Quantifying the significance of recent glacier recession in the Cordillera Blanca, Perú: a case study of hydrological impact and climatic control

Bryan G. Mark

1 Max Planck Institute for Biogeochemistry, Jena 07745 Germany and Department of Geography & Geomatics, University of Glasgow, Glasgow G12 8QQ, UK

1. Introduction
The Peruvian Cordillera Blanca is by far the most extensively glacierised mountain range in the tropics, and is an important location to study the practical impact and climatic control of ongoing glacier volume loss (i.e. Kaser and Osmaston, 2002). Draining most of the glacierised area in the Cordillera Blanca, the Río Santa (Fig. 1) maintains the second largest and least variable annual discharge of the all rivers in Perú flowing to the Pacific Ocean, from which the economically-developing population derives water for irrigation, domestic supply, and hydroelectric power generation. If the glaciers disappear, as predicted in other tropical regions (e.g. Thompson et al., 2002), important climatic archives would be lost, and the region could face a future water supply crisis (Barry and Seimon, 2000). While detailed instrumental measurements are rare or discontinuous in this remote region, important compilations of glacier maps and observational data quantify glacier mass changes over time (e.g. Kinzl, 1942; Kinzl, 1949; Kinzl et al., 1964; Ames et al., 1989; Kaser et al., 1990; Morales Arnao, 1998; Georges, 2003). A program of routine surveying was established in 1968, and four target glaciers were selected to monitor the magnitude of changes to these frozen reservoirs, providing a particularly important geographic database (Ames, 1998). Moreover, a number of gauges in tributary basins discharging to the upper reaches of the Río Santa known as the Callejón de Huaylas provide a half-century record of runoff and precipitation. This case study first focuses in on one of these target glaciers, where the magnitude of recession is specified, then zooms outward to quantify the downstream impact of the glacier meltwater volume. Taken in context with other work from the tropical Andes, these observations yield insights into glacier-climate interactions in this sensitive region of global relevance (i.e. Kaser, 2001).

2. Quantifying a half-century of net glacier recession: Glaciar Yanamarey
Survey data spanning over three decades from Glaciar Yanamarey were compiled to provide one of the first quantitative evaluations of recent tropical glacier volume loss (Hastenrath and Ames, 1995a, b) (Fig 1). While the terminus had some small advances, the late-20th century featured extensive glacier recession, consistent with other tropical glaciers (Kaser, 1999) and pervasive wastage of glaciers globally (Meier et al., 2003). Recession rates also increased, as in other Andean locations (Brecher and Thompson, 1993; Casassa et al., 1998; Thompson et al., 2000). These length variations express a rapid response to mass balance changes, captured by the basin hydrologic balance (Kaser et al., 2003). Using a simplified annual mean budget based on a decadal scale velocity and net balance data, Hastenrath and Ames (1995b) estimated that about 50% of the water discharging from Glaciar Yanamarey was not renewed by precipitation, but provided by progressive thinning, and that the receding glacier would survive another half century in the present climate. Thus, a quantitative estimate of how much the downstream hydrology is impacted by glacier wastage is required for water resource planning.
3. Quantifying downstream impact of glacier meltwater: *Callejon de Huaylas*

Monthly observations of specific precipitation and discharge ($P$ and $Q_t$, respectively) were collected with hydrochemical samples over the 1998-99 hydrological year at the Yanamarey glacier catchment (YAN) and in the larger Querococha watershed downstream, where a confluence of glacierised (YAN, Q2) and non-glacierised (Q1) streams forms a tributary stream to the Río Santa (Q3) (Fig 1). Maximum $Q_t$ precedes the peak in average $P$ by 4 months at YAN, whereas $Q_t$ is diminished and closely correlated in time to $P$ at Q3 (Fig 2). A simple water-balance calculation shows that the maximum in specific melt occurs in October for Glaciar Yanamarey, and the April minimum is negative, representing net accumulation (Fig 2a). However, melt contributes a maximum relative percentage of the monthly $Q_t$ during the dry season months (Jun - Sep). During this period of little to no precipitation, glacier melt contributes up to 100% of $Q_t$, thereby buffering the downstream flow. Assuming that the loss in glacier storage is exclusively by melting, then glacier meltwater comprises 35-45% of the total annual stream discharge from YAN. The Querococha watershed is a good analogue for the entire Callejon de Huaylas, as both are about <10% glacierised. Here, the relative influence of glacier meltwater to the annual runoff regime diminishes downstream of YAN at Q2, to becomes precipitation dominated at Q3, as in the non-glacierized Q1 (Fig 2b). A volume-weighted hydrochemical mixing model (using dissolved anions and cations) revealed that YAN contributes about a third of the discharge at Q3 over an annual cycle (Mark and Seltzer, 2003). By analogy, the larger Río Santa watershed thus receives a significant amount (10-20%) of its annual discharge from melting glacier ice. Historical records of discharge from tributary basins of the Callejon de Huaylas confirm watersheds feature enhanced mean annual discharge and less variable runoff in proportion to glacierised area (Fig 2c).

4. Insights into climatic control

The tropical austral spring climate during maximum glacier discharge is conducive to melting ice, emphasizing the hydrological and climatological significance of these transitional months between the late dry-early wet seasons. Mass balance and basin hydrology are most closely tied to atmospheric condition during these spring-summer months when a lower surface albedo absorbs more long-wave energy and an increase in humidity shifts the latent energy balance at the glacier surface towards producing more melting than sublimation/evaporation. Thus cloudiness, humidity and precipitation probably have more control on melt in the short term (Francou et al., 2003). This confirms a combination of climatic variables originally hypothesized to have forced 20th century recession at Glaciar Yanamarey (Hastenrath and Ames, 1995b). Recent research on tropical glaciers and runoff in Bolivia and Ecuador (Francou et al., 1995a; Ribstein et al., 1995; Francou et al., 2000; Wagnon et al., 1999a; Wagnon et al., 1999b; Francou et al., 2000) has shown that total net all-wave radiation, not temperature, is the main factor controlling ablation. However, because temperature is strongly interconnected with these variables, it remains an important indicator of longer term glacier evolution linked to large scale climate processes such as ENSO (Francou et al., 1995b; Vuille et al., 2003; Kaser et al., 2003). Observational evidence from Andean meteorological stations shows a strong positive trend in temperature (Mark, 2002), and model results confirm that the century-scale Andean glacier recession is best explained by a increased temperature and humidity (Vuille et al., 2003). Temperature measurements from the Yanamarey catchment show that
discharge is actually better correlated well with temperature than precipitation (Fig 2a). Moreover, discontinuous time series show an intriguing association of higher temperature with increased precipitation during at least the 1982 and 97-98 El Niño events (Fig. 3), opposite from the expected deficit of precipitation driving enhanced ablation during El Niño further south along the Andes (i.e. Francou et al., 1995a; Wagnon et al., 2003). Downstream, the seasonal contrast in discharge due to a strong amplitude precipitation signal is mitigated by glacier melt, distinct from mid-latitude glaciers responding to strong seasonal temperature contrasts (Mark and Seltzer, 2003).

References


Georges, C., 2003. The 20th century glacier fluctuations in the tropical Cordillera Blanca (Peru). Arctic, Antarctic and Alpine Research accepted,


Figure captions:

Figure 1: Case study location maps of successively larger scale: (a) Callejon de Huaylas, a watershed of ~5000 km² on the upper Rio Santa delimited by the hydroelectric power plant at Huallanca, 1800 m.a.s.l. Glacierised areas, the Querococha watershed boundary, and stream gauge locations mentioned in the text are identified; (b) Querococha watershed, 60 km², showing the discharge and water sampling points: YAN, proglacial lake discharge; Q1, non-glacier stream; Q2, downstream of YAN; Q3, discharge from Lake Querococha; (c) Yanamarey catchment, 1.3 km² between 4600 m and 5300 m, 75% of which is covered by glacier ice. The shaded region shows the outline of Glaciar Yanamarey in 1982, with contours and a centre-line to show distance from headwall with 100 m intervals (after Hastenrath and Ames, 1995a). A variety of surface elevation maps and measurements of terminus position are synthesized into a consistent geographic database to quantify cumulative terminus recession and annual recession rate. Terminus positions are mapped onto a common datum, based on surveys for 1939, 1948, 1962, 1973, 1982, 1988, 1997, 1998, and 1999. The latter three positions were mapped using differential GPS. The cumulative terminus recession from the 1939 position is shown (m) on the inset graph as solid line, with solid rectangles for years with corresponding terminus position mapped (data from A. Ames, pers. communication), along with average recession rate between years with mapped termini (in meters/year). Asterix marks the location of a weather station, where daily temperature and monthly precipitation were recorded discontinuously from 1982.

Figure 2: Hydrological and climatologic data from the successively larger catchments of the case study: (a) observational data from the Yanamarey glacier catchment, including monthly measurements of specific discharge ($Q_t$) (mm) from YAN plotted with the monthly precipitation totals ($P$) (mm) and monthly average temperature ($T$) (degrees C) sampled over the 1998-99 hydrological year, plotted with the glacier melt ($\text{Melt}$) calculated from a simplified hydrological mass balance; (b) specific discharge data from locations (see Fig 1) in the Querococha watershed plotted with monthly precipitation at the Querococha gauge (both in mm), on the same scale as (a); (c) magnitude and variation of annual stream discharge with percentage of glacierised area in the Río Santa tributaries, shown by ratio of maximum monthly discharge to mean monthly discharge (max $Q$ / mean $Q$); labelled data points correspond to gauge locations shown in Fig.1.

Figure 3: Total annual precipitation ($P$) (in mm) and mean annual temperature (in degrees C) anomalies for the Yanamarey catchment during years with complete data (1981-94, 1998-99). Monthly measurements were aggregated over course of a hydrological year (Jun – May). Temperature data are shown with one standard deviation error bars based on monthly means from the weather station in Yanamarey catchment ($YT$) where available, and corrected using lapse rate computed from 1956-1997 time series measured at the Querococha stream gauge ($QT$). Observations are incomplete after 1994, and only re-established in 1998, as denoted by the break x-axis.
Figure 1
Figure 2
Figure 3