ICIMOD Working Paper 2017/7

ICIMOD

FOR MOUNTAINS AND PEOPLE

In Situ Monitoring of Mountain Glaciers

Experiences from Mountain Ranges around the World and Recommendations for the Hindu Kush Himalaya

UNI FR

UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

CENTRO DE ESTUDIOS AVANZADOS EN ZONAS ÁRIDAS
CEAZA

About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush Himalaya – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

ICIMOD gratefully acknowledges the support of its core donors: the Governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom.

ICIMOD Working Paper 2017/7

In Situ Monitoring of Mountain Glaciers

Experiences from Mountain Ranges around the World and Recommendations for the Hindu Kush Himalaya

Contributing Authors

Dorothea Stumm[1], Sharad Prasad Joshi[1], Nadine Salzmann[2], Shelley MacDonell[3]

[1] International Centre for Integrated Mountain Development, GPO Box 3226, Kathmandu, Nepal

[2] Department of Geosciences, University of Fribourg, Chemin du Musée 4, 1700 Fribourg, Switzerland

[3] Centro de Estudios Avanzados en Zonas Áridas, Universidad de La Serena, Campus Andrés Bello, Raúl Bitrán 1305, La Serena, Chile

International Centre for Integrated Mountain Development, Kathmandu, Nepal, May 2017

Published by
International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal

ISBN 978 92 9115 471 5 (printed) 978 92 9115 472 2 (electronic)

Production Team
A. Beatrice Murrey (Consultant editor)
Christopher Butler (Editor)
Dharma R Maharjan and Punam Pradhan (Layout and design)
Asha Kaji Thaku (Editorial assistant)

Corresponding author: Dorothea Stumm, dorothea.stumm@icimod.org

Photos: CEAZA archive – 8; Dorothea Stumm – cover, 4b, 5, 9, 10, 11; Sharad Prasad Joshi – 3, 4a, 6; Shelley MacDonell – 4c

Cover photo: The field team drills a hole into Yala Glacier, Nepal, to install bamboo stakes for glacier mass balance measurement

Note
This publication is available in electronic form at www.icimod.org/himaldoc

Citation: Stumm, D., Joshi, S.P., Salzmann, N., MacDonell, S. (2017) *In situ monitoring of mountain glaciers: Experiences from mountain ranges around the world and recommendations for the Hindu Kush Himalaya*. ICIMOD Working Paper 2017/7. Kathmandu: ICIMOD

Contents

Acknowledgements

This work was supported by ICIMOD's Cryosphere Initiative funded by Norway, and core funds of ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom.

Summary

Mountain glaciers are important climate indicators, impact on downstream water availability and sea level rise, and potentially influence natural hazards. However, field-based glacier measurements are sparse, especially in remote high mountain ranges. This paper compares and contrasts the challenges of fieldwork in the Nepalese Himalayas, New Zealand, the European Alps, the semiarid Andes, and the McMurdo Dry Valleys in Antarctica. Based on this, it distils a set of recommendations for institutions who plan to set up new glacier monitoring programmes in the Himalayas. Key aspects influencing the quality and sustainability of long-term monitoring programmes are skills, physical setting, and funding.

Introduction

Mountain glaciers are important climate indicators and glaciers are considered essential climate variables (ECV) by the Global Climate Observing System (GCOS). Understanding glacial change is necessary to predict future water availability, to assess potential hazards, and to estimate the contribution of glacier melt to sea level rise (Vaughan et al., 2013). In situ measurements are one of the key methods for improving our understanding of climate-glacier interactions. Field-based annual mass balance measurements, in particular, can be used as direct and immediate climate indicators. A combination of these measurements with hydro-meteorological information provides an excellent basis for improving understanding of the relationships between glaciers and the local climate, as well as estimates of glacial and snow contribution to river discharge (e.g. Anderson et al., 2010). Such information is important for policy makers, planners, and industry to estimate, and adapt to, downstream water availability, for example for hydropower plants, irrigation, or drinking water (e.g. Salzmann, Huggel, Rohrer, & Stoffel, 2014). They are also important to raise awareness about and sensitise local people to the changes in the glaciers that feed their rivers. Field measurements are essential to understand glacial dynamics and processes and to assess possible risks, such as glacial lake outburst floods (GLOFs) (Mool, Bajracharya, & Joshi, 2001).

Better understanding of what is happening to the glaciers requires a comprehensive research strategy that includes in situ measurements, remote sensing techniques, and modelling approaches. In situ measurements provide the necessary information for understanding large-scale and small-scale processes as they enable ground truthing and can be used for calibrating both remotely-sensed information and modelled output. Remote sensing analyses are used in models to scale up results to larger areas and to cross check field measurements with an independent method. The models can then be used to project future scenarios, for example for water availability. However, in the Himalayan region frequent cloud cover during the monsoon and seasonal snow cover make it difficult to obtain suitable freely available satellite images for small-scale applications. In addition, the very steep mountainous terrain decreases data accuracy and mountains often obscure parts of the area of interest. Thus ground-based information is necessary to georectify satellite images and verify data. But the availability of such in situ data in the Himalayan region is low (Bolch et al., 2012; Kääb, Berthier, Nuth, Gardelle, & Arnaud, 2012) due to the challenging nature of glacier fieldwork, the cost of expeditions, and the high level of fitness and experience required by the monitoring team. Glacier mass balance monitoring programmes have been established in many major mountain ranges in the world (Zemp, Hoelzle, & Haeberli, 2009; Nussbaumer et al., 2017), however, the challenges in carrying out fieldwork are manifold, and depend on the climate, topography, available financial and human resources, and infrastructure in the specific environment.

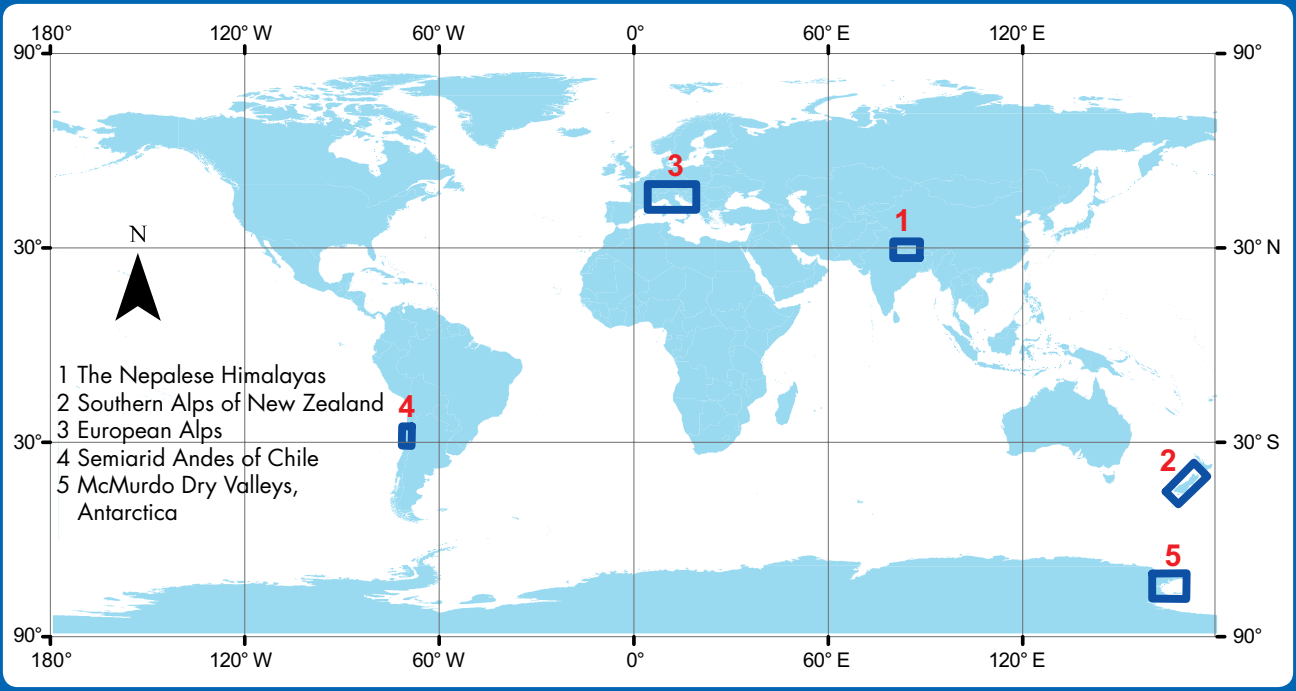
Compared to most other mountain ranges, the Himalayas have very few long-term glacier monitoring programmes. In order to fill the data gap in the Himalayan region, it is important to establish consistent and long-term mass balance measurements. This working paper discusses the nature, challenges, and differences of field work on mountain glaciers in different parts of the world, and provides recommendations for implementing organisations, academics, and funding agencies to estimate the human resources, required skills, and logistic support necessary to set up and maintain a sustainable long-term glacier monitoring programme to produce consistent and continuous data in the Himalayas.

Characteristics of Glaciological Fieldwork in Different Parts of the World

The latitude and continentality of a location influence the climate and seasonality of a study area, and determine the most feasible time for glacier fieldwork. At higher latitudes, winter and summer seasons are more distinct due to high variations in solar radiation, and restrict the time window to access field sites. At lower latitudes, distinct wet and dry seasons more often determine the field season. Whilst safety is the number one limiting factor for site access, ultimately the best time for undertaking glacier measurements depends on the research questions as well as the mass balance monitoring.

The duration of the expedition depends on the time needed to travel to the site and if necessary acclimatise, in addition to the time needed for measurements. The altitude range of a glacier determines whether extra acclimatization days are necessary and whether medical precautions need to be taken against altitude related illnesses such as acute mountain sickness (AMS), high-altitude cerebral edema (HACE), and high-altitude pulmonary

Figure 1: **Map with field sites in mountain ranges described in the text.**



edema (HAPE). Participants in glacier expeditions may also be exposed to extreme conditions such as very cold or stormy weather and there is a risk of hypothermia, frostbite, and other more serious health issues.

The remoteness of a study area determines the frequency and duration of field visits, the planning period, logistical requirements, and type of transport. The mode of access depends largely on the existing infrastructure, such as roads and tracks. Guesthouses can simplify the logistical support to reach the study area and mobile phone networks allow easier communication for weather forecasts, exchange of information on measurements and instruments, and support in case of emergency. Access on foot to the study site and glacier travel are also associated with risks such as exposed and slippery rocks, debris covered terrain, snow or ice avalanches, rock falls, landslides, landslips, and falls and injuries related to accidents on the glacier such as stumbling with crampons or falling into a crevasse.

In the following sections, the characteristics of fieldwork in Nepal, New Zealand, the European Alps, the semiarid Andes, and the McMurdo Dry Valleys in Antarctica are discussed based on the personal experience of the authors with a view to describing the wide range of possible issues that can arise at different locations (Figure 1).

The Nepalese Himalayas

The Hindu Kush Karakoram Himalayas stretch from 27–38° N to 67–98° E and act as a barrier for monsoon winds moving north, and cold, dry Arctic winds blowing south. The climate in the entire region is influenced by the Indian summer monsoon; the East Asian monsoon also influences the eastern Himalayas; and westerly winds bring winter precipitation to the Hindu Kush, Karakorum, and western Himalayas (Burbank, Bookhagen, Gabet, & Putkonen, 2012; Bookhagen & Burbank, 2010). The Nepalese Himalayas lie in the central part of the range (27–30° N, 80–88° E).

Japanese researchers initiated cryosphere research in Nepal in the 1960s, and began mass balance measurements on the Rikha Samba Glacier, Hidden Valley in 1974 (Fujii, Nakawo, & Shrestha, 1976; Fujita, Nakawo and Fujii, 1997), and the AX010 Glacier, Shorong Himal in 1978 (Ageta, Ohata, Tanaka, Ikegami, & Higuchi, 1980). Sporadic mass balance measurements were started on Yala Glacier, Langtang, in the 1980s (Higuchi, 1984; Ageta, Ilda, & Watanabe, 1984; Fujita, Takeuchi, & Sekoi, 1998). The International Centre for Integrated Mountain

Development (ICIMOD) initiated a regular mass balance programme together with various partners on the Yala and Rikha Samba Glaciers in 2011 (Baral et al., 2014; Ragettli et al., 2015). French researchers and their partners initiated mass balance measurements on the Mera Glacier in 2007 and Pokalde Glacier in 2009 (Wagnon et al., 2013).

The glaciers in Nepal are located in the highest mountains in the world; the majority of precipitation is brought by the monsoon and glacier accumulation mostly occurs in summer. There are approximately 3,800 glaciers with a total area of 3,902 km^2 (Bajracharya, Maharjan, Shrestha, Bajracharya, & Baidya, 2014). Most are found within an elevation range of 4,500 to 6,500 masl; thus acclimatisation days are indispensable for glacier fieldwork. The best time for access and fieldwork of summer accumulation type glaciers is post-monsoon when clear weather can be expected. Pre-monsoon is also suitable, however, there might be thicker snow cover and more convection precipitation. During the monsoon, the weather can be challenging; roads are often obstructed by landslides and tracks can be slippery. In winter, the temperature can be very low, increasing the risk of frostbite, especially at very high altitudes and in wind exposed places. Generally, the overland roads in Nepal are unpaved and narrow and transport is slow and unpredictable. In contrast, tracks are often on trekking routes or used by local villagers for their everyday life and are well maintained. There are settlements along famous trekking routes such as Langtang, Everest, and Annapurna, which may provide accommodation, food, and telephone access, although caution is required regarding food hygiene to prevent diarrhoea. Reaching a field site typically takes about a week, including some days in a vehicle, or a flight which relies on good weather, and several days of trekking and intermittent acclimatization. Thus changes to field plans at short-notice are not feasible, despite occasionally erratic weather patterns such as an early or extended monsoon.

In general, trekking agencies are used to provide logistical support, including organizing trekking permits in national parks; research permits are obtained separately. As well as scientists, larger expeditions will include trekking agency

dGPS survey of Yala Glacier, Langtang, Nepal, with an automatic weather station on the glacier. The peak of Ganchenpo (6,387 m) is visible in the background.

staff such as guides, cooks, and porters, who may have different backgrounds, perceptions, and values which influence social interaction, safety and the environment. In the Himalayas, Hindus and Buddhists believe that gods reside in certain lakes, mountains, and rocks and it is important to respect such beliefs.

In Nepal, the main accumulation and main ablation glacier seasons are both in summer during the monsoon, thus it is difficult to quantify the maximum annual melt and accumulation (Ageta and Higuchi, 1984). Precipitation typically covers parts of the ablation area, making the snowline inadequate as an equilibrium line proxy. In the upper parts of the glacier, snow accumulation is best measured with an ice corer, which easily penetrates the hard monsoon snow (Figure 2a). Efforts have been made to calculate the geodetic glacier mass balance, however, suitable remote sensing data is sparse. Glacier mass balance measurements are mainly carried out by government agencies and national universities in collaboration with international institutions and universities.

Southern Alps of New Zealand

The Southern Alps of New Zealand stretch from southwest to northeast (41–46°S). They have a temperate climate with a strong maritime influence and dominating westerly winds that bring moisture from the Tasman Sea. There are approximately 3,100 glaciers, which typically range between 1,500 and 2,300 masl at latitudes between 42 and 46°S (Chinn, 2001). The first glacier mass balance programme with intensive measurements was run on Ivory Glacier from 1969 to 1975 (Anderton & Chinn, 1978); several other short-term mass balance measurements were carried out thereafter (e.g., Bishop and Forsyth, 1988; Anderson, Lawson, Owens, & Goodsell, 2006). The first long-term mass balance programme was established in 2004 on Brewster Glacier by the University of Otago and Victoria University of Wellington (Anderson et al., 2010).

Most mass balance measurements are carried out during a few days in spring and autumn. Due to the frequent fronts passing through New Zealand, good weather windows are short and require flexibility for short-notice changes to access the glacier and carry out field measurements. Access to the glacier involves driving by car to

Figure 2: **a) Snow density measurement using a Pico ice corer in the accumulation area of Yala Glacier, Nepal. b) Accessing field sites in New Zealand often involves crossing rivers carrying all the equipment. c) Ablation measurements on a glacier covered with penitentes in Chile.**

Snow depth and density measurements on Park Pass Glacier, New Zealand

the road head, and hiking for one or two days to the field site with the entire equipment, including measurement instruments, safety gear, camping gear, and food. If funding is available, helicopter flights allow for very quick and safe glacier access, and are especially useful in the case of avalanche prone slopes along the access route in spring, and when there is excessive gear, e.g. for automatic weather station (AWS) maintenance.

Tracks in New Zealand often lead through dense forest, involve crossing rivers (Figure 2b), and ascend steeply along ridges and slopes. Tracks are well marked along common trekking routes, but on seldom travelled routes, they can be overgrown, exposed, and challenging, or even non-existent, hence requiring good navigation skills for off-track travel. There are simple huts and cabins in the Southern Alps, but most are not attended and work on a first come, first serve basis. For communication, a volunteer Mountain Radio Service can be used with prescheduled timeslots for weather forecasts, updates on planned trips, and emergency calls. Personal locator beacons with inbuilt GPS can be set off to send an emergency signal to call for rescue. Mobile phone reception should not be counted on in the sparsely populated mountains of the Southern Alps, however, satellite phones are a good alternative for regular monitoring field campaigns.

Many landmarks have a spiritual and religious meaning for the Maori, the indigenous people of New Zealand, and the local Maori community has to be consulted before conducting research to ensure potential holy sites are treated appropriately. In addition, many glaciers lie in national parks and research permits must be obtained from the Department of Conservation. The mass balance programmes are run and financed by universities in collaboration with government organisations. In the past, hydropower companies have also invested in glacier measurements.

European Alps

The European Alps stretch about 1,200 km along an east-west arch from about 4–19°E and 43–49°N, encompassing several countries including Slovenia, Austria, southern Germany, northern Italy, Lichtenstein, Switzerland, and southern France. The mountains rise from sea level to 4,810 masl (Mt Blanc), with the highest mountains above 4,000 masl concentrated in the western part. Despite the relatively small extent and elevation of the Alps, they are characterized by several climate and climate variability features (Auer et al., 2007). The Alps act as a north-south barrier; the northwestern part is strongly influenced by the nearby Atlantic and the southwestern part by the Mediterranean, while the east is influenced by continental features (Böhm et al., 2001). Westerly winds transport moist and mild maritime air to the Alps, creating a cooling effect in summer and a warming effect in winter, and ensuring that there is precipitation in most regions throughout the year. The southern Alps, which are mainly influenced by the Mediterranean Sea, are characterized by much milder winters. In general, air temperatures decrease with altitude, but inversion situations often occur during autumn and winter. At altitudes higher than 1,200–1,500 masl, winter precipitation mainly occurs in the form of snow, so continuous snow cover can often be observed for several months.

The general climatic characteristics are disturbed by the relatively small-scale, complex topography of the Alps. As a result, several valleys have very specific climatic characteristics, such as the inner alpine dry valleys (e.g., Valais and Vinschgau) shielded from precipitation from both the north and south. These valleys receive only about 500–600 mm/y of rainfall compared to about 2,000 mm/y on average across the Alps.

The European Alps have about 4,000 glaciers (Paul, Frey, & Le Bris, 2011), with the majority found at elevations between 2,600 and 3,300 masl (Hoelzle et al., 2007). Glacier mass balance monitoring started with index measurements on Claridenfirn in 1914 (Müller & Kappenberger, 1991). Several long-term mass balance monitoring programmes are running in nearly all the Alpine countries, with data regularly reported to the World

Drilling ablation stakes on Findelen Glacier, Switzerland. The Matterhorn stands in the background.

Glacier Monitoring Service (WGMS, 2012; 2013). Most of the glacier mass balance programmes have a very comprehensive monitoring programme including direct and geodetic measurements, hydro-meteorological measurements, and modelling approaches.

In contrast to most mountain ranges, the Alps are relatively densely populated. As a result, the mountains are very well developed with high-standard infrastructure including roads, cable cars, and trails. There are many well-maintained hiking trails, including those originally developed to reach settlements and summer pastures as well as those used for alpine tourism. Well-developed facilities enable frequent glacier visits and allow for flexibility in field planning based on changing meteorological conditions. Acclimatization is generally not required, unless a researcher is flying by helicopter and working at altitudes above 3,500 masl.

There is a clear accumulation and ablation period following the hydrological year (October to September). For the annual mass balance, it is thus sufficient to measure once a year at the end of the hydrological year. At this time, the atmospheric conditions are often relatively stable and dry (the so-called 'Altweibersommer' in German, or 'Indian summer' in English), which often simplifies fieldwork.

Extensive datasets exist for glaciological research, to support field measurements and comprehensive research approaches. In particular, a dense and long-term meteorological observation network (several stations date back to 1850) provides a unique climate dataset (as station data or gridded products), which is often homogenized (Böhm et al., 2001; Begert, Schlegel, & Kirchhofer, 2005; Frei, 2013). These meteorological and hydrological data from high-altitude stations are mostly maintained by government organizations or hydropower companies. Accurate maps based on aerial photographic surveys are available and updated on a regular basis, and allow regular geodetic mass balance calculations for all glaciers. These datasets are available partly because they are important for the region and highly valued, but also because the financial resources and access are good. The majority of the mass balance measurements are carried out and funded by national universities.

Semiarid Andes of Chile

In the semiarid Andes of Chile (26–32°S), snow- and ice-melt are the primary sources of water for downstream users (Favier, Falvey, Rabatel, Praderio, & López, 2009). Glaciers form on south-facing slopes above approximately 4,500 masl (Nicholson et al., 2010) where snow has been preferentially deposited (Gascoin, Lhermitte, Kinnard, Bortels, & Liston, 2013). Glaciers and rock glaciers cover approximately 11% of catchments above 4,000 masl (Nicholson et al., 2010). Understanding the role of the cryosphere within the hydrological system is not easy, however, due to the difficult logistical and environmental conditions.

Mass balance studies in the semiarid Andes have been largely funded by two distinct groups – government agencies (principally the Dirección General de Aguas, or from government science funding agencies such as FONDECYT) and mining companies as part of environmental monitoring requirements. The requirements and conditions for studies greatly impact the logistical support available, and therefore the approach taken.

Studies undertaken within government funded mass balance or science programmes are generally confined to areas with unrestricted access for the community. As much of the high Andes is privately owned, it is usually necessary to get permission from landowners to install permanent structures (for example AWSs), or to access generally closed sites. The main mass balance site in the Norte Chico is the Tapado Glacier (30.1° S, 69.6° W, 4,500–5,536 masl), which is located four hours drive from La Serena city, near the Agua Negra pass. Access to the site is typically limited to the summer months, when the pass is open to vehicles crossing between Argentina and Chile. During the winter months, the road is often covered by snow or rock falls, and is not maintained. From the vehicle access point, it is a 2–3 hour walk to the glacier terminus where teams set up camp sites. Depending on the nature of the fieldwork, teams either carry all equipment in, or use mules to get closer to the glacier surface. Helicopters are not a feasible option given the flight distance from Santiago.

Studies in central Chile are often logistically simpler due to the possibility of using helicopters as a result of the proximity to Santiago. In addition, glaciers may be a close driving distance from Santiago, and many valleys have huts or refuges suitable for use by field researchers. Further south, the weather is often more changeable, and precipitation rates are higher. In addition, the glaciers generally have more developed crevasse zones, which cause complications during the summer field season.

Horses deliver scientific equipment to a glacier field site in the Chilean Andes.

The mass balance programmes supported by mining companies are often logistically less complicated as mining roads generally lead to the edge of glaciers, and bases are at a much lower elevation than the glaciers themselves, which helps for acclimatisation and sleeping. In addition, the mining company supplies food and shelter, as well as office and laboratory space, where necessary. However, undertaking fieldwork within a mining operation comes with complex health and safety requirements as well as potential conflicts with releasing results. Recent experience with projects connected with mining companies has encountered few problems in releasing results into the scientific literature (e.g. MacDonell, Fitzsimons, & Mölg, 2013a; Abermann, Kinnard, & MacDonell, 2014), but Chilean law regarding glacier protection is currently being strengthened and it is not known how commercial sensitivity might impact the publication of future results.

Finally, in terms of mass balance measurements themselves, researchers in the semiarid Andes have had to be creative in order to monitor glacier surface changes. Many glacier surfaces form penitentes, or ice pinnacles, during the summer, which means that traditional stake measurements will not accurately represent surface lowering. To remedy this, ablation frames are used which spatialize measurements to get a surface averaged result (Figure 2c). Penitentes can grow to several metres in height, which also greatly limits transit across the glacier surface late in the summer mass balance period. These features also impact AWS use on glacier surfaces (Abermann et al., 2014; Lhermitte, Abermann, & Kinnard, 2014).

McMurdo Dry Valleys, Antarctica

The McMurdo Dry Valleys consists of three principal valleys that contain several valley, outlet, and piedmont glaciers (Fountain, Dana, Lewis, Vaughn, & McKnight, 1998). The area is the largest ice-free area on the Antarctic continent and is characterised by low precipitation (less than 100 mm), high wind speeds, and low temperatures. The valleys are located at 75–80° S and in the height of the austral summer receive 24 hours of sunlight, but are plunged into darkness during winter. The strong seasonal signal of radiation input impacts all glaciological processes that occur in the valleys, and also impacts fieldwork conditions.

In the early years of field research in the McMurdo Dry Valleys, some stations were manned year round, but over the last two decades or so, fieldwork is mainly completed during the austral summer, with only short visits outside of that. Glaciological work has been limited to the summer months since the late 1980s. Access to the valleys is generally by helicopter from nearby bases (e.g. Scott Base, McMurdo Station, or Zucchelli Station), however it is possible to arrive by heavy vehicle (e.g. Piston Bully) if necessary. It is a 45 minute helicopter flight from McMurdo Station, and helicopters travel between the base and the valleys several times a week at the height of summer (in good weather). Whilst there are few storms in the summer that include large precipitation events, winds can be high, and cloud cover dense and low, which can hinder access for several days. Furthermore, snow storms are common at Ross Island (where Scott Base and McMurdo Station are located), which can hinder helicopter operations.

Preparing fieldwork campaigns takes several months, as gear often needs to be shipped several weeks in advance. In addition, given the distance to the closest major settlement, forgotten or broken items are not easily replaced, and so preparations must consider any possible outcome. As all equipment must be transported by helicopter to the field, gear must be well packed with as little packaging and excess weight as possible. As the McMurdo Dry Valleys form part of an Antarctic Specially Managed Area, there are also limitations as to the types of equipment, chemicals, and fuels that can be used, as well as on how waste is handled and where you are allowed to walk or land a helicopter. Glacier travel is generally safe and roping up is not necessary because the cold ice has no large crevasses. However, great care needs to be taken when crossing ice-covered ponds and streams.

Due to isolation from other field parties and bases, undertaking fieldwork in the McMurdo Dry Valleys can be mentally taxing. Depending on the programme, field parties may be as small as three people and left largely to their own devices for several weeks at a time between field resupply visits. In addition, strict environmental protocols surrounding water use, access, and camp layout can put additional strain on field parties.

The most successful long-term mass balance programmes have included a stake network on glaciers in the Wright Valley from the 1960s to the1980s by the New Zealand Department of Scientific and Industrial Research (Chinn,

The South Shetland Islands, Antarctica.

1980), and more recently, stake and AWS networks by the National Science Foundation (NSF; from the USA) funded Long-Term Environmental Research (LTER) programme in Taylor Valley (Fountain, Nylen, MacClune and Dana 2006). The LTER programme has supported mass balance monitoring and hydrological and ecosystem research since the mid 1990s. Outside of these programmes, short-term monitoring has been undertaken on several glaciers, however only at 1–3 season scales (e.g. Fitzsimons et al., 2008; MacDonell, Kinnard, Mölg, Nicholson, & Abermann, 2013b). Stake networks are generally straightforward to maintain as average annual ablation rates are of the order of 100 mm w.e. and accumulation zones record similar values.

Discussion and Recommendations

Undertaking fieldwork requires overcoming different kinds of challenges in different parts of the world. In the European Alps, the accumulation and ablation seasons can be easily distinguished. In contrast, in Nepal these seasons overlap, making it difficult to measure the absolute total mass gain and loss, while fresh snow in the ablation area obscures spatial melting patterns, making the snowline an unreliable proxy for the equilibrium line. Strong winds may carry snow away from exposed sites in winter, removing also the artificial layers marking measurement horizons from autumn (Wagnon et al., 2013). Generally, monsoon snow is compacted because of warm temperatures, refreezing, and rainfall onto the snowpack (Takeuchi et al., 2009). Thus ice cores are preferred for measuring the snow pack instead of digging snow pits (Figure 2a). In the semiarid Andes, ablation measurements are challenging if penitentes are present. In New Zealand, maritime glaciers receive several metres of winter snow, requiring deep snowpits for accumulation measurements. Ice corers are unsuitable because the snow is too soft. Furthermore, the seasons are less distinct because of the maritime setting in the mid latitudes, and it is more difficult to capture the main ablation and accumulation seasons. Only annual measurements can be carried out in the very arid McMurdo Dry Valleys, however, measurements are relatively straightforward because of the minimal mass gains and losses.

Working under difficult weather conditions on Greenwich Island, South Shetland Islands, Antarctica.

Frequent measurements lead to a better understanding of the seasonal mass balance, a better rating curve for discharge, and regular maintenance of instruments. In the European Alps, New Zealand, and the semiarid Andes, several visits are possible during the year because of the relatively fast access. In the Nepal Himalayas, pre- and post-monsoon trips are both feasible and the tracks are often in good condition at these times, however, the number of field visits is limited because of the long duration and logistical effort required. In the McMurdo Dry Valley, typically only one annual field visit is possible, requiring thorough and early planning.

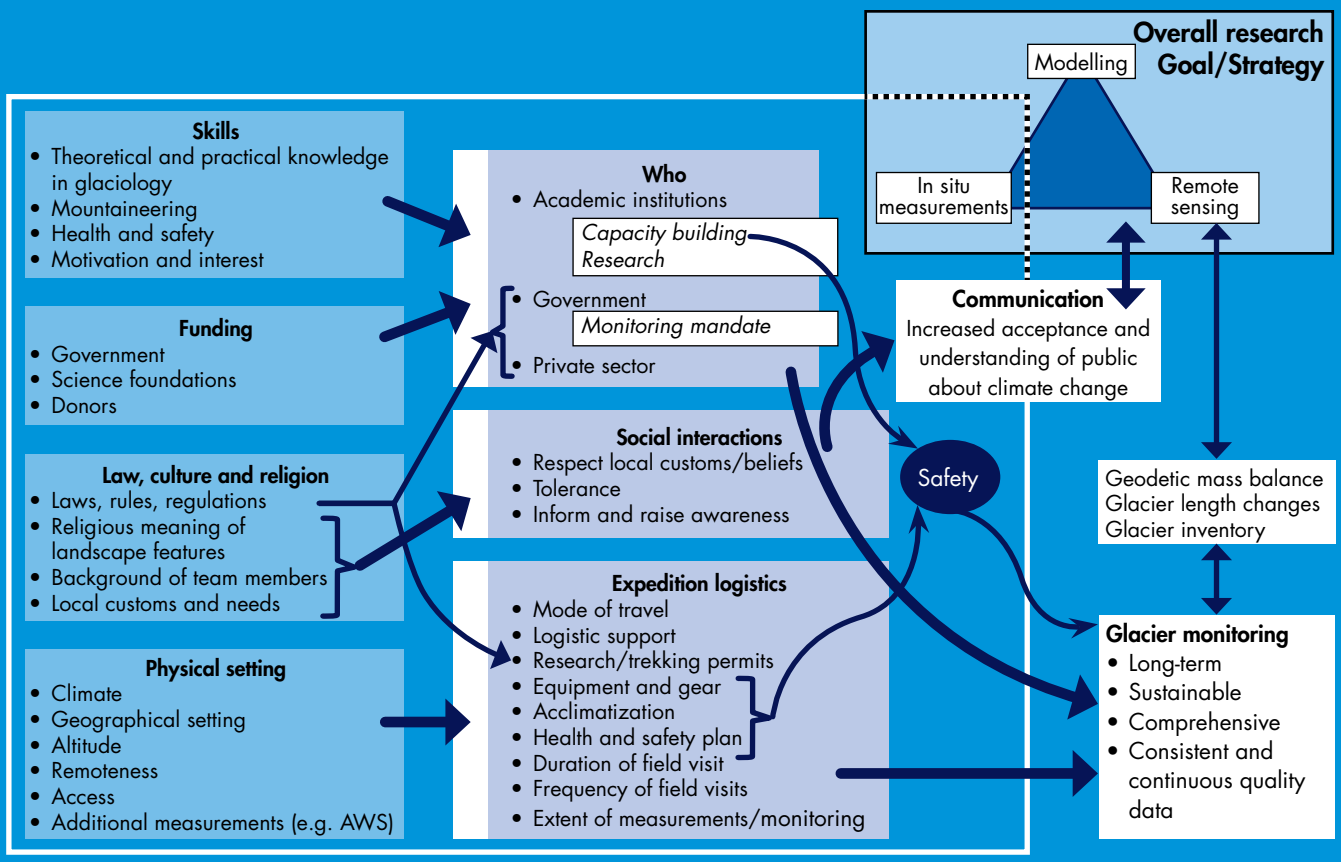
The climatic conditions in the European Alps are favourable during the main measurement season in autumn. In New Zealand, westerly winds bring regular frontal systems making the autumn season less distinct and field planning and measurement campaigns more challenging. Intense precipitation can cause river levels to rise suddenly, increasing the risks for river crossings. In the Nepal Himalayas, the weather is generally favourable for fieldwork during the main field seasons post- and pre-monsoon, however, unusual weather patterns or shifts in the monsoon season can complicate the fieldwork. The weather in the McMurdo Dry Valleys is often pleasant during the short summer due to the long hours of sun. However, in other seasons the temperature can be extremely cold, causing practical challenges for electrical equipment, liquids, and health. Stormy weather on Ross Island is dangerous, making it impossible to fly to the field sites.

Glacier fieldwork in the Himalayas and Andes is at high altitude and requires acclimatisation, precautions, and knowledge about potential high altitude illnesses. Such challenges can also be faced on glaciers in the higher reaches of the European Alps.

In the European Alps, the well-established infrastructure allows fast and easy access to the glaciers. In the Nepalese Himalayas, access takes many days, but there are often settlements along the access route. In New Zealand and the very remote parts of Nepal, settlements in the mountains are sparse and the fieldwork has to be more self-sustaining. This also applies to fieldwork in Antarctica, where bases can only be reached by air or ship. For communication, satellite phones are common, as well as radios in New Zealand and Antarctica.

Maintenance of the automatic weather station at Brewster Glacier, New Zealand

Figure 3: **Schematic diagram of aspects to consider when planning and maintaining a sustainable long-term mass balance monitoring programme that provides consistent and continuous data of good quality.**



In Chile, glacier monitoring is an environmental monitoring requirement for mining companies. Similarly, in Norway and France, glacier monitoring is required by law for hydropower companies, as well as economically important information for water management; companies compensate for their use of common resources and impact on the environment. Fieldwork costs typically increase with the remoteness of a field site such as in the Nepalese Himalayas or Antarctica. However, besides absolute costs, the relative costs for a country compared to GDP have to be considered; the relative monitoring costs for countries with a low GDP are substantially higher.

Scientific aspects and other factors should also be considered when planning and maintaining a long-term and sustainable glacier monitoring programme. The main points to consider are summarized schematically in Figure 3; some specific points for fieldwork, especially in the Himalayas, are discussed below.

- *Selection of field site:* The preferred physical characteristics of a glacier include large altitude range; mid-sized area; simple geography; uniform, smooth, and clean surface; well confined catchment area; and insignificant non-climatic processes like avalanches or calving (Kaser et al., 2003), and these may constrain the choice of field sites. However, safe access to the glacier may determine the success of sustainable long-term measurements.
- *Additional measurements and information:* Ideally additional data are available to support a comprehensive monitoring approach, including hydro-meteorological data, maps, and historical records. A regularly updated high quality digital elevation model (DEM) is valuable for analysis and geodetic glacier mass balance calculations, which serve as an independent method to cross-check the field-based measurements and are an integral part of a modern mass balance monitoring programme.
- *Prioritise key measurements:* Identifying essential measurement parameters and priority stakes for mass balance measurements ensures that the minimum amount of data necessary to maintain the mass balance programme is collected. Often mass balance programmes are initiated with a dense measurement network, which is then reduced to strategically selected measurements after gaining an increased understanding of the glacier.

- *Skills:* Field researchers have to be well trained regarding theoretical and practical knowledge in glaciology, mountaineering, and health and safety. Cogley et al. (2011) provide a glossary of glacier mass balance terms for reference. Since the work environment is harsh and demanding, physical fitness, motivation, and interest are fundamental, and appropriate personal equipment that protects and keeps the researchers warm and safe, as well as health and rescue insurance, must be assured. Suitable compensation should be considered for long trips under harsh conditions.
- *Funding and implementing organisations:* Ideally, glacier monitoring is funded and carried out by national government agencies with a mandate for monitoring, which ensures regular, consistent long-term monitoring with an established methodology. Collaboration with academic institutions facilitates teaching students the methodology and carrying out additional extensive short-term measurement campaigns; this will help ensure long-term sustainable measurements and increased understanding of the processes involved. In some countries, the law requires companies using natural resources, such as hydropower producers, or impacting on the natural environment, such as the mining industry, to monitor glaciers. An even more effective approach is to have a glacier law requiring glacier monitoring. Governments with the capacity and financial resources should be encouraged to support long-term glacier monitoring in parts of the world outside their own countries with challenging measurement conditions to address global issues of climate change, water availability, and sea level rise.
- *Capacity building:* Continuous capacity building is an important strategy to ensure sustainable long-term glacier monitoring. Especially in the HKH Region and the Andes, it is imperative to increase the scientific capacity with postgraduate degree programmes at master, doctoral, and postdoctoral level. Ideally, the same local support staff should be involved in long-term monitoring to learn all necessary tasks and utilize indigenous knowledge.
- *Expedition logistics:* A flexible field plan with extra days is important so that team members can adjust to the current conditions (e.g. weather, acclimatization). The logistical requirements such as a safe access route, camp sites, typical local weather patterns, glacier access, required permits, and so on must be identified. Advice gained from previous experience of other field parties in similar locations can greatly increase the safety and success of a field trip. In the Nepalese Himalayas, it is advisable to engage a trekking agency with guides who are experienced in glacier travel and fieldwork. Due to wage costs in Nepal, it is still cheaper to employ porters rather than helicopters to carry equipment and instruments. These jobs bring income to the remote valleys; however, the trekking agency should be urged to respect weight limits for the porters, ensure they have sufficient quality gear, provide insurance, and not employ underage porters. The support expected from guides and porters for glacier fieldwork should be communicated beforehand and acknowledged by extra tips. All expedition participants, including staff from the trekking agency should be encouraged to dispose of rubbish environmental friendly.
- *Research and trekking permits:* Many glaciers are in national parks where permits or approval from the government and/or landowners are required. The application process should be initiated early to meet all requirements. In some regions, consent should also be sought from religious leaders and the community with respect to local cultures and beliefs.
- *Social interactions:* Working in an extreme environment influences social interactions, especially if members have different cultural and hierarchical values. Therefore, a friendly environment with respect and tolerance for all team members, including for their physical capacity, is important for carrying out the planned tasks. Clear rules should be agreed, which can be vital if there is an emergency. These include rules to respect and protect the environment with regard to collection of refuse and use of water. A buddy system should be established at the start of high-altitude field trips, in which tent or room partners keep each other updated about their health conditions. This ensures fast action if someone falls sick, with a high-altitude illness in particular.
- *Health and safety:* For any field trip, risks should be analysed and an appropriate plan of action established. First aid kits should be adjusted to the circumstances of the expedition and the means available to raise the alarm during emergencies. Practical mountaineering, health and safety, and first aid training should be conducted regularly. Quality mountaineering equipment in good condition is vital for safe glacier travel. As always, it is mandatory to know and practise the use of any safety gear. At high altitudes, such equipment may include oxygen cylinders and/or a high-pressure chamber.
- *Communication:* Communicating the details and results of fieldwork is a fundamental part of science. Besides communicating these to the general public and the scientific community, it is generally a good practice to raise awareness and sensitize local people to glacier work, and to share with them the research results.

Conclusions

A comprehensive research strategy has to be followed in order to understand glacier response to climate change better, to evaluate the impact of any changes on water availability, hazard risk, and sea level rise, and to use the glaciers as a climate indicator. The strategy should include in situ measurements, remote sensing techniques, and modelling. This triangle of methods is a strong strategy in which each method reinforces the other (Figure 3). A strong scientific basis is required for all three methods, but in situ measurements require additional practical skills and resources to access the remote and harsh study sites and to carry out the measurements. These skills include a good understanding and experience of glacier monitoring, mountaineering skills, and a good knowledge of health and risks in the mountains. All these skills are needed to ensure safe measurements that result in consistent data of good quality. Geodetic mass balance calculations and a good quality DEM, typically based on remotely sensed data, are an integral part of any glacier mass balance programme. Funding may come from governments, science foundations, or private companies. Climate change is a global issue with high relevance for the international community, and attention should be paid accordingly to providing financial and practical support for glacier in situ measurements.

References

Abermann, J., Kinnard, C., and MacDonell, S. (2014). Albedo variations and the impact of clouds on glaciers in the Chilean semi-arid Andes, *Journal of Glaciology*, 60, 183–191, doi:10.3189/2014JoG13J094.

Anderson, B., Lawson, W., Owens, I., and Goodsell, B. (2006). Past and future mass balance of "Ka Roimata o Hine Hukatere" Franz Josef Glacier, New Zealand. *Journal of Glaciology*, 52(179), 597–607.

Anderson, B., Mackintosh, A., Stumm, D., George, L., Kerr, T., Winter-Billington, A., and Fitzsimons, S. (2010). Climate sensitivity of a high-precipitation glacier in New Zealand. *Journal of Glaciology*, 56(195), 114–128.

Anderton, P., and Chinn, T. J. (1978). Ivory Glacier, New Zealand, an IHD basin Study. *Journal of Glaciology,* 20(82), 67–84.

Ageta, Y., Ohata, T., Tanaka, Y., Ikegami, K., and Higuchi, K. (1980). Mass balance of Glacier AX010 in Shorong Himal, East Nepal during the Summer Monsoon season. *Seppyo* 41, 34-41.

Ageta, Y., Ilda, H., and Watanabe, O. (1984). Glaciological Studies on Yala Glacier in Langtang Himal. *Bulletin of Glaciological Research Publication*, Data Center for Glacier Research, Japanese Society of Snow and Ice, 2, 41–47.

Ageta, H., and Higuchi, K. (1984). Estimation of Mass Balance Components of a Summer-Accumulation Type Glacier in the Nepal Himalaya. *Geografiska Annaler. Series A, Physical Geography*, Vol. 66, No. 3. (1984), pp. 249-255.

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R,. Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P.D., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., Nieplova E. (2007). HISTALP—historical instrumental climatological surface time series of the Greater Alpine Region. *Int. J. Clim*. 27, 17–46.

Bajracharya, S.R., Maharjan, S.B., Shrestha, F., Bajracharya, O.R., and Baidya, S. (2014). *Glacier status in Nepal and decadal change from 1980 to 2010 based on landsat data*. Kathmandu: ICIMOD 13-27.

Baral, P., Kayastha, R., Immerzeel, W., Pradhananga, N., Bhattrai, B.C., Shahi, S., Galos, S., Springer, C., Joshi, S.P., and Mool, P.K. (2014). Preliminary results of mass balance observations of Yala Glacier and analysis of temperature and precipitation gradients in Langtang Valley, Nepal. *Annals of Glaciology*, 55(66), 9–14. doi:10.3189/201 4AoG 66A106.

Begert, M., Schlegel, T., and Kirchhofer, W. (2005). Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. *Int. J. Clim*. 25, 65–80.

Bishop, G., and Forsyth, J. (1988). *Vanishing Ice. An introduction to glaciers based on a study of the Dart Glacier*. J. McIndoe and New Zealand Geological Survey, DSIR.

Böhm, R., Auer, I., Brunetti, M., Maugeri, M., Nanni, T., and Schöner, W. (2001). Regional temperature variability in the European Alps: 1760–1998 from homogenized instrumental time series. *Int J Climatol* 21, 1779–1801.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., Bajracharya, S., and Stoffel, M. (2012). The State and Fate of Himalayan Glaciers, *Science*, 336, 310. doi:10.1126/science.1215828

Bookhagen, B., and Burbank, D.W. (2010). Toward a complete Himalayan hydrological budget : Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge, *Journal of Geophysical Research*, 115, 1–25. doi:10.1029/2009JF001426

Burbank, D.W., Bookhagen, B., Gabet, E.J., and Putkonen, J. (2012). Modern climate and erosion in the Himalaya. *Comptes Rendus - Geoscience*, 344(11-12), 610–626. doi:10.1016/j.crte.2012.10.010

Chinn, T.J.H. (1980). Glacier Balances in the Dry Valleys area, Victoria Land, Antarctica; World Glacier Inventory, In: *Proceedings of the Riederalp Workshop*, September 1978, IAHS-AISH Publ. no. 126, 237–247.

Chinn, T.J. (2001). Distribution of the glacial water resources of New Zealand. *Journal of Hydrology* (NZ), 40(2), 139–187.

Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M., Nicholson, L., and Zemp, M., (2011). *Glossary of Glacier Mass Balance and Related Terms*, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.

Favier, V., Falvey, M., Rabatel, A., Praderio, E., and López, D. (2009). Interpreting discrepancies between discharge and precipitation in high-altitude area of Chile's Norte Chico region (26–32 S), *Water Resour. Res.*, 45, W02424, doi:10.1029/2008WR006802.

Fitzsimons, S.J., Webb, N., Mager, S., MacDonell, S., Lorrain, R., and Samyn, D. (2008). Mechanisms of basal ice formation in polar glaciers: an evaluation of the apron entrainment model. *Journal of Geophysical Research* 113(F02010). DOI:10.1029/2006JF000698

Fountain, A.G., Dana, G.L., Lewis, K.J., Vaughn, B.H., and McKnight, D.M. (1998). Glaciers of the McMurdo Dry Valleys, Southern Victoria Land, Antarctica. In Ecosystems Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica, Priscu JC (ed). *Antarctic Research Series* 72, American Geophysical Union, Washington, D.C.; 65–75.

Fountain, A.G., Nylen, T.H., MacClune, K.L., and Dana, G.L. (2006). Glacier Mass Balances (1993-2001), Taylor Valley, McMurdo Dry Valleys, Antarctica. *Journal of Glaciology* 52(178), 451–462.

Frei, C. (2013). Interpolation of temperature in a mountainous region using nonlinear profiles and non-Euclidean distances. *International Journal of Climatology*, 34, 1585–1605. doi: 10.1002/joc.3786

Fujii, Y., Nakawo, M., and Shrestha, M.L. (1976). Mass balance studies of glaciers in Hidden Valley, Mukut Himal. *Seppyo*, 38 Special Issue, 17-22.

Fujita, K., Nakawo, M., Fujii, Y., and Paudel, P. (1997). Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalaya, from 1974 to 1994. *Journal of Glaciology*, 43(145), 583–588.

Fujita, K., Takeuchi, N., and Sekoi, K. (1998). Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalayas, 1994 and 1996. *Bulletin of Glacier Research*, 16, 75 - 81.

Gascoin, S., Lhermitte, S., Kinnard, C., Bortels, K., and Liston, G.E. (2013). Wind effects on snow cover in Pascua-Lama, Dry Andes of Chile. *Adv. Water Resour.*, 55, 25–39. doi:10.1016/j.advwatres.2012.11.013

Higuchi, K. (1984). Outline of the Glaciological Expedition of Nepal: Boring Project 1981 and 1982. *Bulletin of Glaciological Research*, 2, 1–5.

Hoelzle, M., Chinn, T., Stumm, D., Paul, F., Zemp, M., and Haeberli, W. (2007). The application of glacier inventory data for estimating past climate change effects on mountain glaciers: A comparison between the European Alps and the Southern Alps of New Zealand. *Global and Planetary Change*, 56, 69–82.

Kääb, A., Berthier, E., Nuth, C., Gardelle, J., and Arnaud, Y. (2012). Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas, *Nature*, 488(7412), 495–498. doi:10.1038/nature11324.Final

Kaser, G., Fountain, A., and Jansson, P. (2003). *A manual for monitoring the mass balance of mountain glaciers*. Technical Report 59, International Hydrological Programme. IHP-VI. UNESCO, Technical Documents in Hydrology.

Lhermitte, S., Abermann, J., and Kinnard, C. (2014). Albedo over rough snow and ice surfaces, *The Cryosphere*, 8, 1069-1086. doi:10.5194/tc-8-1069-2014.

MacDonell, S.A., Fitzsimons, S.J., and Mölg, T. (2013a). Seasonal sediment fluxes forcing supraglacial melting on the Wright Lower Glacier, McMurdo Dry Valleys, Antarctica, *Hydrol. Process*. 27(22), 3192-3207. doi:10.1002/hyp.9444, 2013a

MacDonell, S., Kinnard, C., Mölg, T., Nicholson, L., and Abermann, J. (2013b). Meteorological drivers of ablation processes on a cold glacier in the semi-arid Andes of Chile. *The Cryosphere*, 7(5), 1513–1526. doi: 10.5194/tc-7-1513-2013

Müller, H., and Kappenberger, G. (1991). Claridenfirn-Messungen 1914–1984. *Zürcher Geographische Schriften*, 40.

Mool, P.K., Bajracharya, S.R., and Joshi, S.P. (2001). *Inventory of glaciers, glacial lakes and glacial lake outburst foods. Monitoring and early warning systems in the Hindu Kush-Himalayan Region: Nepal*. Kathmandu: ICIMOD, 365 pp.

Nicholson, L., Marín, J., Lopez, D., Rabatel, A., Bown, F., and Rivera, A., (2010). Glacier inventory of the upper Huasco valley, Norte Chico, Chile: glacier characteristics, glacier change and comparison to central Chile. *Ann. Glaciol.*, 50(53), 111–118. doi:10.3189/172756410790595787

Nussbaumer, S.U., Hoelzle, M., Hüsler, F., Huggel, C., Salzmann, N., and Zemp, M. (2017). Glacier monitoring and capacity building: Important ingredients for sustainable mountain development. *Mountain Research and Development*, 37(1), 141-152. DOI: 10.1659/MRD-JOURNAL-D-15-00038.1

Paul, F., Frey, H., and Le Bris, R. (2011). A new glacier inventory for the European Alps from Landsat TM scenes of 2003: challenges and results. *Annals of Glaciology*, 52(59), 144-152.

Ragettli, S., Pellicciotti, F., Immerzeel, W., Miles, E.S., Petersen, L., Heynen, M., Shea, J.M., Stumm, D., Joshi, S., and Shrestha, A. (2015). Unraveling the hydrology of a Himalayan watershed through integration of high resolution in-situ data and remote sensing with an advanced simulation model. *Advances in Water Resources* 78, 94-111.

Salzmann, N., Huggel, C., Rohrer, M., and Stoffel, M. (2014). Data and knowledge gaps in glacier, snow and related runoff research – A climate change adaptation perspective. *J. Hydrol.* 518-B, 225–234. doi.org/10.1016/j.jhydrol.2014.05.058

Takeuchi, N., Fujita, K., Nakazawa, F., Matoba, S., Nakawo, M., and Rana, B. (2009), A snow algal community on the surface and in an ice core of Rikha-Samba Glacier in Western Nepali Himalayas, *Bulletin of Glaciological Research*, 27, 25–35.

Vaughan, D.G., Comiso, J.C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., & Zhang, T. (2013). Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wagnon, P., Vincent, C., Arnaud, Y., Berthier, E., Vuillermoz, E., Gruber, S., Ménégoz, M., Gilbert, A., Dumont, M., Shea, J.M., Stumm, D., and Pokhrel, B.K. (2013). Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since (2007). *The Cryosphere*, 7, 1769-1786.

WGMS (2012). *Fluctuations of Glaciers 2005–2010*, Volume X. Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., and Haeberli, W. (eds.), ICSU(WDS)/ IUGG (IACS)/ UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland: 336 pp. Publication based on database version: doi:10.5904/wgms-fog-2012-11.

WGMS (2013). *Glacier Mass Balance Bulletin No. 12 (2010–2011)*. Zemp, M., Nussbaumer, S. U., Naegeli, K., Gärtner-Roer, I., Paul, F., Hoelzle, M., and Haeberli, W. (eds.), ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 106 pp., publication based on database version: doi:10.5904/wgms-fog-2013-11.

Zemp, M., Hoelzle, M., and Haeberli, W. (2009). Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. *Annals of Glaciology*, 50(50), 101–111. doi:10.3189/172756409787769591

NORWEGIAN MINISTRY
OF FOREIGN AFFAIRS

International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal
Tel +977 1 5003222 **Fax** +977 1 5003299
Email info@icimod.org **Web** www.icimod.org

ISBN 978 92 9115 471 5