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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