored snow, ski resorts and communities can ensure a consistent and high-quality snow base, even during periods of low snowfall. In both high- and low-altitude regions stockpiling excess snow during periods of abundant snowfall, communities can ensure a longer and more reliable skiing season. Preserving the stored snow using insulating materials or cooling systems helps maintain optimal snow conditions, allowing ski resorts to operate even during periods of low natural snowfall. This extension of the skiing season attracts more visitors and boosts the local economy.

Residents in regions prone to snowstorms should establish a dependable and regularly maintained snow removal strategy to swiftly clear pathways, streets, and entrances for safe movement. Stay informed about weather forecasts and road conditions, and if necessary, limit travel during severe snowstorms. Implement proactive measures such as installing snow-retention structures on rooftops and strategically trimming trees to prevent sudden snow slides or damage. Strengthen home's insulation and weatherproofing to conserve heat and reduce energy costs during extreme cold.

The level of implementation and adoption of these practices can vary from community to community. Some regions may have embraced these approaches extensively, while others may still be in the early stages of exploration and implementation. The decision to implement these practices rests with the communities themselves, considering their specific needs, resources, and long-term sustainability goals.

5.4 Suggestions for Downstream Water Users

Snow melt water users should leverage as many of the available datasets as possible, like remote sensing data from satellites like MODIS and AMSR-E, combined with ground-based measurements and citizen science initiatives like the Community Snow Observations project, to gain a comprehensive understanding of snow conditions. This enables informed decision-making regarding water management. Fostering collaboration and data sharing among stakeholders is vital. Snow melt water users should actively engage with local communities, scientists, and water management agencies to exchange knowledge and data. The SNODAS system, operated by the NSIDC (Barrett 2003), integrates various data sources to provide accurate snow cover and snowmelt information. By participating in such platforms, users can access a broader range of data and expertise, leading to improved water management strategies. Diversifying water sources is essential for reducing dependence solely on snow melt water. Users can explore alternative sources, including rainwater harvesting and groundwater recharge, to supplement their water supply. Engaging stakeholders and local communities is essential for effective snow melt water management. Community-based organizations, such as the CSAS in Colorado (Landry et al. 2014), actively involve local communities in snow monitoring, data collection, and water management efforts. By providing training and resources, these organizations empower communities to contribute their traditional knowledge and observations, enhancing the overall understanding of snow dynamics and improving water management strategies.

Addressing the challenges posed by climate change is of paramount importance. Snow melt water users should consider the long-term implications of climate change on snow accumulation and melt patterns. Collaborative research projects, such as the "Climate Impacts on Snow in the Pacific Northwest" initiative, integrate climate models with snow observations to assess future water availability and inform adaptation strategies. This knowledge enables users to adjust water allocation plans, implement water-saving technologies, and develop resilience measures to mitigate the impacts of climate change.

5.5 Suggestions for Snow Sport and Tourism Industry

One area for improvement is the management of snow resources. Snow sport and tourism industry stakeholders should focus on sustainable snowmaking practices to mitigate the impacts of climate change and ensure optimal snow conditions for skiing and other winter activities. This involves using efficient snowmaking systems, such as automated snow guns that produce high-quality snow with minimal water consumption. An exemplary case is to enhance snowpack monitoring and avalanche forecasting capabilities. This can be achieved through the integration of advanced technologies such as ground-based remote sensing instruments and satellite

observations. For instance, the International Centre for Integrated Mountain Development (ICIMOD) (Schild 2008) and the Government of Nepal have utilized remote sensing data from satellites like Sentinel-1 to monitor snow cover and assess avalanche risks in the Himalayas. Implementing similar technologies and collaborations can improve safety measures and inform decision-making processes for snow sport and tourism activities. Furthermore, the industry can benefit from promoting climate change adaptation strategies. This involves diversifying winter tourism offerings beyond traditional snow-dependent activities. For instance, in regions experiencing reduced snowfall, developing alternative attractions like snowshoeing, cross-country skiing, or indoor winter sports facilities can help maintain tourism revenue and sustain local economies. The Swiss Alps provide an example where ski resorts have successfully expanded their offerings to include adventure parks, wellness centers, and cultural events, attracting tourists year-round.

The industry should also prioritize the preservation of natural habitats and ecosystems. Ski resorts can adopt environmentally friendly practices, such as minimizing the expansion of ski slopes into ecologically sensitive areas and implementing habitat restoration initiatives. The "Sustainable Slopes" program by the National Ski Areas Association (NSAA) (Rivera et al. 2006) in the United States serves as a benchmark for ski resorts committed to environmental stewardship, promoting initiatives like waste reduction, renewable energy use, and water conservation. Engaging in research partnerships, such as the Mountain Research Initiative (MRI) (Adler et al. 2020), enables the industry to access scientific expertise and enhance their understanding of climate change impacts on mountain regions. This knowledge can inform decision-making processes and contribute to the development of adaptation strategies tailored to specific regions and resorts.

6 Successful Use Cases of Snow Science

6.1 The Canadian Avalanche Association

The CAA has been at the forefront of employing snow science practices to enhance public safety in avalanche-prone areas of British Columbia, Canada. The region's rugged terrain and heavy snowfall attract outdoor enthusiasts, but also pose significant risks. The CAA recognized the need for effective risk management strategies and implemented an integrated approach, including avalanche forecasting, snowpack monitoring and research, education and outreach, and collaboration with stakeholders. By providing actionable information and promoting widespread adoption, the CAA has successfully addressed the issue of avalanche hazards, ensuring public safety in the region.

To tackle the avalanche risks in British Columbia, the CAA established an extensive avalanche forecasting and warning system (Stethem et al. 2003). Highly trained avalanche forecasters collected and analyzed data on snowpack conditions, weather

patterns, and historical avalanche activity. The integration of advanced snow science techniques enabled the generation of daily avalanche bulletins and advisories, which provided the public with real-time information on hazards and recommended safety measures. This actionable approach empowered individuals, including backcountry users and winter sports enthusiasts, to make informed decisions and take appropriate precautions, such as route planning and slope avoidance. In addition, the CAA conducted thorough snowpack monitoring and research programs to better understand the region's snow characteristics and their contribution to avalanche formation. Field observations, including snow stability tests and snow profile analysis, were performed regularly to assess the stability and structural integrity of the snowpack. These scientific insights not only improved the accuracy of avalanche forecasts but also informed the development of standardized safety protocols. Through collaboration with governmental agencies, ski resorts, search and rescue organizations, and local communities, the CAA ensured a coordinated response to avalanche risks. This collaboration included data sharing, joint research projects, and integrating avalanche information into regional emergency response plans. By fostering partnerships and sharing expertise, the CAA optimized resources and promoted a culture of safety among stakeholders.

The Canadian Avalanche Association's application of snow science practices in British Columbia exemplifies a proactive and actionable approach to addressing avalanche risks. By employing an integrated system of forecasting, monitoring, education, and collaboration, the CAA has successfully enhanced public safety. The CAA's dedication to advancing snow science, fostering partnerships, and raising public awareness has made a significant impact on minimizing accidents and fatalities in avalanche-prone areas of British Columbia.

6.2 The Swiss Alps, Switzerland: Swiss Data Cube Project

In the Swiss Alps, renowned for their snow-covered landscapes and thriving winter tourism industry, scientists, local communities, and policymakers have come together to address the challenges posed by a changing snow environment (Jonas et al. 2009). This collaborative effort led to the establishment of the Swiss Data Cube project, a groundbreaking initiative that took place from 2016 to 2019 (Chatenoux et al. 2021). Involving researchers, data scientists, government agencies, and local communities, the project aimed to leverage Earth Observation data to monitor and understand climate and environmental changes in mountain regions. As part of this endeavor, remote sensing data from the Landsat series, spanning from 1984 to the present (Sun et al. 2019), was compiled and integrated into one comprehensive dataset. By combining traditional knowledge with scientific data, the project gained a deeper understanding of snowpack variability, ice conditions, and associated risks. This collaboration led to the development of culturally appropriate early warning systems for hazards like thin ice and unstable snow cover, ensuring the safety of community members engaged in traditional activities. Land-use

planners and policymakers also benefited from the Swiss Data Cube dataset. The comprehensive snow cover and snow depth information supported evidence-based decision-making in managing water resources, conserving biodiversity, and planning infrastructure projects in mountainous regions. The impact of the Swiss Data Cube project extended beyond Switzerland, serving as an inspiring example of successful collaboration and actionable research in snow-dependent regions worldwide. The comprehensive dataset and methodologies developed during the project have inspired similar initiatives in other countries facing similar challenges. By sharing their experiences and knowledge, the Swiss researchers and stakeholders involved have contributed to a global understanding of the importance of integrating traditional knowledge and scientific expertise to address the impacts of climate change on snow-dependent ecosystems and livelihoods.

Through the Swiss Data Cube project, several positive outcomes were achieved, such as improved monitoring and decision-making in various sectors (Chatenoux et al. 2021). However, there were also challenges and potential areas for improvement that could have been avoided with more careful consideration. One such aspect is the accessibility and usability of the data. While the project successfully compiled a vast amount of remote sensing data, there could have been more emphasis on making it easily accessible and user-friendly for a wider range of stakeholders. This could have involved developing intuitive interfaces, providing training and support for data interpretation, and ensuring that the data is readily available in formats compatible with various analysis tools. Another aspect that could have been better addressed is the engagement of local communities throughout the project's duration. Although the project acknowledged the importance of traditional knowledge and involved local communities in certain stages, there could have been more proactive efforts to ensure their meaningful participation from the inception to the implementation of the project. This could have included establishing regular dialogue, fostering partnerships, and integrating traditional knowledge more deeply into the research and decision-making processes. By doing so, the project could have benefited from a broader range of perspectives, increased community ownership, and improved the relevance and applicability of the research outcomes.

7   Conclusion

The integration of scientific knowledge into snow monitoring practices plays a vital role in understanding and effectively managing snow resources. By leveraging scientific advancements and embracing innovative approaches, stakeholders of snow monitoring can enhance their capacity to adapt to changing snow conditions and improve the sustainable management of snow. Moving forward, it is essential for communities to focus on certain key areas and further improve their snow monitoring efforts. Firstly, enhancing snow accumulation and melt forecasting accuracy can provide valuable information for water resource planning, agriculture, and infrastructure management. By investing in research and technological advancements,

communities can improve the predictive capabilities and lead time for snow-related events, enabling better preparation and response. Communities should strive to deepen their understanding of the impacts of climate change on snow dynamics. By conducting research and monitoring, they can gain insights into the changing patterns of snow accumulation, melt rates, and overall snowpack characteristics. This knowledge will enable communities to develop adaptive strategies to mitigate risks and adapt their practices accordingly.

Community engagement and public awareness initiatives are also mandatory in advancing snow practices. By involving local communities in data collection, monitoring, and decision-making processes, communities can benefit from the wealth of traditional knowledge and observations. Furthermore, raising awareness about the importance of snow monitoring and its implications for various sectors, including water management, agriculture, and tourism, will foster a culture of informed decision-making and collective responsibility. By prioritizing research, collaboration, community engagement, and public awareness, communities can harness the power of scientific knowledge in snow-centered activities to improve the quality of life for individuals living in snow-dependent regions. Embracing these improvements will pave the way for more sustainable and adaptive practices, ensuring the long-term resilience and well-being of communities in the face of changing snow conditions and associated challenges.

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