Abstract
The glaciers of the Cordillera Blanca were much more extensive during the late Pleistocene and Holocene, and have undergone accelerated rates of deglaciation over the late 20th century. Modern deglaciation has contributed to the formation of unstable proglacial lakes and enhanced stream discharge. This paper presents data taken over the year 1997-1998 that contribute new insights into the spatial extent and volume of modern deglaciation, as well as the pattern of meltwater discharge. Modern glacier termini and surface morphology were mapped on modern glaciers with 3 distinct aspects in the Gueshque massif of the southern Cordillera Blanca using differentially corrected global positioning system (GPS) measurements. These measurements were compared to previously mapped glacier positions from traditional terrestrial photogrammetry to establish positions for 1962. Volumetric differences were estimated from surface area and terrain modeling within a geographical information system (GIS). Glaciers with an eastern aspect showed the highest rate of deglaciation, with a 60% decrease in surface area, and 71% decrease in estimated volume from 1962-1999. Southwestern aspect glaciers, which are representative of most valley glacier tongues in the Cordillera Blanca, showed a 30% and 39% decrease in surface area and volume respectively. Estimation of glacier water equivalent contribution to runoff on the alpine watershed has been up to 50% on an annual basis. Recent observations conducted over an annual cycle show that the wet season, accounting for over 80% of annual precipitation, features a bi-modal contribution of glacier melt.

Introduction
Modern deglaciation is defined as the historical recession of glacier ice as observed and recorded by humans. The record of scientific observations in the Cordillera Blanca is most complete for the 20th century, and marks a consistent recession since the middle of the last century (Kaser et al, 1990; Hastenrath and Ames, 1995a, b; Kaser et al, 1996; Ames and Hastenrath, 1996). Historical observations of glacier ice by human visitors to the region date back as far as early European occupation of the area and extend through to the present (see Ames, 1998 for a complete review). Modern deglaciation is important to both the climate researcher seeking for an understanding of the driving mechanisms and relative rates of deglaciation, as well as the civil engineer, managing the regional water resources.

Since glaciers are ultimately responsive to changes in climate, the spatial extent and rate of modern deglaciation have important implications for understanding mechanisms of climate change. Solar radiation, precipitation and temperature are the climate variables with predominant influence on glaciers and the process of deglaciation. Yet of these factors, solar radiation and precipitation are typically controlled by mountain orography. It is hypothesized here that the late 20th century deglaciation in the Cordillera Blanca has been forced by enhanced tropospheric warming that prevents noticeable differences in volume loss relative to glacier orientation. Moreover, modern deglaciation
may demonstrate enhanced rates as a result of anthropogenically induced global warming. It is therefore important to compare measured 20th century volumetric loss from glaciers facing different directions, as well as to compare modern rates of deglaciation with rates of past glacial activity as observed from geomorphological evidence.

Recent studies have shown that deglaciation has important implications for the surface hydrology of the region (Hastenrath and Ames, 1995a, b; Ames and Hastenrath, 1996; INAGGA, 1998). The formation of dangerous pro-glacial lakes are a direct result of modern glacier melting with obvious implications for human inhabitants of the region, and have likewise been the primary focus of concern and research in the region (Ames, 1998). Other work in the Andes has focused on the climatic implications for deglacial hydrology (Ribstein et al, 1995; Francou et al., 1995). Such studies highlight the need to take a more critical look at the hydrology of modern deglaciation. River water is the principle source of potable water, irrigation, and hydroelectrical power to the Andean region. With sustained negative glacier mass balance, significant amounts of modern river water discharge could be derived from glacier meltwater.

Furthermore, there is reason to believe that the proportion of glacier melt contribution to stream flow varies seasonally in the Cordillera Blanca where 70-80% of annual precipitation falls in the wet season (Kaser and Georges, 1997). This uneven distribution of annual precipitation concentrates glacier accumulation primarily to the wet season while ablation is experienced throughout the year. Distinct from higher latitude glaciers, tropical glaciers experience 33% higher ablation rates in the wet season than in the dry (Kaser, 1995; Kaser et al., 1990). However, this higher ablation would not counter balance the more strongly augmented precipitation of the wet season. The discrepancy between seasonal mass input and ablation would lead to a relatively greater proportion of glacier melt contribution to stream runoff in the dry season than in the wet season. Glaciers can thus act as effective storage reserves to 'buffer' the surface hydrology during the dry season or during periods of drought.

In this paper, three new observations related to modern deglaciation in the Cordillera Blanca are presented and discussed in terms of the implications for modern water supply and understanding climate controls. After a brief statement of the climatic setting, each observational method is presented and the results are discussed thematically. (1) The spatial extent of late 20th century deglaciation is evaluated in a single massif as a function of glacier orientation. Past glacial extent is observed by mapping moraines and reconstructing volumes using digital terrain modeling. Volumetric rates of modern deglaciation are compared to the past. (2) New glacier-hydrological observations provide an annual measure of runoff volumes from glaciated and non-glaciated watersheds. (3) Finally, observations of precipitation and runoff for tributaries of the larger Rio Santa permit a consideration of the relative importance of glacier melt to the surface hydrology.

Climatic Setting

The Cordillera Blanca is located in the north-central Andes of Peru between 9-11 degrees S latitude (Figure 1). The mountain range extends over 180 km along the eastern boundary of the Rio Santa watershed, and contains the largest glacier-covered area in the tropics (Kaser et al., 1990). The climate is typical of the tropical highlands (i.e. Hastenrath, 1991). Measurements of temperature and precipitation were taken at daily and monthly intervals over the years 1997-1999, and complement historical data gathered
at specific stations in the Rio Santa watershed. The annual range of temperature shows very little seasonal variation about the mean, while diurnal variations are typically greater (Figure 2). Annual precipitation shows distinct seasonal variations with oscillations in the position of the Intertropical Convergence Zone (ITCZ) (Figure 3). During the austral winter (April-September), the ITCZ lies north of Bolivia, and tropical anticyclones prevail over a cold and dry season. When the ITCZ proceeds to its more southerly location during the austral summer (October-March), the eastern intertropical flux brings increased warmth and moisture from Amazonia. This seasonal climate regime confines mass accumulation on the glaciers of the central Andes almost exclusively to the wet season, while ablation occurs on glacial tongues throughout the year (Kaser et al., 1990).

**Methods**

**(1) Mapping 20th Century Deglaciation**

The Guershque massif in the southern Cordillera Blanca of Peru (9°52′30″ S, 77°15′00″ W) affords an opportunity to combine field mapping and photogrammetry to reconstruct the extent of late 20th century deglaciation for three glaciers in the different geographic orientations of the principle drainages (SW, S and E) (Figure 4). Glacier surface elevations from two distinct time periods (1962 and 1999) were mapped and digitized into an integrated Geographic Information System (GIS). The differences in glacier extent and volume were calculated as the differences between the two digitized surfaces.

Initial base maps of the glacier surface topography were constructed using aerial photogrammetry on stereographic paired photographs taken in 1962. Base maps of the glacier surface topography with a nominal 3m contour interval and scale of 1:6000 were created using analytical photogrammetry on aerial photographs taken in 1962 (e.g. Brecher and Thompson, 1993). Calculations of planimetric scale on the photographs reveal a scale of ~1:30,000. Assuming a 15 micron measuring precision (standard for analytical photogrammetry) in the photograph, a maximum measuring precision of 0.64 m in the horizontal and 1.05 m vertical is possible with the analytical photogrammetry (Brecher, 1998).

Global Positioning Satellite (GPS) technology allowed for collection of modern surface elevation data on the glaciers that is well within the accuracy limitations of the study. Differential correction of the GeoExplorer II hand-held GPS field receivers has an optimal accuracy of < 1 m (Trimble, 1996). As the glaciers in question are on the scale of 1-2 km², a collection of point elevations in a 100 m grid on the glacier surface (depending on surface roughness) was proposed to provide ample data to interpolate a surface elevation map compatible with the photogrammetry. Actual data recovery varied, based on the relative surface roughness of the glacier and safety concerns in avoiding dangerously crevassed areas. Figure 4 shows the density of recovered GPS points.

GIS technology was employed to create a digital elevation model (DEM) of the region and integrate the two glacier surfaces within the same map projection. Such an elevation model gives a proper three-dimensional context on which to analyze the spatial and volumetric variance of deglaciation. Existing 1:25,000 scale topographic maps of the surrounding area were digitized as contour lines with associated elevation attributes. The DEM was constructed with these line features and other relevant point elevations using
ArcInfo™, ver. 7.0 for UNIX on a Sun SparcStation 20. A SPOT panchromatic satellite image from 1997 was also geographically rectified to the same projection and datum as the maps (UTM zone 18, 1956 Provisional South American datum for Peru). This provided a 10 m resolution image to help define the extent of the present glaciers.

(2) Measuring deglacial hydrology

Measurements of stream discharge were made over the course of a full year at glacial and non-glacial streams. The Yanamarey and Uruashraju glaciers have been the focus of previous investigations (e.g. Hastenrath and Ames, 1995; Ames and Hastenrath, 1996). However, regular observations of discharge at the different streams have not been maintained over a full hydrological year to date. Over the year 1998-99, monthly discharge measurements were made in the effluent streams directly below the glaciers using direct calculations of cross-sectional area and velocity. Downstream of the Yanamarey glacier, lake Querococha is fed by streams from both the glaciated valley of the Yanamarey as well as from a non-glaciated valley. Monthly discharge measurements were made at four sites within the Querococha watershed over the hydrological year spanning from June 1998 to July 1999 (Figure 8). Direct measurements of stream discharge were made by measuring stream velocity across a cross-sectional area of the stream.

(3) Historical data analyses

Historical discharge measurements and some limited precipitation data from stations in the tributaries to the Rio Santa exist as monthly averages for about 40 years. These data were gathered from the hydroelectrical company Egenor and analyzed as a function of watershed area determined from topographic maps. Previous work has tested the historical data and shown that the observations gathered are of good quality (Tamayo, 1996).

Observations and Discussion

Spatial Deglaciation

While solar radiation has been generally accepted as the primary source of energy responsible for alpine glacier melt (Oerlemans and Knap, 1998), its influence depends on the orientation of a glacier relative to the sun and surrounding topography. Alternatively, enhanced tropospheric temperatures occurring throughout a region would potentially override other directionally-dependent influences and result in spatially uniform volume loss (i.e. Hastenrath and Kruss, 1992). Climate research has demonstrated at least two plausible mechanisms for late 20th century warming of the troposphere that would affect tropical glaciers: (1) mechanisms of enhanced hydrologic cycling (i.e. Diaz and Graham, 1996); and (2) anthropogenic influences and increased carbon dioxide levels (i.e. Hansen et al., 1981; Ramanathan, 1981). Such influences have been observed elsewhere on tropical glaciers (Kruss and Hastenrath, 1987, 1990; Hastenrath and Kruss, 1988, 1992). These studies conducted on tropical glaciers in Africa established that uniform spatial retreat of glaciers after 1963 overshadowed the spatially variable deglaciation patterns
from the early 20th century as a result of ‘greenhouse forcing’ involving increased temperatures and absolute humidity.

Spatial variations in modern glacier fluctuations have been undertaken in only one study, focusing on the changes in equilibrium-line altitude of glaciers in the Northern Cordillera Blanca as studied remotely using aerial photography (Kaser and Georges, 1997). The study suggests that changes in glacier response have been partly influenced by a uniform rise in temperature and partly a result of changes in precipitation and effective global radiation. The question still remains how regionally extensive is the response, and what effect it has had on resultant volumes of glacier melt.

New observations of deglaciation were conducted in this study on 3 glaciers of different aspect to evaluate the relative ablative influence of spatially homogenous temperature rise over spatially-dependent climate variables such as precipitation and solar radiation. The results are summarized in Table 1 and shown graphically in Figure 4. Observations show an enhanced proportion of change in surface area melt on the glacier with eastern aspect between 1962 and 1999. Volume change was calculated using an empirically derived proportion relating surface area to volume in alpine glaciers (Chen and Ohmura, 1990a). The exponential relationship of volume to surface area explains the increase in percentage of volume change over surface area. An enhanced volume change is seen on the glacier with an eastern aspect.

Table 1: Difference in surface area and volume between 1962 and 1999 for 3 glaciers of different orientation on the Gueshque massif. Orientation is given in parentheses.

<table>
<thead>
<tr>
<th>Surface Area (km²)</th>
<th>1962</th>
<th>1999</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guesh (SW)</td>
<td>4.24</td>
<td>2.95</td>
<td>30</td>
</tr>
<tr>
<td>Guesh (E)</td>
<td>0.51</td>
<td>0.20</td>
<td>60</td>
</tr>
<tr>
<td>Mururaju (S)</td>
<td>1.30</td>
<td>0.74</td>
<td>43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volume (km³)</th>
<th>1962</th>
<th>1999</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guesh (SW)</td>
<td>0.203</td>
<td>0.124</td>
<td>39</td>
</tr>
<tr>
<td>Guesh (E)</td>
<td>0.011</td>
<td>0.003</td>
<td>71</td>
</tr>
<tr>
<td>Mururaju (S)</td>
<td>0.041</td>
<td>0.019</td>
<td>54</td>
</tr>
</tbody>
</table>

Hydrology of Deglaciation

Measurements of discharge from the Yanamarey and Uruashraju glaciers reveal interesting patterns for the understanding of seasonal variability of glacial melt water infusion to stream flow. When viewed with the mean monthly averaged precipitation they show how glacier discharge reaches a maximum ahead of the normal pattern dictated by precipitation (Figure 5). The maximum percentage of discharge from the glaciated watershed is seen in the early wet season (October), leading the later maximum downstream at the end of the wet season (March).

Glaciated and non-glaciated watersheds merging into Querococha lake were monitored separately to compare the seasonal hydrological response. Distinctive
seasonal variation in discharge volume is observed at each site, and the presence of
glacial ice dramatically changes the pattern of discharge, especially noticeable during the
wet season (Figure 6). A clear maximum in glaciated watershed discharge is reached
well before the maximum in the non-glacial stream. This pattern reinforces the notion of
the glacier ice acting to decrease the variation of discharge, retaining precipitation during
the wet season, and releasing more in the dry season. As the watershed area is extended
by moving the measurements downstream, the influence of the glaciers is diminished as
the relative percentage of ice cover decreases.

Stage recordings of monthly averaged discharge for different watersheds in the
CB reflect the clear seasonality of precipitation, as well as a modulating effect of glaciers.
Monthly averaged discharge data are available for certain locations within the Rio Santa
watershed (Table 2). Seasonal variations in precipitation have a strong control over the
discharge, as shown by the general increase in discharge during the wet months of
November through April. However, the contrast between maximum discharge in the wet
season and minimum in the dry season is decreased with a greater percentage of
contributing watershed area covered by glaciers (Figure 7). Glaciers tend to modulate
stream flow by storing precipitation of the wet season, decreasing runoff, and then
releasing melt slowly over the year, supplementing discharge in the dry season. This
modulating effect of glacier melt on stream flow is illustrated in Figure 8, comparing the
precipitation and discharge in two watersheds with different percentages of glacier
coverage. The calculated difference of monthly percentage of annual precipitation (%P)
subtracted from discharge (%Q) quantifies the buffering role of glaciers on runoff. A
positive value represents net glacier contribution to discharge, while negative value
indicates net glacier storage.

Table 2: Stream gauge stations in the Rio Santa watershed.

<table>
<thead>
<tr>
<th>Station</th>
<th>Dates</th>
<th>Contributing Area (km²)</th>
<th>Glacier Coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chancos</td>
<td>1953-1997</td>
<td>209.9</td>
<td>25</td>
</tr>
<tr>
<td>Paron</td>
<td>1953-1992</td>
<td>53.3</td>
<td>52.81</td>
</tr>
<tr>
<td>Querococha</td>
<td>1952-1997</td>
<td>62.7</td>
<td>5.62</td>
</tr>
<tr>
<td>Olleros</td>
<td>1970-1997</td>
<td>174.3</td>
<td>10.96</td>
</tr>
<tr>
<td>Llanganuco</td>
<td>1952-1997</td>
<td>86.4</td>
<td>40.83</td>
</tr>
<tr>
<td>Quitaracsa</td>
<td>1952-1997</td>
<td>384.9</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Conclusions and Implications for Future Research

The spatial variation in late 20th century deglaciation suggests the influence of
various directionally determined forcing elements. Solar radiation potentially has over-
riding influence, as explained in a previous study of the northern Cordillera Blanca
(Kaser and Georges, 1997). Simply explained, since the rainy season features most
precipitation in the form of convection that forms in the late afternoon, eastern facing
glaciers would receive a differentially greater proportion of radiation. Late afternoon
clouds would obstruct the western-facing glaciers from the direct solar rays. However, it
is also conceivable that the steep walls surrounding the east-facing glacier provide a
positive feedback to the energy supply at the surface, both longwave re-radiation and
shortwave reflection. Future work will focus on the development of an energy balance model using the terrain model to simulate the radiation receipt at the glacier surface.

Hydrologic observations of glacier runoff indicate an annual maximum during the early wet season. This correlates with periods of maximum temperature but not maximum precipitation, and furthermore precedes the maximum runoff at stations downstream. The only other hydrological studies conducted on a tropical glacier also show a maximum in discharge during November (Francou et al., 1995). It is suggested that the temperature maximum at the onset of the wet season has a predominant influence on runoff. Moreover, this challenges the notion that maximum ablation is coincident with maximum accumulation to the glacier (i.e. Kaser et al., 1996), and presents a 2-stage wet season with relative glacier storage occurring later in the wet season. Future work should focus on conducting a more complete mass balance study involving monthly measurements from snow stakes. To date, only annual stake observations have been made on a few select glaciers and for discontinuous periods of time.

Finally, stream discharge is clearly buffered by the presence of glaciers within the watershed. The degree of ice coverage controls the amount of contrast between the wet and dry seasonal discharge. This is consistent with previous studies conducted on alpine glaciers (e.g. Chen and Ohmura, 1990b). However, future work is needed to evaluate with more precision the volumetric contribution of glacier melt water to stream discharge.
References


Tamayo, W., 1996: Influencia de los glaciares en el comportamiento hidrológico de cuencas de alta montaña, estudio de casos en Perú y Bolivia. Tesis para optar el título de ingeniero civil, Universidad Nacional de Ancash, Perú.

Figure 8a: Monthly averaged precipitation and discharge recorded at stations in two watersheds of different percentage glacier coverage. Llanganuco (top) has 41% glacier coverage, and shows more discharge in the dry season, while Querococha has 6% glacier coverage, and a discharge that closely reflects the precipitation pattern.
Figure 7: Monthly averaged discharge for streams in the Callejon de Huaylas shows a distinct seasonality based on the nature of precipitation. However, the difference between runoff in the wet and dry seasons is modulated or 'buffered' by the presence of glacier meltwater discharge. Streams draining watersheds with less percentage of ice cover show more extreme variation from wet to dry season.
Figure 6: Annual discharge for different streams in the Querococha watershed. Yanout represents the effluence from the tarn below the Yanamarey glacier, and it reveals a peak discharge in the early part of the wet season, before the maximum in precipitation. Non-glacier fed stream, Quero1 shows a maximum value coincident with maximum precipitation. Quero2 is discharge at the mouth of the valley heading in the Yanamarey glacier, and reflects the glacial influence with a minor peak in November, while the peak discharge occurs later in the wet season. Quero3 is discharge from the lake Querococha, and also closely follows the annual precipitation signal.
Figure 5
A. (above): Monthly precipitation and glacier meltwater discharge for the Yanamarey glacier (top) and the Uruashraju (bottom). A peak in discharge is seen in the early part of the wet season (October - November), which precedes the annual peak of precipitation (January – March).

B. (below): Discharge at the mouth of Yanamarey glacier (Yanout) with the discharge at Querococha downstream (top); discharge at the mouth of Uruashraju glacier (Uruout) with discharge downstream at Olleros (bottom). These illustrate that the influence of glacier melt is most predominant during the end of the dry season, early wet season.
Figure 4: Contour map of the Gueshque massif and the three glaciers measured to show the spatial nature of deglaciation. The three glaciers face different orientations equal to the primary directions of drainage from the Cordillera Blanca: Gueshque (SW) is the main valley glacier, flowing to the southwest; Gueshque (E) faces to the east from the summit; and Mururaju (S) faces to the south. The black dots represent GPS measurements made to map the 1999 glacier position. The 1962 glacier position (in gray hatchure) was mapped from aerial photography.
Figure 3: Mean position of the Inter-Tropical Convergence Zone (ITCZ) in January and July (above), which is responsible for the seasonal precipitation regime in Peru. After Kaser et al. (1990). The averaged precipitation for Huaraz (below) shows the resulting variation: during the wet season (Nov-Apr), the ITCZ is closer, and large-scale convection brings abundant rain, while the northward displacement of the ITCZ is associated with a dry season (May-Oct).
Figure 2: Diurnal temperature variations (top) recorded over 35 days at the Yanamarey glacier show much greater range of variability than monthly averaged temperatures (bottom). This is because the solar variation over the course of the annual cycle is minimal in the tropics, and the high alpine environment is dry and highly responsive to radiative heating.
Figure 1: The Cordillera Blanca is located in the north-central Andes of Peru between 9-11 degrees S latitude. The mountain range extends over 180 km along the eastern boundary of the Rio Santa watershed, and contains the largest glacier-covered area in the tropics.
Figure 8b: The percent difference between monthly averaged discharge (Q) and precipitation (P) for 2 valleys of different glacier coverage of the watershed (Llanganuco, 41% glaciers; Querococha, 6% glaciers). Negative values represent storage in the watershed, as more precipitation is falling than discharging. Positive values represent loss of storage from the watershed. Greater glacier coverage yields higher storage of water in the wet season, and greater release of storage in the dry season.