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Tracing tropical Andean glaciers over space and time: Some lessons and transdisciplinary implications

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Abstract

Tropical Andean glaciers are sensitive to climate changes over different temporal and spatial scales and are important hydrological resources. They exist in a dynamic interface between the atmosphere and lithosphere, hypothesized to influence rates of tectonic uplift. An accurate understanding of the extent and timing of past tropical glacial advances is a crucial source of paleoclimatic information for the validation and comparison of global climate models. Both present-day glacier recession and field evidence of past episodes of deglaciation in the Central Andes of Perú and Bolivia have been used to test hypotheses about how these glaciers respond to climatic forcing, and likewise impact developing societies and ecosystems downstream. Results from three facets of this research into tropical glacial recession are reviewed. In this context, glacial-environmental assessment is discussed as a focal point for transdisciplinary investigations of both physical and human dimensions of climate change. Important insights are gained when these ice masses are evaluated from different disciplinary perspectives as transient phases of water in specific topographic contexts.

Keywords: tropical glaciers; Andes; climate change; human impact; transdisciplinary

1. Introduction

Tropical Andean glaciers occupy an important nexus between physical and human dimensions of global climate change because they are both sensitive indicators of climate changes and potentially critical hydrologic reservoirs in highland regions. Scientific efforts to evaluate the mass changes and impact of these glaciers comprise multidisciplinary methods of "tracing" the glaciers. Tracing glaciers is accomplished across various spatial and temporal scales, incorporating diverse disciplinary traditions ranging from glacial geology, geomorphology, geochemistry, and limnology on ancient glaciated terrain to glaciology, climatology, hydrology, and surveying in modern glacierized catchments. The objectives of such research include understanding when, how and why glacier mass changes occur, as well as how much ice was involved and with what hydrologic impact. Hence, tracing glaciers involves both explanatory deduction and quantitative accounting.

This paper reviews recent studies that involve different methods of tracing tropical Andean glaciers. After reviewing the multidisciplinary motivation and dynamic geologic setting, three specific topics will be addressed: (1) the timing and extent of late Pleistocene and Holocene glaciations; (2) the spatial variability and

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forcing of late twentieth century recession; and (3) the hydrological significance of meltwater to streamflow. This selective review will elucidate how the nuanced concept of tracing glaciers is developed in each topic, and discuss some transdisciplinary implications for future research.

2. Multidisciplinary motivation

Tracing the extent and nature of tropical glacier mass variations over time holds clues for understanding global climate dynamics, both in the past and into the future (e.g. Kull and Grosjean, 1998). The tropics are the heat engine of the planet: the net positive radiation balance and constant thermal regime in the tropics initiate a transfer of energy to higher latitudes that drives global circulation, and a large component of atmospheric moisture (and latent heat) originates in the tropics (McGregor and Niewolt, 1998). However, there is disagreement about how sensitive the homeostatic tropics are to changes in temperature over time (Stocker et al., 2001). Efforts to resolve this have used multiple paleoclimate proxies and advanced climate modeling to examine the extent of tropical cooling during the last glacial maximum (LGM, conventionally defined as 21,000±2000 yr before present, following Mix et al., 2001), the most geologically recent period of extremely contrasting global climate (CLIMAP, 1976; Crowley, 2000; Mix et al., 2001). The geomorphologic record of tropical glaciers during the LGM has permitted computation of snowline (or equilibrium line altitude (ELA)) depressions that have played a key role in this discussion (e.g. Mark et al., 2005a). However, the greater extent of cooling inferred from tropical glacial geomorphology versus relatively small changes in sea-surface temperatures based on records of planktonic microfossils remains un-reconciled (Broccoli, 2000; Greene et al., 2002).

Observational evidence compiled over the past century indicates that modern tropical Andean glaciers have been retreating along with glaciers globally, prompting research on the climate forcing (e.g. Francou et al., 1997; Kaser, 1999; Mark and Seltzer, 2005). What seems to be organizing this shift in glacier regime on a global scale are rising average air temperatures, with accompanied altitude rise in the freeze isotherm and intensification of the hydrologic cycle (Diaz et al., 2003; Dyurgerov, 2003; Meier et al., 2003; Vuille et al., 2003). Yet fundamentally, local glacier mass balance fluctuations are very sensitive to variations in the surface energy budget which determines the magnitude of mass loss (ablation). On this scale, conceptual and empirical approaches in the tropical Andean region have shown modern glaciers to be sensitive to a broad range of variables beyond temperature, most notably humidity-related, and that glacier–atmosphere interactions are complex on varying scales (e.g. Wagnon et al., 1999; Francou et al., 2003; Kaser et al., 2004).

Approximately 75% of humanity abides within the tropical latitudes, 30° N and S of the equator (Thompson, 2000), and the majority of them live in poor, developing nations (Sachs et al., 2001). Greater than 80% of the fresh water supply for arid to semi-arid regions of the tropics and subtropics originates in mountainous regions, affecting more than half of Earth's population (Messerli, 2001). Glacier recession is thus a large-scale transformational change with profound local consequences for water resources and the populations that rely upon them for livelihoods (IPCC, 2001). If these tropical glaciers disappear, there may be water supply crises in developing regions like the Andes (Barry and Seimon, 2000), where ongoing urbanization in cities like Lima and La Paz have relied on naturally enhanced water availability from glacier melt in a seasonally arid climate. Recent analysis of seven global climate models (GCMs) has predicted intensified warming (+2.5 °C) by the end of the century over the Andes, with warmest changes concentrated at the high elevations of the tropical glaciers (Bradley et al., 2004).

3. Geologic context

In the Central Andean region (Fig. 1), glaciers dynamically couple atmospheric and tectonic processes through erosion. Located along a convergent plate boundary, the Andes have formed during the relatively continuous subduction of the oceanic Nazca plate beneath the South American continental plate since the Mesozoic (Allmendinger et al., 1997). The hypsometry, cross-range asymmetry, width, and maximum elevation of the Central Andes display a direct correspondence between climate zones and morphology (Montgomery et al., 2001). Investigations have shown that climate-induced sediment starvation during the Cenezoic may have played a roll in the uplift and formation of the most prominent physiographic zone in the region, the internally drained Altiplano plateau (Lamb and Davis, 2003). To the north of the Altiplano, the Andes ranges narrow, increase in relief, and become more dissected. The regional hypsometry of this section reveals a distinct dominance of glacial and fluvial erosion over the topography (Garver et al., 2005).

The locations highlighted in this paper extend from the Cordillera Real on the northern edge of the Altiplano

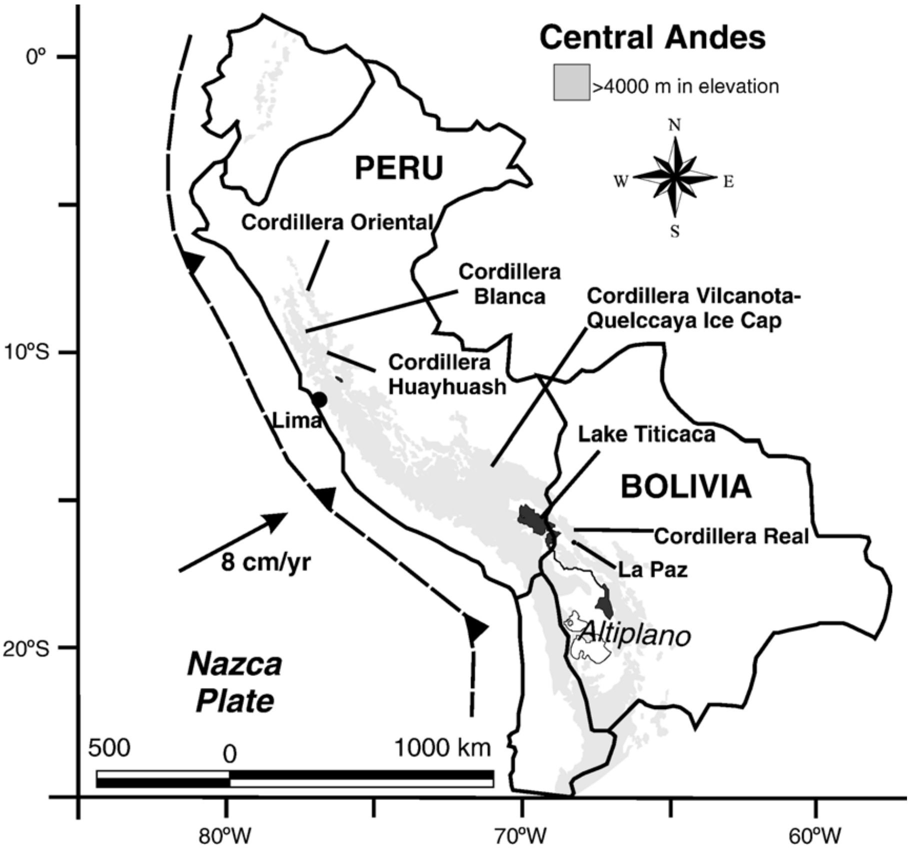

Fig. 1. Location map of the tropical Central Andes, describing the tectonic context of subduction and showing key locations mentioned in the text. The shaded areas represent land areas above 4000 m elevation, and show the first order topography and strike of the Andes.

in Bolivia to the Cordillera Blanca. Featured within this span are the Cordillera Vilcanota–Quelccaya region, 13° S, and the Cordillera Huayhuash, just to the south of the Cordillera Blanca. The highest and second highest summits of Perú are located along this section of the tropical Andes, and recent investigations of Quaternary slip rates along the active Cordillera Blanca detachment fault suggest that the uplift of the high peaks has been driven to a great degree by glacial erosion (Farber and Hancock, 2005).

Cordillera Blanca (Figs. 2 and 3) glaciers thus interface with climate and unique extensional tectonics to profoundly shape the landscape, but in their current topographic context also contribute to extreme natural hazards and provide valuable water resource (e.g. Arnao and Hastenrath, 1998). It is the most glacierized mountain range in the tropics, and spans 120 km along the South American continental divide. Modern glaciers occupy steep slopes, causing concern for hazards in the form of ice fall and dangerous lake formation. The combination of active tectonic faulting, steep topography, and melting glaciers is tragic for human residents; the region is most famed for being the site of two of the world′s most deadly three single landslides (Carey, 2005). The majority of glacierized watersheds within the Cordillera Blanca discharge towards the SW to the Río Santa, the second largest Pacific-discharging river in Perú, with the least variability in mean annual discharge. Four hydroelectric power stations are situated between the Cordillera Blanca and the coast.

4. Timing, extent and rate of late Pleistocene and Holocene glaciations

Large arcuate forms of glacier moraines are dramatic evidence that tropical Andean climate was much different in the past (Fig. 3). Researchers have used the geomorphologic evidence of these relict moraines to trace the extent of the paleoglaciers and to infer how past climate differed to conditions over (much reduced) modern glaciers. Early field work in the tropical Andes focused on cataloging the chronology of moraines (e.g. Clapperton, 1972; Mercer and Palacios, 1977), as well as making observations of modern snowlines in relation to those inferred for the Pleistocene (e.g. Hastenrath, 1971). The one-dimensional vertical displacement from modern to paleoglacier snowline altitude was an

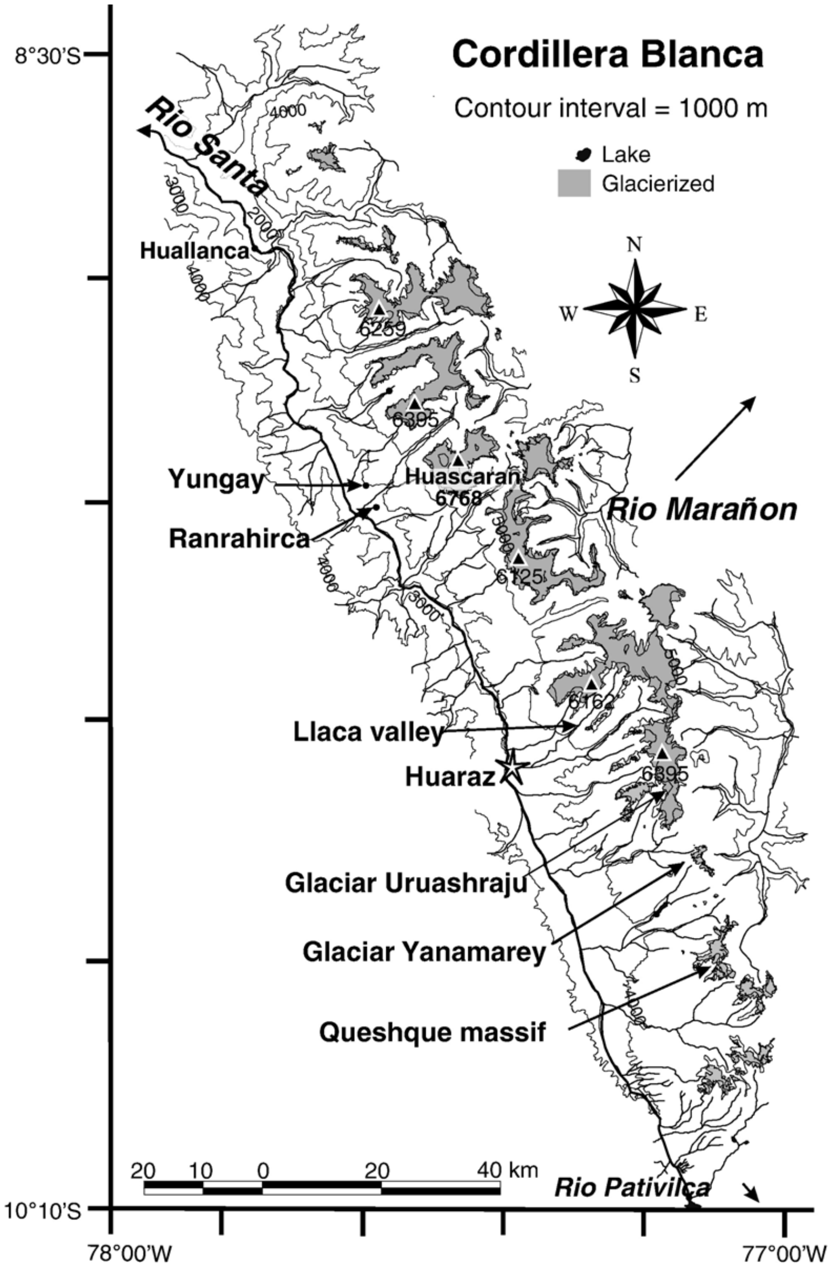

Fig. 2. Location map of the Cordillera Blanca. Shaded areas are glacierized, and the principal drainages are labeled and indicated with arrows.

assumed lowering of the annual freezing level in the atmosphere, and tropical moraines were likewise noted to represent greater LGM cooling than sea-level proxies (e.g. Webster and Streten, 1978). However, such a simple temperature change derived from a lapse rate and snowline depression is an oversimplification of glacier response between equilibrium positions. A sensitivity analysis using a coupled heat and mass balance approach shows that unique climate interpretations of ELA depressions are impossible to discern from moraine positions, but demonstrates a range of probable solutions may be quantified (Seltzer, 1994). Furthermore, a review of methods employed to reconstruct paleoglacier ELAs has shown that area-based methods that account for the full hypsometry of paleoglaciers are more reliable though often less applied in tropical regions (Porter, 2001).

Important insights have been gained from the reconstruction of late Pleistocene and Holocene ELAs in the tropical Andes by considering the topographic context of glaciation, both on a regional scale and for individual glaciers. Pleistocene snowlines derived from mapped Central Peruvian cirque elevations implied steeper regional horizontal climate gradients in the past (e.g. Nogami, 1976; Wright, 1983). In a similar work for the northern Peruvian Cordilleras Blanca and Oriental, a

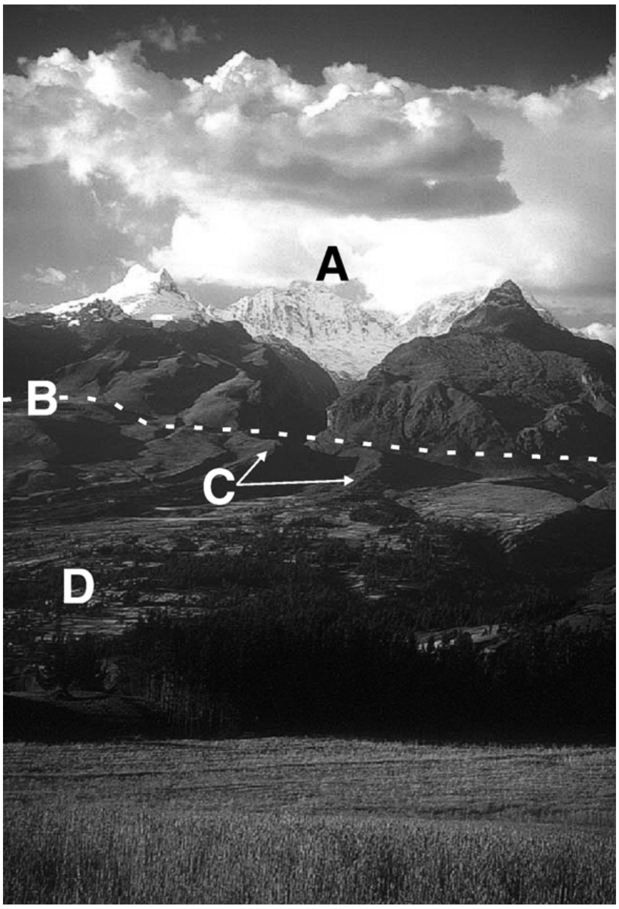

Fig. 3. Modern Andean glaciers of the tropical Cordillera Blanca, Perú, are steep alpine glaciers mantling the central granodioritic batholith of Miocene and Pliocene age (A). A clear truncation in topography delimits the SW-facing active Cordillera Blanca detachment fault zone (dashed line, B), where the crystalline basement is separated from the Mesozoic aged metasediments in the hanging wall. The active normal fault dramatically cross-cuts the Pleistocene moraines (C), which indicate much greater extent of past ice volumes. The down-faulted valley of the Callejon de Huaylas containing over 2000 m of Pliocene and Quaternary fluvial, colluvial, and glacial sediments (D). This photo shows the summits of Vallunaraju (left, 5686 m and center, 5675 m) and Ocshapalca (right, 5888 m) above the lateral moraine ridges descending from the Llaca valley above the city of Huaraz (foreground, 9°30′ S, 77°30′ W). The region contains one of the steepest topographic gradients of the entire Andes with 4500 m of vertical descent along one 15 km continuous stretch. Similar moraines preserved throughout the Central Andes of Perú and Bolivia have guided the glacial chronology which is further refined by investigations of lake sediments.

mapped synthesis of cirque headwalls, termini, and reconstructed ELAs confirmed steeper climate gradients during the LGM (Rodbell, 1992). Reconstruction of paleoglacier surface morphology in individual valleys of the Bolivian Cordillera Real, as constrained by consideration of basal shear stress, further improved the accuracy and range of error for ELA computation. The resulting climatic interpretation showed late Pleistocene glaciation occurring with as much as 200 mm/yr more precipitation and temperature depressions of 3.5°±1.6 °C, less divergent from sea-level estimates (Seltzer, 1993). The regional mapping approach was expanded by use of satellite imagery to map moraines, and compute ELA with digital elevation for the entire glaciated portion of the Peruvian-Bolivian Andes (Klein et al., 1999). Here, individual glacier moraines were seen as not only delimiting the maximum vertical extent of change, but also the full glacier area and distribution of mass with elevation. A model of climate sensitivity at the paleo-ELA was also incorporated to reveal plausible climate change scenarios consistent with observed ELA depression. This work confirmed regional gradients in glacier climate response due to precipitation variability, but affirmed a temperature depression of 5–9 °C. However, moraine chronology remains critical to tracing glaciers in time, and without dates, this extensive mapping work only traces a relative local late-glacial position.

Recently refined chronology of glacial geomorphic features using cosmogenic radio nuclides (CRN) has challenged the understanding of the spatial extents achieved by past tropical Andean glaciations. In the geodynamic Cordillera Blanca, well-defined multiple staged moraines offset by the active detachment fault are stratigraphically constrained by radiocarbon dates (Rodbell, 1993), and provide a check on the CRN production rates that are central to the accuracy of the dating technique (Farber et al., 2005). CRN-based chronologies with multiple samples from moraines near Lake Junin and in the Cordillera Real show a maximum glacial extent during the last glacial occurred earlier in the Andes, but was much reduced in extent than earlier assumptions (Smith et al., 2005a). Moreover, the extreme variance in ELA depression seen on opposite sides of the Cordillera Real watershed affirms the importance of considering individual paleoglaciers in topographic context, and is a clear warning against assigning regional ELA changes from single valley reconstructions. This technique holds great promise for more accurately tracing glaciers over time scales far beyond the range of radiocarbon dating, and at high elevation sites lacking organics. Nevertheless, it is highly sensitive to many factors such as erosion rate, surface exposure, and uplift, requiring cross-disciplinary geologic understanding (Smith et al., 2005b).

Accurate mapping and dating of moraines combined with digital terrain modeling yield analyses of glacial volume traced through time, including mass flux and recession rates. In the Cordillera Vilcanota and Quelccaya Ice Cap regions, multidisciplinary teams have

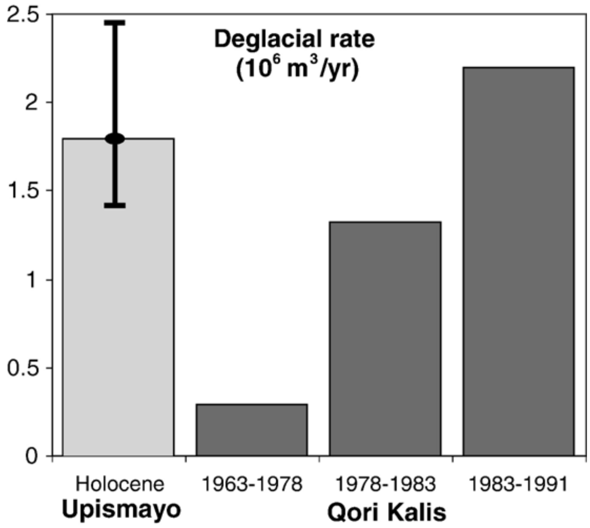

Fig. 4. Volumetric rates of deglaciation (10^6 m^3 yr^{-1}) for the Qori Kalis glacier, largest outlet glacier from the Quelccaya Ice Cap (from Brecher and Thompson, 1993), compared to reconstructed Holocene rates for the Upismayo paleoglacier located in the same region. The calculations were made from terrestrial and aerial photogrammetry for three different time intervals: 1963–1978; 1978–1983; and 1983–1993. A clear acceleration in rate over time towards the present is apparent. The rate for the Upismayo moraine position includes an error range associated with a one-sigma range in calibrated radiocarbon ages used in the moraine chronology. Nevertheless, it falls within the range of values observed for the Qori Kalis over late 20th century (after Mark et al., 2002).

mapped and dated relict moraines with radiocarbon (Mercer and Palacios, 1977; Goodman et al., 2001; Mark et al., 2002) and CRN (Kelly and Thompson, 2004), and have also systematically charted the recession of the Qori Kalis glacier using terrestrial photogrammetry (Brecher and Thompson, 1993; Thompson et al., 2000). These chronological traces of glaciers were combined with digital terrain models of the surface topography to compute paleoglacier volumes. A comparison of different volumetric rates of glacier recession was then facilitated, and results showed that regional rates computed for the Holocene fell within the range of accelerating late 20th century rates at Qori Kalis (Mark et al., 2002) (Fig. 4). The regional hypsometry explained the different recession rates on opposite sides of the massif as a function of glacier area exposed with respective ELA rise, and also led to further insights into both the chronology of glacial moraines, and the climate forcing of glacier recession.

Multidisciplinary field research combining accurate moraine mapping, CRN dating and surface modeling hold great promise for resolving issues of timing and climatic forcing across different spatial and temporal scales. Satellite remote sensing, GIS technology, and digital elevation models provide a systematic comparative estimation of ELA change in the Central Andes of Perú using different methods (Ramage et al., 2005). One innovation of this approach includes a digital hypsometry computation based on the valley morphology with the depth of paleoglaciers mapped from GPS surveys of lateral moraines in valley cross-sections. While this simplification assumes constant thickness, the computerized algorithm facilitates automation that permits more paleoglaciers to be reconstructed, increasing the sample size and thus the robustness of climatic inferences (i.e. Kaser and Osmaston, 2002).

An improved evaluation of the change of global tropical glacier mass balance over time and space that can be used to verify and compare climate models has involved consideration of individual glacier response in valley-specific context (Mark et al., 2005a). Valley-specific ΔELA (ELA$_{\mathrm{modern}}$ − ELA$_{\mathrm{LGM}}$) is used as the basic unit of analysis to rigorously examine both intra and inter regional patterns. Valley-specific paleoglaciers mapped in the Central Andes (n = 44) show the

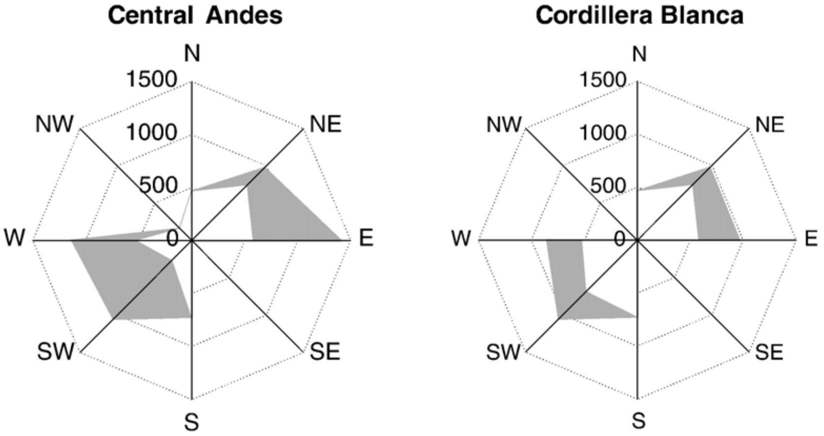

Fig. 5. Radar plots of the range of ΔELA (ELA$_{\mathrm{modern}}$ − ELA$_{\mathrm{LGM}}$) (m) for all valley specific paleoglaciers by aspect for regions of finer scale (from Mark et al., 2005a). The Cordillera Blanca sites (n = 21) are included in the Central Andes region (n = 45).

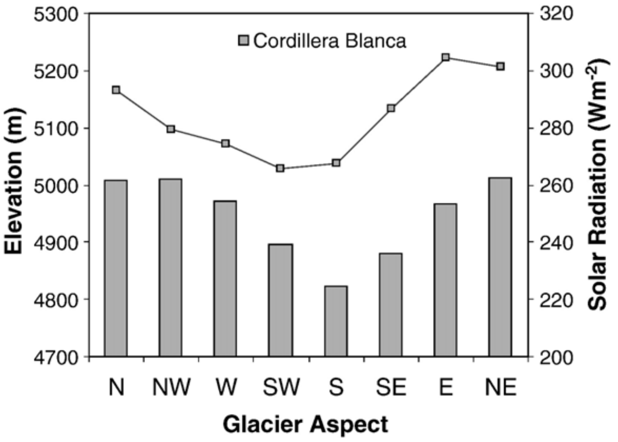

Fig. 6. Median glacier elevations (m), graphed with connected points, and mean annual clear-sky radiation (W m^{-2}), graphed with columns, averaged over the glacierized areas of the Cordillera Blanca sorted by aspect (data from Mark and Seltzer, 2005, Table 1).

highest degree of intra-regional variance in ΔELA (max = 1403 m, min = 260 m) globally, while the range is moderated strongly by aspect (Fig. 5). These patterns reflect the topographic control by the NW–SE strike of the Andes, as well as likely orographic influence on precipitation.

5. Spatial variability and climatic forcing of late 20th century recession

Glaciers in the tropics differ from those in higher-latitudes given relatively unchanging temperatures and highly seasonal precipitation. Different climatic variables have been identified as having predominant influence, depending on the spatial and temporal scale of analyses. Detailed short-term studies of the annual surface energy balance of individual tropical Andean glaciers imply changes in precipitation and humidity affecting mass balance through altered all-wave radiation that actually controls glacier mass balance (Wagnon et al., 1999; Francou et al., 2003). When the perspective is extended to decadal time scales, temperature is strongly correlated to regional glacier recession, as it integrates many closely interconnected surface energy/mass fluxes (Vuille et al., 2003). Tracing the variability of glacier volume loss with respect to glacier orientation provides important insights into both climate forcing and the regional impact of recent recession since these different climate variables (i.e. radiation, precipitation, temperature and humidity) impact glaciers in fundamentally different spatial patterns. Such a spatial analysis has been warranted in the Cordillera Blanca region as mass balance monitoring efforts are rare and discontinuous.

The orientation of glaciers in the Cordillera Blanca is controlled to a first order by the strike of the Andes and also reflects regional gradients in precipitation and solar radiation (Fig. 6). Glaciers with a southwest aspect are the most numerous and largest, accounting for 22% of glacier area throughout all of Perú, and 20% of total glacier area in the Cordillera Blanca (Ames et al., 1989). Over the entire Cordillera Blanca, average glacier medium and terminus elevations are lowest in watersheds that drain the eastern side of the divide to the Marañon River (Table 1), reflecting the easterly source of moisture. A similar spatial distribution of ELAs has been hypothesized to be a result of variations in both precipitation and effective global radiation (Kaser and Georges, 1997). Generally, ELAs rise from lower altitudes in the east to higher altitudes in the west as a function of precipitation gradients, but diurnal convection patterns cause a zonal asymmetry in the radiation balance. As a result, in regions where glaciers are more sensitive to this diurnal radiation imbalance, individual glaciers with western aspects reach lower altitudes locally.

Two studies have traced the spatial variation of glacier recession in the Cordillera Blanca over different time periods of the 20th century, and the results suggest a possible change in climate forcing in the later half of the 20th century. Both studies highlight the importance of the topographic context to the climate sensitivity of glacier masses, particularly to the solar radiation receipt. Kaser and Georges (1997) applied an energy balance model to ELA changes between presumed equilibrium positions that occurred in 1930 and 1950, as mapped from aerial photography. They attributed glacier mass loss to a combination of drier conditions with fewer

Table 1
Elevation dimensions of glaciers in the Cordillera Blanca in meters, listed by watersheds (from Ames et al., 1989)

River	Drainage	Maximum elevation	Minimum elevation	Average Maximum Elevation	Average Median Elevation	Average Minimum Elevation
Santa	Pacific	6768	4225	5436	5099	4819
Pativilca	Pacific	5289	4725	5208	5019	4981
Marañon	Atlantic	6375	4225	5302	4980	4700

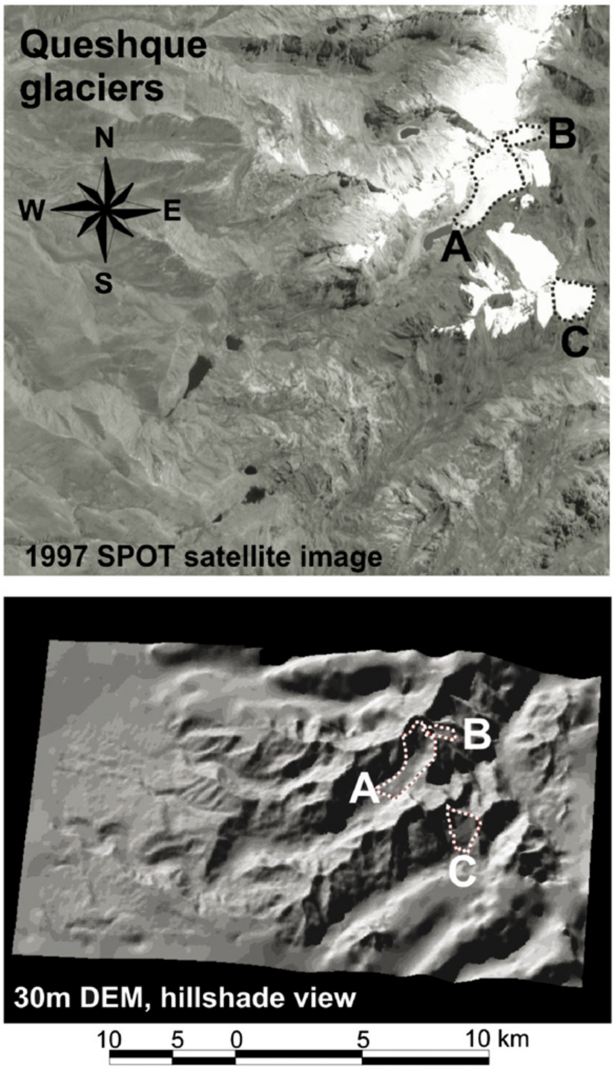

Fig. 7. (top) The 3 glaciers of distinct aspect in the Queshque massif of the Cordillera Blanca, shown in dashed outline on 1997 SPOT satellite image: A = Queshque Main (southwest); B = Queshque East (east); C = Mururaju (S). (bottom) Same glaciers are outlined on 3D hillshaded perspective view of 30 m digital elevation model (DEM). These coarse resolution images serve to indicate the orientation of the glaciers, and portray the geospatial data used in this type of tracing approach. They are oriented with north upwards, and vary slightly in scale, given the oblique perspective of the hillshade view.

convective clouds, and a slight temperature increase. Mark and Seltzer (2005) used a combination of aerial photography, satellite imagery, and differential GPS mapping to quantify volume loss between 1962 and 1999 from three glaciers in different orientations of the Queshque massif (Fig. 7). In light of trend analyses of regional temperature and precipitation, they account for the ice mass loss through a combination of 1 °C temperature rise and 0.14 g kg^{-1} increase in specific humidity. Observed asymmetry in ice melt is explained by the glacier hypsometry as computed with a digital terrain model; more area in 1962 was exposed at the lower elevations of the southwest facing Queshque Main glacier, and that the resulting change to 1999 was largest at lower elevations (Fig. 8).

Related research on annual tropical glacier surface energy balance (SEB) at different sites has affirmed the need to account for specific glacier locations and topographic characteristics. Throughout the tropics, glacier mass balance is directly related to the atmospheric moisture content and SEB is predominantly controlled by surface albedo (Kaser et al., 2004). However, glaciers show distinct sensitivities to temperature and precipitation and react differently to climate forcing depending on latitude. Low latitude inner tropical Andean glaciers, such as those in Ecuador, show enhanced response to temperature through the partitioning of solid and liquid precipitation, while outer tropical glaciers in Bolivia with a distinct dry season are more sensitive to precipitation amount and timing (Favier et al., 2004). In a similar comparative SEB study, recent changes in tropical Andean glacier mass are compared with those observed in the European Alps (Vincent et al., 2005). The work combines glacier specific dimensions and snout positions with mass balance measurements to account for regional similarities and differences through surface energy balance considerations. While the timing and pattern of net recession are similar for the glaciers in both regions, the tropical Andean glaciers show

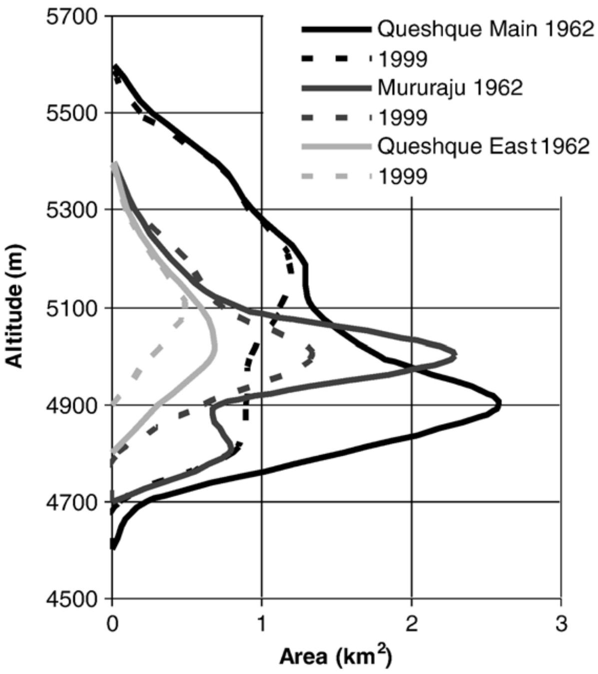

Fig. 8. Hypsometric curves for the Queshque glaciers in 1962 and 1999 (adapted from Mark and Seltzer, 2005).

enhanced sensitivity to the solid precipitation receipt impacting albedo rather than temperature. This is explained by differences in the turbulent heat fluxes: a positive sensible flux in the Alps is contrasted to a strong negative latent flux in the Andes.

6. Hydrological significance of meltwater to streamflow

Tracing the actual volumetric contribution to discharge provided by the ongoing net mass loss of Andean glaciers presents a challenge to scientists and engineers in the highlands where reliable stream gauge and glacier mass balance observations are scarce and discontinuous (Ribstein et al., 1995; Thompson, 2000; Seltzer, 2001; Ramirez et al., 2001; Casassa et al., 2002). Glaciers provide only one component of the hydrologic budget, but they provide a critical buffer against a strong seasonal precipitation regime (Barry and Seimon, 2000; Mark and Seltzer, 2003; Kaser et al., 2003). As the glacier recession rates increase, glacial fed streams initially have greater discharge; however, the subsequently decreased discharge, enhanced seasonality of runoff and increased future demand portend imminent socio-economic conflicts as glaciers melt progresses (Juen et al., in press).

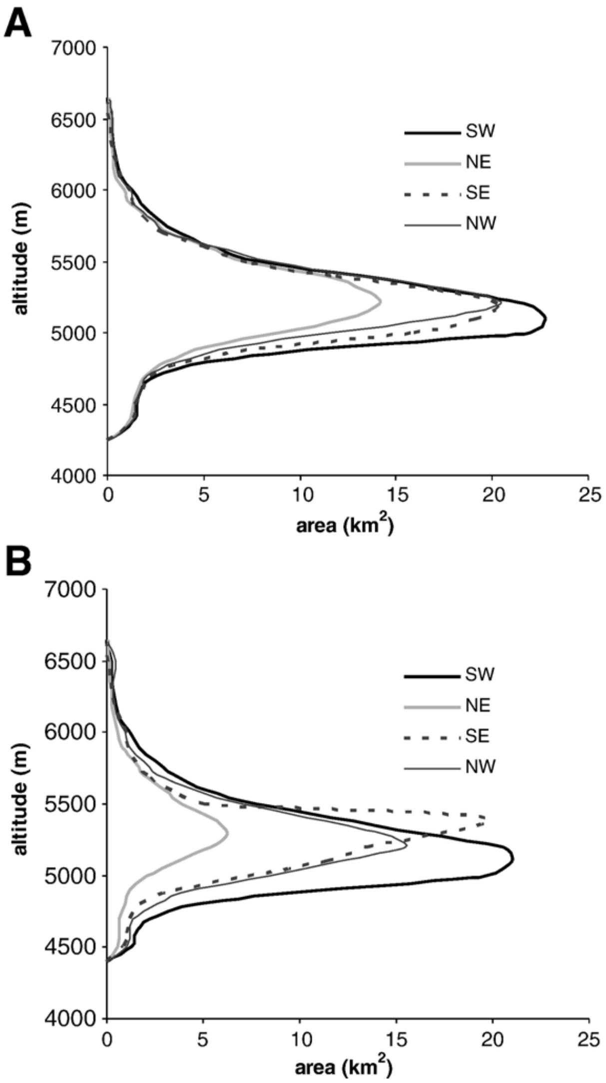

Fig. 9. Hypsometric curves for the glacierized area by aspect of the (A) entire Cordillera Blanca; (B) area draining to the Rio Santa. Glacierized area taken from 1997 Landsat imagery, and terrain elevation extracted from 100 m DEM of the Cordillera Blanca (Mark and Seltzer, 2005).

Quantitative estimates of the volumetric contribution to stream flow made by glacier mass loss have come from small individual glacier catchments with multiyear mass balance measurements and detailed surface mapping. For instance, over half of the mean annual discharge from Glaciar Yanamarey (<1 km^2) of the Cordillera Blanca was supplied from net ice mass loss from glacier recession (Hastenrath and Ames, 1995). Likewise, the small Glaciar Chacaltaya in the Cordillera Real, Bolivia (<0.06 km^2), could disappear within a decade, causing an estimated 30% loss of stream discharge (Ramirez et al., 2001).

Scaling up these single-glacier estimates to the regional scale where humans utilize water resources represents a challenge for researchers. Normalizing the available historical precipitation and discharge data by watershed area has shown a predictable buffering capacity of glacier meltwater on stream discharge as a function of percent glacier coverage (Tamayo, 1996; Mark and Seltzer, 2003; Kaser et al., 2003). Integrated modeling combining climatic, hydrologic, and hydraulic parameters has been applied to simulate runoff from glacierized and non-glacierized sub-basins of a 95 km^2 Andean watershed (Caballero et al., 2004). This approach can provide practical guidance for estimating flow to hydroelectric systems, but relies on critical assumptions and tuned parameterizations using historical discharge records.

Novel insights have also been gained by using hydrochemical environmental tracers and volumetric mixing models, across spatial and temporal scales. Based on 1999 results from the Yanamarey–Querococha tributary valley (<10% glacierized), hydrochemical mixing estimates were scaled up to predict 10–20% of the total annual discharge in the Callejon de Huaylas section of the Rio Santa, which drains a 5000 km^2 area that also has <10% glacier ice coverage (Mark and Seltzer, 2003). This was repeated in 2004 to show that two-thirds (66%) of averaged dry-season Rio Santa water in the Callejon de Huaylas (~8% glacierized) is comprised of Cordillera Blanca water. Again, based on the Yanamarey–Querococha mixing analysis, estimate

~40% of Rio Santa discharge is glacier melt (Mark et al., 2005b). Stable isotope (^{2}H and ^{18}O) ratios in watershed runoff also show promising patterns of variability that track percent glacier cover and hypsometry (McKenzie and Mark, 2005).

The hypsometry of glacierized area by aspect for the entire Cordillera Blanca as mapped from satellite imagery provides a measure of vulnerability to continued recession. Orientations with large, lower-lying glacier tongues are likely to face the most negative changes. Dividing the glacierized area into four principal aspect classes centered on NE, SE, SW, and NW shows that the largest area is concentrated in the SW, at a slightly lower elevation (Fig. 9A). When the glacierized area is further restricted to the westward draining Rio Santa watershed, the relative importance of this concentration of lower elevation and SW aspect is enhanced (Fig. 9B).

7. Transdisciplinary implications for future work

Beyond tracing the physical dimensions and hydrochemistry of glacier recession, there is an outstanding need to situate glaciers within specific social and cultural contexts where future management decisions must be made. Evaluating how and in what ways hydrological transformations due to glacier recession are affecting human and social dynamics is critically important for understanding the nature of adaptation strategies to these changes as well as how future changes can be anticipated and managed.

Tracing tropical Andean glaciers in a changing climate to understand impacts to water availability is an inherently socially relevant problem characteristic of transdisciplinary research (Lawrence and Despres, 2004). Problem oriented research is different than both basic and applied research. It is primarily concerned with applying general understanding to solving problems of some relevance "that are not structured according to disciplinary categories and delimitations" (Conrad, 2002). The context of tropical glacier-environmental change presents researchers with the challenge to provide socially applicable knowledge not conformable only to glaciology, climatology, paleoclimate reconstruction, or hydrology. Results must transcend the specialized scientific realm, and resident Andean stakeholders of natural resources should be included in framing research questions. Such an intentional involvement of stakeholders in the process of defining the problems, criteria, objectives and resources to resolve them is representative of the shift from interdisciplinary to transdisciplinary contributions (Klein, 2004).

UN SOL **Expreso**

AÑO I. Director: JOSE ANTONIO ENCINAS P. LIMA, JUEVES 27 DE SETIEMBRE DE [illegible] AÑO DE SAN MARTIN DE PORRAS Nº [illegible]

Dramática revelación de científicos

DANTESCO ALUD AMENAZA YUNGAY

LOS MONTAÑISTAS y científicos norteamericanos David Bernays (con sombrero) y Charles Sawyer (con lentes), regresaron a Yungay después de permanecer 3 semanas a más de 6 mil metros de altura en el nevado El Huascarán. Allí estudiaron el glaciar de donde se desprendió el alud q' sepultó Ranrahirca.

SERIA 3 VECES MAYOR QUE EL DE RANRAHIRCA

YUNGAY, Setiembre 26 (EXPRESO). — El "Techo del Mundo" se ha convertido en un peligro mortal. Un alud cuyas dimensiones triplicarían al que arrasó el distrito de Ranrahirca, pende como una "espada de Damocles" sobre las ciudades de Yungay, Mancos y el lugar donde se está reedificando el pueblo desaparecido.

El peligro lo originan las rocas cuarteadas, que se encuentran a más de seis mil metros de altura sobre el Huascarán, en el glaciar 511. Fue de este lugar de donde se desprendió la masa que sepultó Ranrahirca en enero del año pasado, originando 4,000 muertes.

Esta dramática revelación la hicieron ayer a EXPRESO, los alpinistas norteamericanos David Bernays y Charles Sawyer, quienes llegaron anoche después de estar a 6,200 metros de altura estudiando durante tres semanas el glaciar 511 de la Cordillera Blanca. Sólo les faltó 450 metros para alcanzar la cima del pico Norte del Huascarán, a la que se dirigían por la ruta más peligrosa: Llanganuco.

Los escaladores fueron declarados en emergencia desde el 19 último, cuando durante cuatro días dejaron de transmitir las señales de luces convenidas. Recién se tuvo noticias de ellos cuando una expedición salió en su búsqueda.

(Pasa a la Pag. [illegible])

Fig. 10. Headline from the Lima newspaper, Expresso, Thursday, 27 September, 1962. It tells of the dramatic prediction of two American scientists, David Bernays and Charles Sawyer, who had just climbed the North Peak of Huascaran, source of the January 10th ice fall and landslide that killed an estimated 4000 people and destroyed 9 towns, including the major center of Ranrahirca. They warned of remaining precarious ice that held imminent danger for the city of Yungay; they actually predicted the ice would cause a much bigger slide. Their words were not heeded, and 8 years later became a tragic premonition of the world's most deadly single slide.

Furthermore, tracing the hydrological impact of Andean glaciers involves many cross-scale considerations and uncertainty. Integrating social dimensions only adds to the complexity of the system. Transdisciplinary approaches that combine participatory and conventional methods to include diverse inputs, from local, informed experts as well as scientists from different disciplines, have been heralded as essential tools in understanding such complex systems (Cundill et al., 2005). Understanding the complexities of global change impacts to tropical glacial watersheds and human-social dynamics requires an evolved methodology drawn from different disciplines in an integration of knowledge (Horlick-Jones and Sime, 2004).

A transdisciplinary approach to tracing Andean glaciers therefore implies a move from conceptualizing glacier ice as merely a passive recorder of climate and topography to seeing it as a transient form of water that is an invaluable and limited human resource, but also a source of risk and hazard. Such a shift in perspective requires not only a new fusion of (disciplinary) skills and advanced techniques, but a different quality of practice and better communication. In other words, its not just what topics are studied or even what results are produced, but how the research is conducted and communicated that defines the success, impact and ultimately significance. It has been shown that transdisciplinary projects involving social and physical scientists in collaborative environmental research are prone to become discipline-specific divisions of labor under the pressure to produce (and publish) “usable results” (Pohl, 2005). Instead, results must be communicated between investigators and multiple audiences, from those living in direct proximity to the transforming ice, to those ultimately funding the science.

An historical case study of the human-social response to glacier-related hazards in the Cordillera Blanca has shown the tragic consequences that result from a lack of effective communication and trust between different elements of a society facing environmental transformation in the wake of climate changes (Carey, 2005). A central anecdote from this history illustrates the poignant challenge that faces any efforts for scientists to inform social adaptation or motivate action. On January 10, 1962, an ice fall and landslide from Huascaran killed an estimated 4000 people and destroyed 9 towns, including the major center of Ranrahirca. The Peruvian Geomorphology Commission of the Geographic Society of Lima put together a report on the disaster. They concluded that serious study was needed to analyze these dangers, apt to increase during ongoing 20th century glacier recession, and consider relocation of people and whole towns. Moreover, two American scientists, David Bernays and Charles Sawyer, climbed the North Peak of Huascaran in the following dry season, and predicted that more danger remained from additional hanging glacier ice. In fact, they predicted the possibility of a much bigger ice fall and landslide (3× the size) might threaten the city of Yungay, which was published in national newspapers and widely discussed (Fig. 10). Tragically, these warnings were not heeded, and concerned citizens were forcibly prevented from even speaking in favor of the predicted disaster. Eight years later in 1970, the cities of Yungay and Ranrahirca were buried, killing an estimated 18,000 people.

In this devastating example, complex social and cultural variables hampered communication and application of scientific insights. A vital distrust between relevant social and political actors resulted in an effective lack of information exchange between distinct realms of understanding (Carey, 2005). While this reality cannot be refuted, the incident serves to underline the relative importance of the human social dynamics. Future research on the problems of tracing glacier recession and hydrologic impact should not ignore the tacit human dimensions, but engender concern for communication and impact at all levels. Researchers should be “engaged problem solvers” rather than disciplinary specialists (Pohl, 2005). The complexities of changes in tropical glaciers are best understood from a wide variety of disciplines and perspectives, fostered in long-term international research partnerships. Whatever may be the scientific merit of any results, the process of conducting research should prioritize cross-cultural exchange of ideas and understanding. Recent instructional symposia exemplify constructive efforts to bring together international researchers with local students and engineers, including two International Courses on Glaciology and Environmental Geology (2000 and 2002, B. Morales Arnao) and a Symposium on Recent Glacier Shrinkage and Consequences for Water Resources, sponsored by International Commission on Snow and Ice (ICSI), International Hydrological Association, and French IRD, held in Huaraz, Perú, 6–9 July, 2004.

8. Summary and outlook

Tropical Andean glaciers are transient solid phases of water. That glaciers exist at all is testimony to the regional tectonism that has uplifted the topography high enough for perennial ice to be sustained. Yet research has also shown that these glaciers have a feedback through erosion on the rate and extent of the uplift. Changes in the mass of these glaciers over time are studied to discern climatic forcing and evaluate impact to stream flow. This involves multidisciplinary efforts to trace the glaciers over space and time using digital geospatial technology, terrain modeling, CRN dating, and hydrochemistry. Quantifying the spatial distribution and topographic context of glacier mass has led to important new understanding.

The accuracy of climate interpretation derived from the glacial moraine record relies on the extent to which the full paleoglacier volume is traced over space and time. LGM glaciers in the tropical Central Andes appear to be smaller than previously thought, but with large intra-regional variance reflecting a likely topographic limitation to western advances. The valley-specific hypsometry of paleoglaciers improves the robustness of ELA reconstructions by accounting for variations to the most sensitive variables controlling SEB: radiation and humidity. Modeled volumetric rates of Holocene glacier recession are comparable to modern observations, indicating the important control of hypsometry. Digital elevation-based modeling of mass balance and glacier flow for valley-specific moraine positions will facilitate future sensitivity testing of climate controls (e.g. Plummer and Phillips, 2003; Fairman et al., 2006).

The majority of remaining modern glaciers are small and steep, controlled to a first order by solar radiation geometry. The relative amount of volume loss experienced over the past half century indicates an enhanced sensitivity to temperature and humidity rise. The remaining largest volume glacier tongues having SW aspect are most vulnerable to melt, anticipating locations of greater hydrologic impact. Steep, hanging ice masses are vulnerable to tectonic dislocation, and particular orientation, slope and context determine relative risk for human populations down valley.

The prospect of ongoing tropical Andean glacier recession in the future poses new problems for scientists of many disciplines where the physical context of glacier mass must be extended to consider social, political and cultural dimensions. Evaluating the nature and scale of glacier recession impacts to better inform adaptation strategies and plan future water availability requires transdisciplinary exchange of knowledge about forcing, hydrology, local perception, and livelihood strategies. Effective communication of the science between people in all spheres of society is likewise a priority concern, and is enhanced through ongoing cross-cultural collaboration and educational symposia.

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