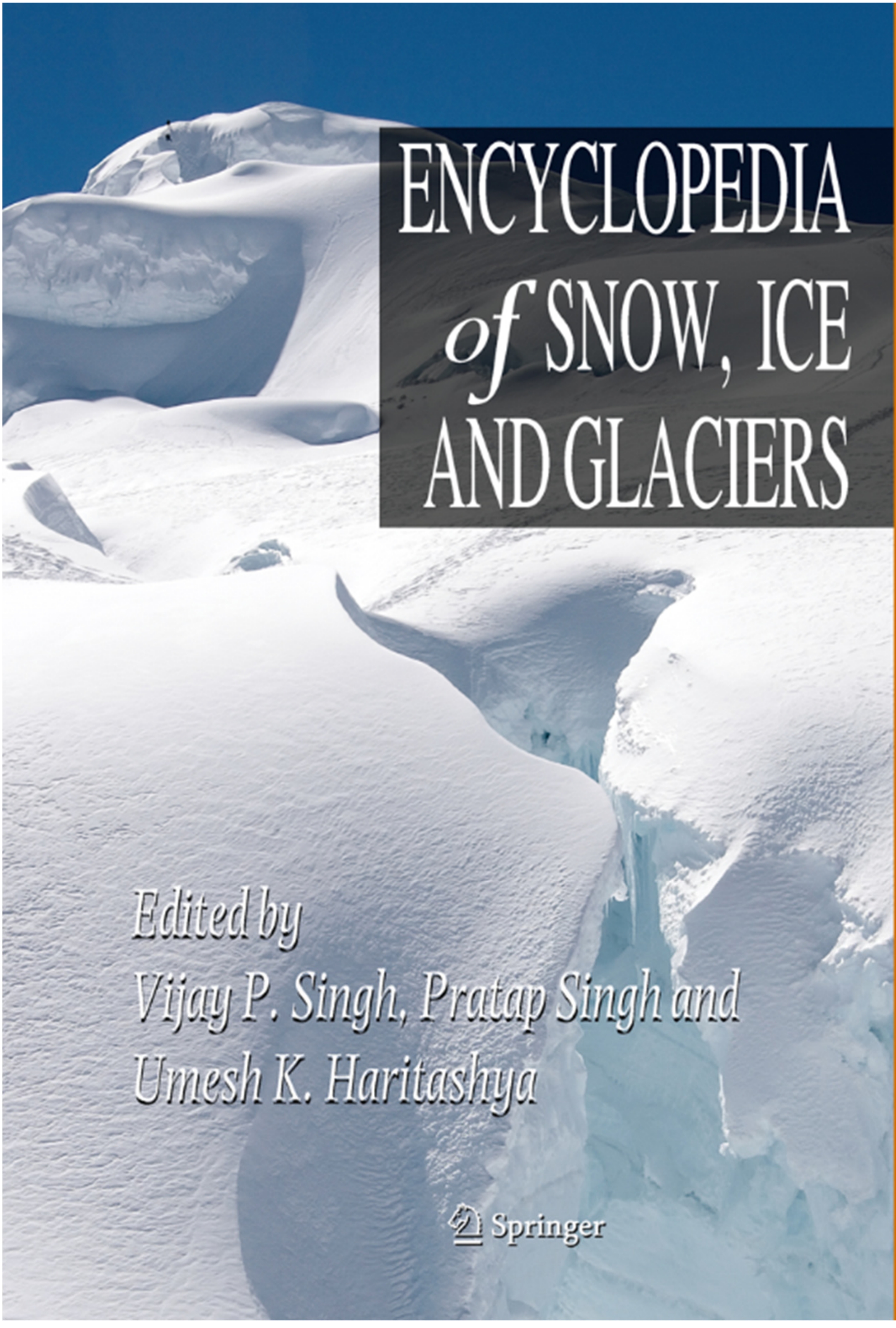

ENCYCLOPEDIA *of* SNOW, ICE AND GLACIERS

Edited by

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Umesh K. Haritashya

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ENCYCLOPEDIA *of* EARTH SCIENCES SERIES

Encyclopedia of Earth Sciences Series

ENCYCLOPEDIA OF SNOW, ICE AND GLACIERS

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Anabatic Winds: In Relation with Snow/Glacier Basin, Figure 1 Anabatic winds flowing upslope during daytime. Chhota Shigri Glacier in the Western Himalaya can be seen on the background. Photo by Umesh Haritashya June 20, 2006.

relations between melting and other meteorological parameters, including wind velocity. In general, anabatic winds are considered to be responsible for producing lower melt rates than the katabatic (downslope) winds (Hannah and McGregor, 1997), and they are also less stronger than katabatic winds. For details see the article entitled *Atmosphere-Snow/Ice Interactions*, and *Katabatic Wind: In Relation with Snow and Glaciers*.

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Cross-references

Atmosphere-Snow/Ice Interactions
Katabatic Wind: In Relation with Snow and Glaciers

ANCHOR ICE

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Definition

Anchor ice is formed on ground stones and other objects at the bottom of running water and thus remains attached or anchored to the ground. Ice crystals are formed and may coalesce or adhere to submerged objects like stones, marine organisms, rocks, man-made structures, etc. Anchor ice is most commonly observed in fast-flowing rivers during periods of extreme cold, in the shallow sub or inter-tidal during or after storms when the air temperature is below the freezing point of the water, and in the sub tidal in the Antarctic along ice shelves or near floating glacier tongues. The flow of the rivers having anchor ice is disturbed because it works as a barrier to the flowing water.

ANDEAN GLACIERS

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Definition

Andean glaciers: All glaciers located in the Andes of South America.

Introduction

In all Andean countries of South America, the highest peaks are covered by glaciers. These can be subdivided into tropical glaciers, located in Venezuela, Colombia, Ecuador, Peru, Bolivia and northernmost Chile, and extratropical glaciers, located in central and southern Chile and Argentina. The latter also include the northern and southern Patagionian ice fields (*Patagonia*, qv). While most Andean glaciers outside of Patagonia are fairly small and contain a limited amount of ice, they are nonetheless very unique and important. The tropical Andes, for example, are home to more than 99% of all tropical glaciers (Kaser, 1999) and they provide very important environmental services, such as freshwater during the dry season to downstream populations. Andean glaciers are also unique with regard to their mass and energy balance and their sensitivity to climate change (*Climate Variability and High Altitude Temperature and Precipitation*, qv), which is very different from glaciers at mid- and high latitudes.

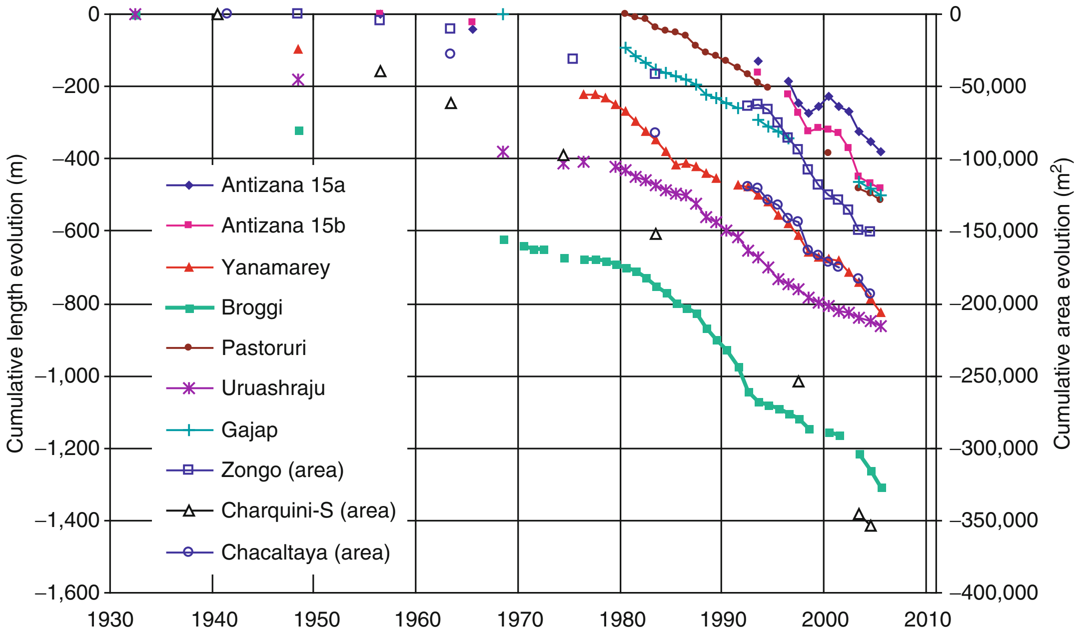
Tropical Andean glaciers

Glacier evolution over the past centuries and current extent

The northernmost tropical glaciers are located in Venezuela, but the country has lost more than 95% of its glacier-covered area since the mid-nineteenth century and the few remaining glaciers total less than 2 km^2 (Vuille et al., 2008a). In Colombia, six different mountain ranges still have some glacier coverage, but glaciers are rapidly retreating there as well. In Ecuador, glaciers are mostly located on volcanoes along the country's two mountain chains, the Cordillera Occidental and the Cordillera Oriental. These glaciers reached a maximum extent during the Little Ice Age (LIA) and have retreated since, interrupted by short periods of advance. Peru contains the largest fraction of all tropical glaciers (~70%) and is home to the world's most extensively glacier-covered tropical mountain range, the Cordillera Blanca. As in all other Andean countries, glaciers reached their maximum extent during the Little Ice Age and have retreated since. In the Cordillera Blanca, for example, the ice coverage decreased from ~850 to 900 km^2 during the LIA to 620 km^2 in 1990. The ice coverage at the end of the twentieth century was slightly less than 600 km^2. Glaciers in Bolivia can be found in two main mountain ranges, the Cordillera Occidental along the western border with Chile and the Cordilleras Apolobamba, Real, Tres Cruces, and Nevado Santa Vera Cruz in the east. The maximum glacier extent in Bolivia was reached during the second half of the seventeenth century (Rabatel et al., 2006). Afterwards glaciers started to retreat, with recession accelerating after 1940 and especially since the 1980s. In many locations of the Cordillera Real glaciers have lost between 60% and 80% of their LIA size and much of the surface and volume loss occurred over the past 30 years (Rabatel et al., 2006). In some instances such as on Chacaltaya, glaciers have disappeared altogether within the past 10 years (Francou et al., 2003). Chile also has a few glaciers along the border with Bolivia that can be considered tropical in the broadest sense (Vuille et al., 2008a). Figure 1 summarizes the retreat of glacier tongues and the reduction of surface area of ten glaciers in the Andes of Peru and Bolivia (from Vuille et al., 2008a).

Tropical Andean glacier mass and energy balance

In tropical locations, temperature stays more or less the same throughout the year but the *Hydrologic Cycle and Snow* (qv) shows a pronounced separation into wet and



Andean Glaciers, Figure 1 Change in length and surface area of ten tropical Andean glaciers from Ecuador (Antizana 15a and 15b), Peru (Yanamarey, Broggi, Pastoruri, Uruashraju, Gajap), and Bolivia (Zongo, Charquini, Chacaltaya) between 1930 and 2005. (Reproduced from Vuille et al., 2008a. With permission from Elsevier.)

dry seasons. Therefore, the mass and *Surface Energy Balance* (qv) of tropical glaciers is fundamentally different from mid- and high-latitude glaciers (Kaser, 2001). While at mid- and high latitudes winter represents the accumulation and summer the ablation season, ablation and accumulation occur at the same time on tropical glaciers. Also, because temperature does not change much throughout the year, ablation occurs predominantly in the ablation zone below the Equilibrium Line Altitude (ELA), and accumulation is restricted to regions above the snow-rain line that remains at a more or less constant altitude throughout the year (Vuille et al., 2008a). Actual mass and energy balance studies on Andean glaciers are fairly limited because they have to be restricted to glaciers that are easily accessible and safe to work. The longest continuous mass balance measurements with stake networks are located on Zongo and Chacaltaya glaciers in Bolivia (Francou et al., 2003). These studies reveal that the largest mass loss and gain occurs during the wet seasons, while mass balance is almost always near equilibrium during the dry and cold months. On interannual timescales, the El Niño-Southern Oscillation phenomenon (ENSO) appears to play a prominent role, dictating mass balance variability, with El Niño years featuring a strongly negative mass balance and La Niña events producing a nearly balanced or even slightly positive mass balance on glaciers in Bolivia (Wagnon et al., 2001; Francou et al., 2003), Peru (Vuille et al., 2008b), and Ecuador (Francou et al., 2004). These results can be explained by the dominant influence of ENSO on climate in the tropical Andes with La Niña years tending to be cold and wet, while warm and dry conditions usually prevail during El Niño years. Energy balance studies on several tropical Andean glaciers indicate a strong sensitivity to changes in atmospheric humidity, which governs sublimation, but also to the timing, amount and phase of *Precipitation* (qv), as this determines the glacier reflectance or albedo, and hence the amount of absorbed shortwave radiation. Net radiation receipts at the glacier surface are further affected by cloudiness, which controls the incoming long-wave radiation. Hence, the sensitive heat flux does not appear to play an equally important role as on mid- and high-latitude glaciers (Wagnon et al., 2001).

Tropical Andean glaciers, climate change, and water resources

The observed glacier retreat in the tropical Andes may soon lead to water shortages in many parts of the tropical Andes, especially in Bolivia and Peru (Vuille et al., 2008a). Studies show that temperature has increased significantly throughout the region (Vuille et al., 2003) and projections of future climate change indicate a significant rise in freezing levels (*Global Warming and its Effect on Snow/Ice/Glaciers*, qv) and hence the Equilibrium Line Altitude over the course of the twenty-first century (Bradley et al., 2006; Urrutia and Vuille, 2009).

This situation is of grave concern as Andean glacier *Discharge/Streamflow* (qv) provides water for human consumption, agriculture, hydropower production, etc., and is also crucial to maintain the integrity of threatened Andean ecosystems. On the Pacific side of Peru, most of the water resources originate from snow and ice in the Andes. Many large cities in the Andes are located above 2,500 m and thus depend almost entirely on high altitude water stocks to complement rainfall during the dry season. In addition, as glaciers retreat and lose mass, they add to a temporary increase in runoff (*Runoff Observations*, qv) to which downstream users quickly adapt, even though this increase is temporary and not sustainable once the glaciers become too small to sustain dry season runoff. Indeed it is estimated that in rivers draining the western side of the Cordillera Blanca 10–20% of the water is from nonrenewed glacier melt and that during the dry season this value jumps up to ~40% (Mark and Seltzer, 2003). Simulations with a tropical glacier-climate model suggest that glaciers will continue to retreat in the twenty-first century and in some cases (depending on location and climate change scenario considered) completely disappear (Juen et al., 2007). As a result dry season runoff will be significantly reduced, while wet season runoff may actually be higher due to the larger glacier-free areas and the enhanced direct runoff (Juen et al., 2007; Vuille et al., 2008a). Hence, while the overall discharge may not change very much, water availability during the dry season, when it is the most needed, will be significantly reduced.

Extratropical Andean glaciers

South of ~18°S glaciers are absent along the Andean cordillera due to the extreme aridity, with the snow line reaching above 6,000 m, before they reappear as small ice caps in the central Andes of Chile and Argentina south of the "South American Arid Diagonal" at ~29°S. Due to the enhanced winter *Precipitation* (qv) and high topography (including the highest elevation in the Southern Hemisphere, Aconcagua at 6,954 m), glaciers to the south of 31°S rapidly increase in size and form true valley glaciers. The total area covered by glaciers south of the arid diagonal but north of 35°S was estimated to be about 2,200 km^2 in 1998 (Lliboutry, 1998). Between ~35°S and the northernmost limit of the Patagonian ice fields (*Patagonia,* qv) at ~46°S more than 35 isolated volcanoes, many of them active, have elevations high enough to support glacier ice (Lliboutry, 1998). Glaciers in this region are famous for their penitents, east-west oriented formations of ice in the shape of blades, tilting toward the sun, and created by intense solar radiation and differential ice sublimation rates.

Snow and ice from this part of the Andes helps sustains some of the richest agriculture and large population centers on both sides of the Andes. Despite their importance for regional water supply, little is known about glacier mass balance in this region. Consistent with the meridional gradient in precipitation both accumulation and ablation values increase southward, with the net balance in the accumulation zone reaching values as low as 30 cm water equivalent (w. eq.) at Cerro Tapado (29°S) to a record value of 1,540 cm w. eq. at glacier Tyndall in Patagonia (Casassa et al., 2006). Mass balance also shows a clear east-west gradient, in particular south of 33°S, due the prevailing westerly circulation, which leads to higher accumulation on the western, windward side of the Andes. On interannual timescales, mass balance is closely related to ENSO events, with dry La Niña years and wet El Niño years (Casassa et al., 2006).

Glacier monitoring on the Chilean side of the central Andes between 32°S and 41°S has revealed a significant tongue retreat, area shrinkage and ice thinning (*Thinning of Glaciers*, qv) over the past decades, with the trend accelerating over the most recent period (Rivera et al., 2006). A glacier inventory (*Inventory of Glaciers*, qv) of nearly 1,600 glaciers with a total ice area of ca. 1,300 km^2 shows a total volume loss due to thinning (*Thinning of Glaciers*, qv) and retreat of 46 ± 17 km^3 of water equivalent between 1945 and 1996 (Rivera et al., 2006), most likely attributable to a combination of atmospheric warming (*Global Warming and its Effect on Snow/Ice/Glaciers*, qv) and a significant reduction in *Precipitation* (qv) (Bown and Rivera, 2007).

Summary

Glaciers exist in all Andean countries and can be subdivided into tropical glaciers, located in Venezuela, Colombia, Ecuador, Peru, Bolivia, and northernmost Chile and extratropical glaciers, located in central and southern Chile and Argentina. They are mostly fairly small in size and contain a limited amount of ice, but provide important environmental services, such as freshwater during the dry season to downstream populations. Glaciers in the tropical Andes are also unique in terms of their mass and energy balance (*Surface Energy Balance*, qv), which is fundamentally different from mid- and high-latitude glaciers, as accumulation and ablation seasons are not separated into distinct seasons, but occur at the same time. Andean glaciers have been in retreat over the past few decades and many are projected to completely disappear in the twenty-first century.

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Cross-references

Climate Variability and High Altitude Temperature and Precipitation
Global Warming and its Effect on Snow/Ice/Glaciers
Inventory of Glaciers
Patagonia
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