

An Embedded Sensor Network for Measuring Hydrometeorological Variability Within an Alpine Valley

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ABSTRACT

Conditions of glacier recession in the seasonally dry tropical Peruvian Andes motivate research to better constrain the hydrological balance in alpine valleys. Studies suggest that glacial mass balance in the outer tropics of the Andes is particularly sensitive to variations between the dry and wet season humidity flux. In this context, we introduce a novel embedded network of low-cost, discrete temperature microloggers and an automatic weather station installed in the Llanganuco valley of the Cordillera Blanca. This paper presents data for distinct dry and wet periods sampled from a full annual cycle (2004-2005) and reports on modeled estimations of evapotranspiration (ET). The transect of temperature sensors ranging from about 3500 to 4700 m revealed seasonally characteristic diurnal fluctuations in up-valley lapse rates that promote up-slope warm air convection that will affect the energy balance of the glacier tongue. Nocturnal rainfall dominated the wet season. Strong solar forcing dominated during both dry and wet periods, but extreme seasonal variations in soil water content and cooler wet season near-surface air temperature suggests the importance of considering the process of ET. Estimates of potential ET using the widely applied Penman-Monteith FAO model suggest nearly twice as much for the dry period, and we attribute this primarily to the five times higher dry period vapor pressure deficit. We ran a process-based water balance model, BROOK90, to estimate actual ET, which was nearly 100 times greater for the wet season. These results reinforce the importance of diurnal cloud cover variability in regulating ET in the Peruvian Andes.

Keywords: tropical, alpine, embedded sensors, evapotranspiration, diurnal, seasonal modeling

INTRODUCTION

Tropical Andean glacier recession over the past century has profound local consequences for water resources, and motivates further hydroclimatic research (Francou *et al.*, 1997; Hastenrath and Kruss, 1992; Mark and Seltzer, 2003, 2005).

While observations of continued glacier recession exist throughout the Andes, only a few efforts have been made to quantify the hydroclimatic changes on a scale most relevant to human impact. Previous studies primarily focus on the rates, controls, and flux of glacier melt water directly from and within the glaciers (Francou *et al.*, 1995; Ribstein *et al.*, 1995; Wagnon *et al.*, 1999; Wagnon *et al.*, 1998), but few studies look at the fate of the water once it leaves the glacier system. Moreover, lack of accompanying precipitation and stream discharge data also preclude analyses in

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all but a handful of sites. There is an outstanding need to better quantify the volume of contributions from all hydrologic components in this dynamic climate on the regional scale where humans utilize water resources, and where future management decisions must be made.

Only initial attempts have been made to account for the regional flux of hydrologic components in the valleys of the tropical Andes, utilizing major simplifying assumptions for lack of empirical data. It has proven very challenging to maintain regular meteorological observations due to human disturbance and technical issues in the extreme environment (Georges and Kaser, 2002). Groundwater and evaporation have been assumed negligible in glacierized valleys, given high relief and steep slopes (Caballero *et al.*, 2004; Kaser *et al.*, 2003). The hydrological processes in these high tropical mountain valley deposits remain understudied, and there is a need for systematic research to better understand the impact of runoff down valley by different morphological zones (Caballero *et al.*, 2002).

The hydrologic balance of tropical glaciers at various time scales (Hastenrath and Ames, 1995; Kaser *et al.*, 2003; Francou *et al.*, 2000; Francou *et al.*, 2003) has been the focus of recent research, but measurements and model simulations of the role of evapotranspiration (ET) in the pro-glacial valleys are lacking. The low barometric pressure in high elevations promotes ET, but incident solar radiation, wind, humidity, precipitation and temperature are primary regulating components of meteorological forcing. Studies of mid-latitude pro-glacial valleys suggest significant contributions of ET to the hydrologic balance. For example, Konzelmann *et al.* (1996) found that the type of vegetation and surface texture strongly control the rate of ET at different elevations in the Dischma valley, near Davos, Switzerland. Konzelmann *et al.* concluded that ET in this alpine valley was regulated by soil moisture and the physiological behavior of the vegetation. However, the influence of soil, vegetation, and local meteorological forcing on ET in tropical pro-glacial valleys is largely unverified and assumed negligible. Current ground-based meteorological observations in the Peruvian Andes, such as Hardy *et al.* (1998) and Vuille *et al.* (2003) do not extend to pro-glacial valleys, so it is necessary to develop and deploy a new measurement network. ET is largely controlled by a combination of available surface moisture, atmospheric vapor pressure, air temperature and wind speed. Vuille *et al.* (2003) report significant increases in near-surface air temperature throughout most of the tropical Andes. Interestingly, the temperature increase varies markedly between the eastern and western Andean slopes with a much larger temperature increase to the west.

In this paper, we introduce a new network of monitoring instruments from the northeast-southwest trending Llanganuco pro-glacial valley of the western Cordillera Blanca, and report on model estimations of ET. We present data for dry and wet periods from a full annual cycle (2004-2005) and report on the sensor network design, including a transect of automatic temperature sensors ranging from about 3500 to 4700 m. We applied the Penman-Monteith FAO method of estimating hourly potential ET (ET_0) during the wet and dry periods. We ran a process-based water balance model (Brook90: Federer, 2003) to examine the influence of meteorological forcing on ET rates and compare the contributing sources of ET, and made comparisons with the ET_0 estimations. Unlike most research on processes affecting ET, which targets mid-latitude and subtropical sites, we present methods and results for a hydroclimatologically sensitive region at the tropical-sub-tropical interface, the outer tropics.

Study area

The Andean Cordillera Blanca is home to the greatest concentration of tropical glaciers on earth (Fig. 1). It is the largest and most northerly mountain range in Peru, trending NW-SE over 130 km between 8°–10° S latitude (Ames, 1998) along the Andean continental divide. Most of the glacierized area in the Cordillera Blanca discharges northwest via the Santa River, that has the least variable monthly runoff of all Pacific draining rivers.

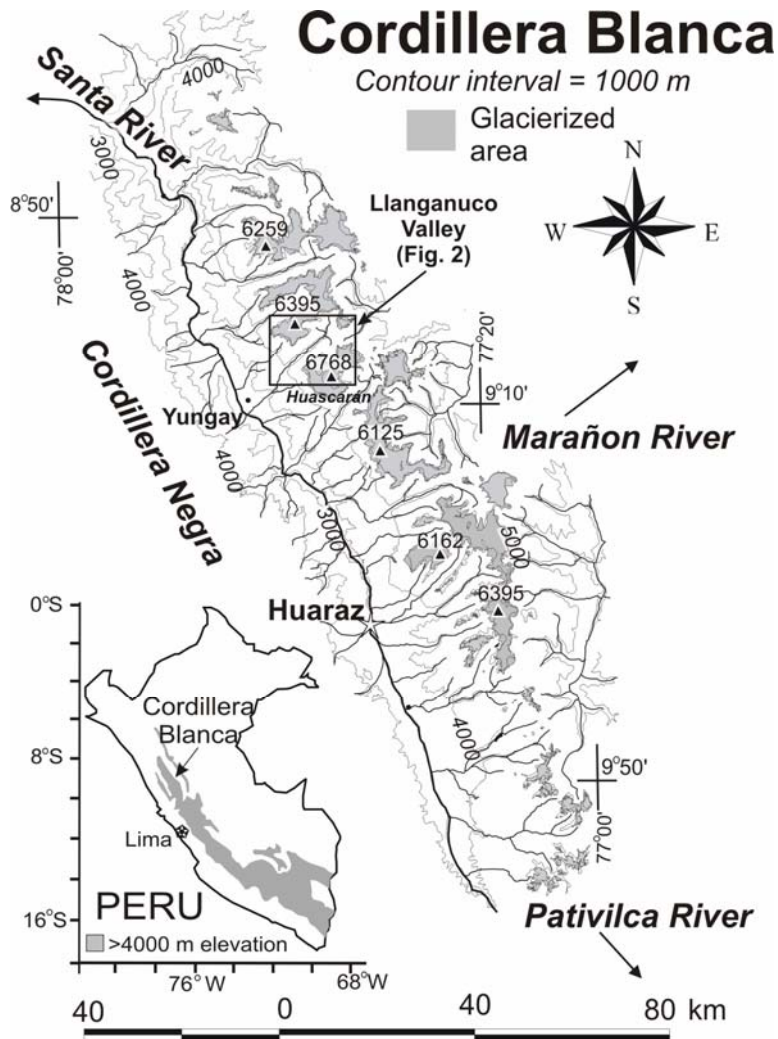


Figure 1. Cordillera Blanca regional map. The Llanganuco is one of several pro-glacial valleys in the region.

The Llanganuco valley is a classic U-shaped hanging valley tributary draining SW to the Santa River (Figs. 2 and 3). Its mouth is flanked by steep walls of the glacially sculpted granodiorite bedrock that comprises the Upper Miocene batholithic core of the range (McNulty et al., 1998). Summits that border the catchment include Huascarán (6768 m) to the south, highest in Peru, the Huandoy massif (6395 m) to the north, and Chacaraju (6113 m) at the NE valley head. The valley contains two lakes, and is a well-visited tourist attraction within the Huascarán National Park and International Biodiversity Reserve. The road along the long axis of the valley forms one of three principal transect routes over the Cordillera Blanca and reaches a high pass at the Portachuelo de Llanganuco (4767 m) and it continues down the east side.

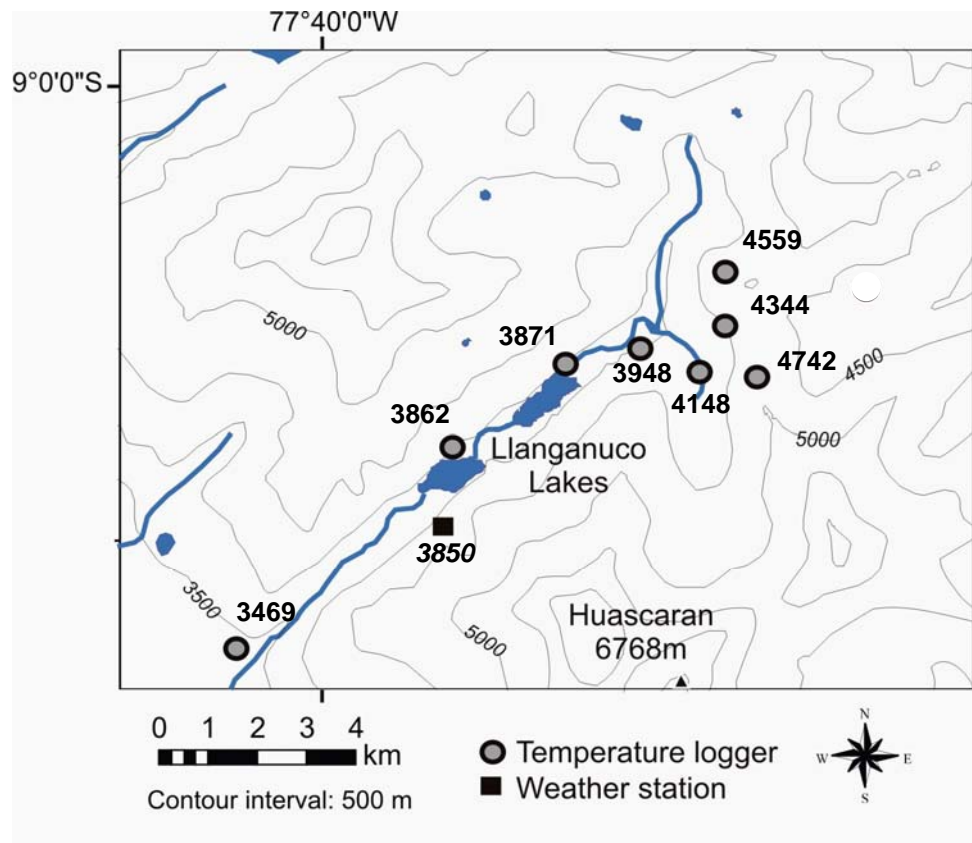


Figure 2. Llanganuco valley and location of weather instruments: note the glaciers north and south of SW-NE trending valley.



Figure 3. SW-looking view of Llanganuco valley from Portachuelo site near the highest elevation iButton logger. Note the highland grasses, steep rocky walls, terminus of glacier above the north wall, and Santa River valley in the distance.

MATERIALS AND METHODS

Field Measurements

In July 2004, we installed an automatic weather station (Onset HOBO®) in the Llanganuco tributary valley (3850 m.a.s.l.). Instrumentation specifications are available: http://www.onsetcomp.com/Products/Product_Pages/weatherstation/weather_station_logger.html. Hourly data are being collected in collaboration with the University of Innsbruck including soil moisture, soil temperature, air temperature, wind speed and direction, relative humidity, solar radiation, and precipitation.

In June 2005, we installed a set of 9 temperature loggers (iButton Thermochron®) at different elevations ranging from 3469 to 4742 m above mean sea-level (Fig. 2). Each logger is powered by an internal battery (1 year lifetime) and was programmed to record hourly intervals of air temperature. The reported iButton resolution is 0.5°C, accuracy is $\pm 1^\circ\text{C}$ with a range of -40°C to $+85^\circ\text{C}$ (<http://www.maxim-ic.com>). Each iButton logger was placed inside a specially designed $\frac{3}{4}$ " PVC shields that allowed us to embed the sensors in small trees and other inconspicuous locations (Figs. 4 and 5).



Figure 4. HOB0 weather station at base of lower lake, looking SW. Note the Polylipus (Queñual) trees and grass vegetation cover. The precipitation logger to the right was set up by Kaser, U. Innsbruck.

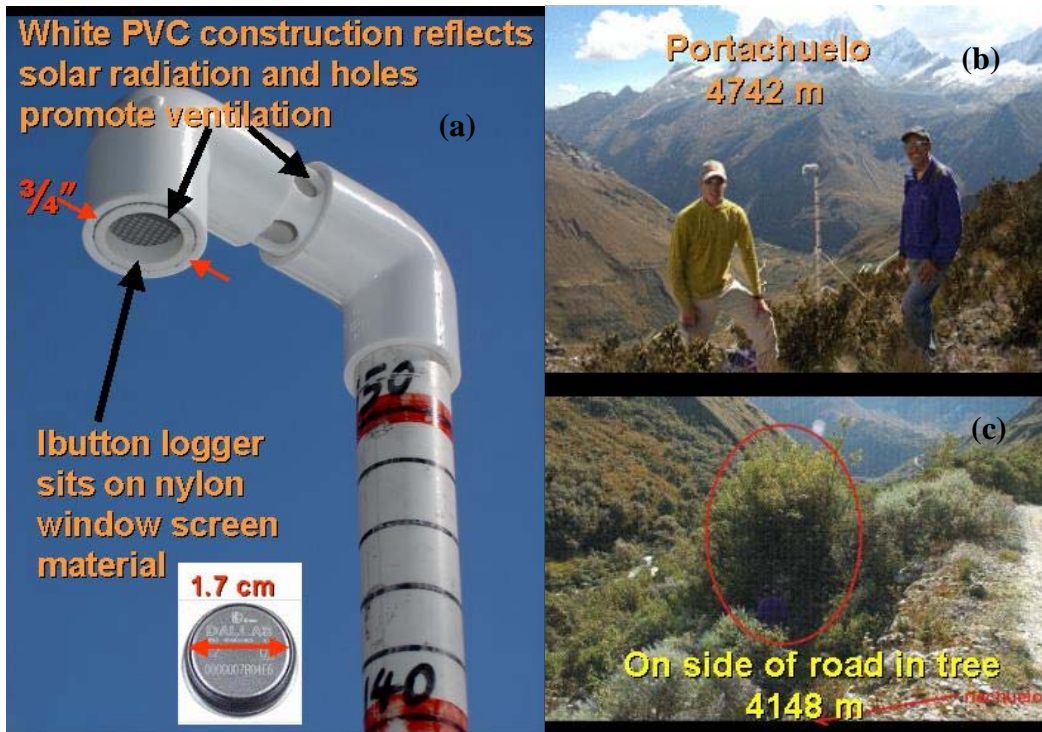


Figure 5. (a) 3/4" PVC ventilated radiation shield for iButton Thermochron logger. Note that the elbow sections are detachable for installation in vegetation. (b) Typical installation of iButton temperature loggers, one atop 1.5 m PVC post (top) and one embedded at 1.5 m inside a Queñual tree.

One iButton was calibrated under actual field conditions against the air temperature from the HOBO weather station (Fig. 6). The calibration is within the tolerance of the iButton sensors (approximately 3%). Every two months, each iButton was checked and the data were downloaded to a laptop computer using the iButton USB port adaptor (Jesus Gomez, INRENA, Perú).

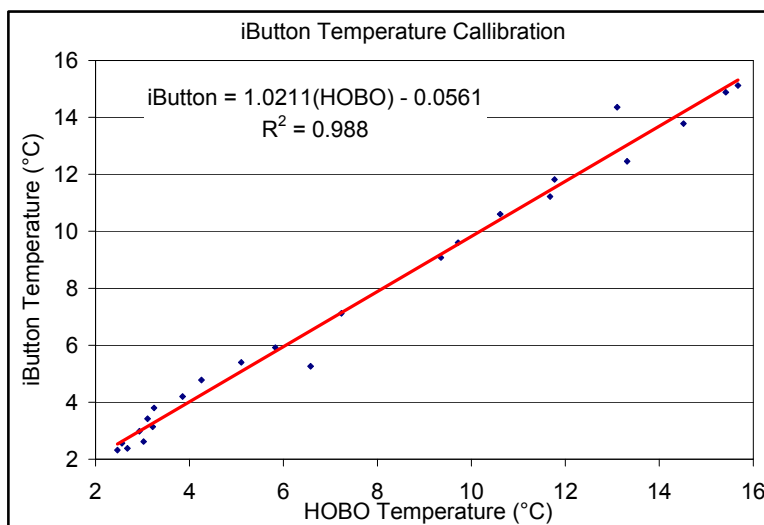


Figure 6. Calibration for iButton sensor inside PVC radiation shield.

Data analysis techniques

We synthesized all data from the 8 iButton temperature loggers on the western slope, the HOBO weather station, and the precipitation logger into hourly values to create 24-day periods during the 2005 dry, 17 June to 11 July, and wet, 7 to 31 December, seasons. These sample periods were chosen based on data availability and central proximity to the dry and wet seasons. We created composite averages of 24 hourly measurements for all 24 days making up the wet and dry periods—the diurnal cycle. Hence, composites are averages for each hour over the 24-day periods. The vector components of wind speed were calculated to create composite averages of speed and direction. Because we were interested in microscale variability, particularly elevation effects, we concentrated on analyzing and comparing the composite diurnal cycles of meteorological components for the wet and dry periods.

Estimating Evapotranspiration

It is difficult to measure ET accurately, particularly in remote mountainous regions with steep topography; most measurements require expensive equipment and frequent maintenance (refs). Consequently, there are a multitude of methods for estimating ET, most of which require site specific parameters and basic meteorological measurements. Evaporation rates, ignoring transpiration, are commonly estimated by energy balance, aerodynamic, and a combination of both methods, such as Penman (1945; 1963) and Penman-Monteith. Xu and Singh (1998; 2002) report on meteorological forcing of and compares methods of estimating ET based on input data from Changines station in Switzerland. We used a similar modeling approach and applied it to the Llanganuco valley. Allen *et al.* (1989) reports on the FAO methods for estimating potential ET (ET_0) based on Penman combination equations for reference surfaces, such as uniform 120 mm tall grass used herein. Because of its inclusion of several commonly used models for estimating ET_0 , we elected to use the REF-ET software developed by Allen *et al.* (1998) and selected the Penman-Monteith FAO method for estimating hourly ET_0 during the dry and wet periods. This will serve as a base-line for comparison to a more realistic physics-based model for ET. The equations for the FAO methods are explained in detail by Allen *et al.* (1998).

We selected the BROOK90 (v.4.4e) model (Federer *et al.*, 2003; Federer, 1995) to estimate the actual ET during the dry and wet season composite days. BROOK90 includes strong physically-based determination of ET, a graphic user interface, and the visual basic code is available for modification. The model simulates deposition and sublimation of frozen water and assumes snowfall for near-surface air temperature below -1.5°C . The model meteorological input includes solar radiation, air temperature, vapor pressure, wind speed, and precipitation. Soil and vegetation parameters were measured in the field. Additional parameters were taken from the literature as reported by Federer *et al.* (2003). Model output includes hydrological balance components of the vegetation canopy and soil surface; we here report on the ET components.

BROOK90 simulates evaporation and soil-water movement using a process-oriented approach for sparse canopies at a single location within a watershed. The model estimates interception and transpiration from a single-layer plant canopy, soil and snow evaporation/sublimation, snow accumulation and melt, and soil water movement through multiple soil layers. Potential evaporation rates are obtained using the Shuttleworth and Wallace (1985) modification of the Penman-Monteith combination equation.

Actual transpiration is the lesser of potential transpiration and a soil water supply rate determined by the resistance to liquid water flow in the plants and on root distribution and soil water potential in the soil layers (Federer, 1979). For potential transpiration, canopy resistance depends on maximum leaf conductance, reduced for humidity, temperature, and light penetration. Each soil layer and the roots of vegetation have a resistance to water flow based on field observations and published results. Aerodynamic resistances are modified from Shuttleworth and Gurney (1990); they depend on leaf area index (LAI), which can vary seasonally, and on canopy height, which determines stem area index (SAI). Potential transpiration or potential interception are obtained using the actual or existing soil surface wetness in the Shuttleworth-Wallace equations. The equations then provide the total soil or ground evaporation. The total ET is the sum of precipitation evaporated from the canopy, soil evaporation, and transpiration from the canopy.

In contrast to the six ET_0 models, the BROOK90 model provided more realistic representation of vegetation and soil parameters and allowed evaluation of the hydrologic components affecting ET. The components included infiltration, surface evaporation, transpiration, and canopy intercepted evaporation.

RESULTS

Field Measurements

We report on the results of intercomparisons for dry and wet composite diurnal cycles of air temperature, relative humidity, insolation, precipitation, wind speed and direction, and iButton temperatures.

HOBO automated weather station

We were particularly careful with our data syntheses from the humidity sensor (naturally aspirated), which was affected by supersaturation during portions of the wet season. We computed the dew point temperatures from humidity and relative humidity measurements and adjusted erroneous humidity values according to our corrections. Table 1 summarizes the results from the HOBO weather station. The ratio of dry to wet was applied to demonstrate differences.

Table 1. Comparison of average daily statistics for variables measured by HOBO weather station during the dry and wet periods.

HOBO Weather Station (daily statistics from hourly data)	Dry	Wet	Dry/ Wet
Air Temp. (°C)	7.6	6.6	1.15
Max. Temp. (°C)	16.0	12.7	1.26
Min. Temp. (°C)	1.5	3.6	0.42
Temp. Range. (°C)	14.5	9.1	1.59
RH (%)	59.5	92.4	0.64
Vap. Press. (kPa)	0.62	0.90	0.69
VP Deficit (kPa)	0.43	0.08	5.38
Insolation (MJ/m ²)	16.82	13.21	1.27
Wind (m/s)	1.42	1.18	1.20
Wind Direction (°)	39	233	N/A
Wind Constancy	0.54	0.72	0.75
0.10 m Soil Moist. (m ³ /m ³)	0.005	0.119	0.04
0.10 m Soil Temp. (°C)	13.8	12.8	1.08
Precip. (mm/day)	0.08	7.36	0.01

Comparisons of the HOBO weather station data for the composite dry and wet periods suggest significant differences between all variables of meteorological forcing. The average day during the wet period is 1°C cooler than the dry period, given the lack of rainfall and greater insolation during the dry period. Because of increased cloud cover associated with higher rainfall, the diurnal temperature range is 5.4°C less during the wet period. The average relative humidity of 59.5% for the dry period is 33% less than that of the wet season. The vapor pressure of 0.62 kPa for the dry period was 69% of that for the wet period, 0.90 kPa.

Figs. 7 through 12 illustrate the diurnal cycles for the dry and wet periods. The persistent valley winds (Figs. 10b, 11b and 12b) during the daylight hours of the wet period controls the efficiency of the impact of turbulent sensible and latent heat flux on ET rate. Assuming a saturated evaporating surface, the aerodynamic term of the Penman-Monteith method maximizes ET_0 with concurrently high wind speed and vapor pressure deficit. This assumption is good for the wet

season, but unacceptable for the dry season when the surface is extremely dry (Fig. 8). The process of near-surface water vapor removal depends to a large extent on wind speed and air turbulence. When vaporizing water, the air above the evaporating surface becomes gradually saturated. If this air is not continuously replaced with drier air, the driving force for water vapor removal and the ET rate decreases. Hence, the dominance of daytime valley winds during the wet season plays a critical role in controlling ET within the pro-glacial valley, particularly given the steep confining walls. Furthermore, drier surface conditions in the lower valley will enhance the potential for ET throughout the valley, which is plausible given the predominantly easterly synoptic flow and the rain shadow effect to the west of the mountain range.

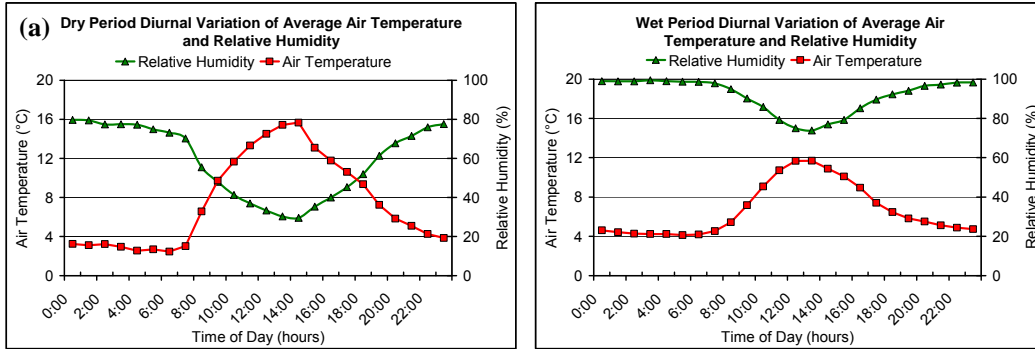


Figure 7. Composite diurnal cycle of air temperature and relative humidity for dry (a) and wet (b) periods.

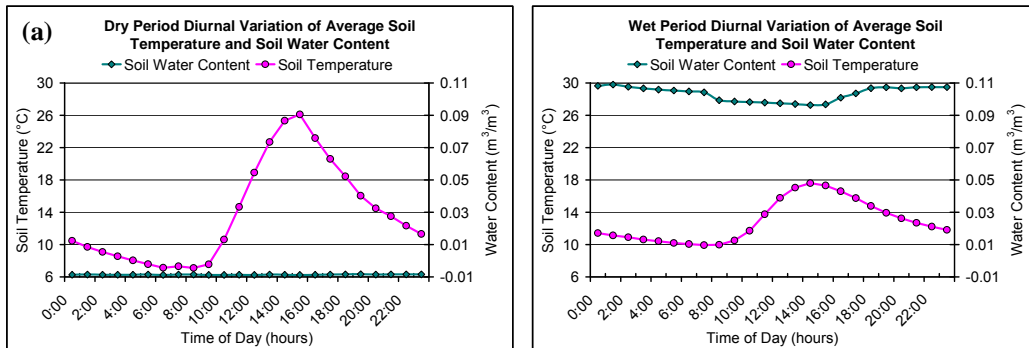


Figure 8. Composite diurnal cycle of incoming soil moisture and temperature for dry (a) and wet (b) periods.

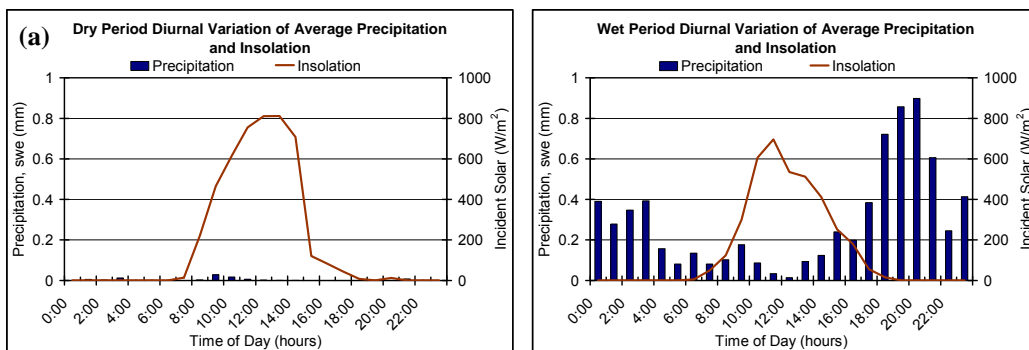


Figure 9. Composite diurnal cycle of incoming solar radiation and precipitation for dry (a) and wet (b) periods.

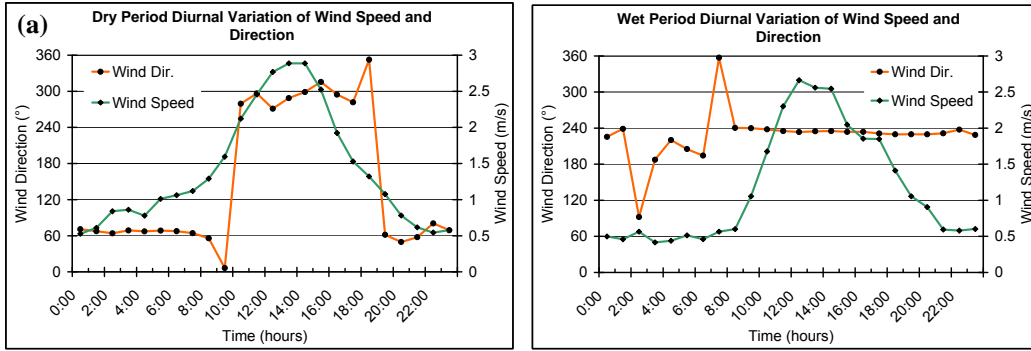


Figure 10. Composite diurnal cycle of wind speed and direction for dry (a) and wet (b) periods.

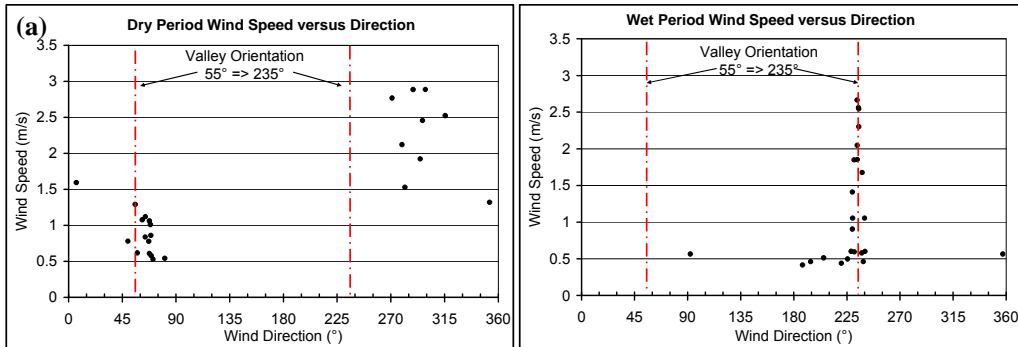


Figure 11: Composite wind speed versus direction for dry (a) and wet (b) periods.

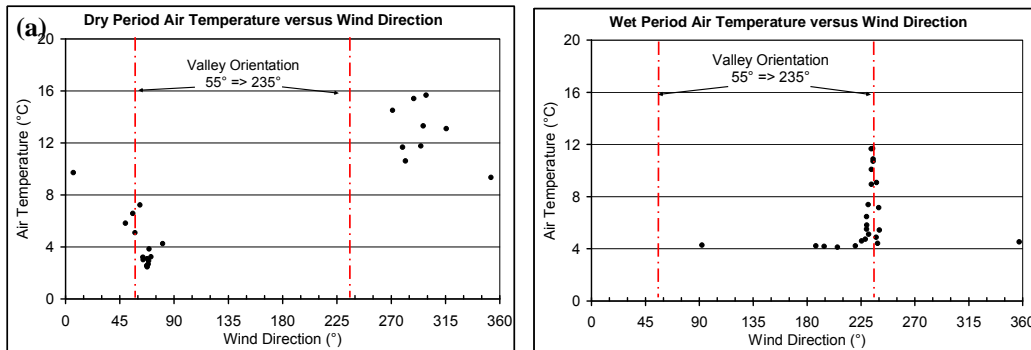


Figure 12: Composite wind speed versus air temperature for dry (a) and wet (b) periods.

iButton temperatures

Table 2 summarizes the iButton temperature profile observed during the wet and dry periods. With exception of the iButton at 3948 m, which is cooler during the wet season due to shading from the south wall off the valley, the general trend is for stronger seasonal contrasts at higher elevation. Although the up-valley “lapse rate” is not the conventional atmospheric lapse rate, it is a strong indicator of sensible heat flux within the surface boundary layer, thereby affecting the rates of ice and snow ablation. Figs. 13 provides a unique perspective on the diurnal variability of temperature as function of elevation. The strong nocturnal inversion below the level of the meltwater lakes during the dry period is not present during the wet period. In general, the lapse rate is greater below the lakes than above for both seasons, with greatest diurnal variability during the dry period. Fig. 14 shows the composite lapse rate for both seasons. The average dry period zero degree isotherm is at 5377 m above sea-level, 344 m higher than the wet period freezing level (Fig. 14). Hence, the local valley impact on ablation rate of the glacial tongue is possibly

significant, although more information on the global and synoptic forcing is necessary to make conclusions at this time.

Table 2. Average temperature recorded by iButtons during the dry and wet periods. Note the seasonal impact of “lapse rate” on the elevation of the freezing line (0°C).

iButton Elevation (m)	Dry (°C)	Wet (°C)	Dry/Wet
4742	2.84	1.77	1.60
4559	4.39	3.06	1.43
4344	5.31	3.56	1.49
4148	6.68	5.66	1.18
3948	8.12	5.48	1.48
3871	8.59	7.45	1.15
3862	7.49	6.24	1.20
3469	9.49	9.48	1.00
Lapse Rate (°C/km)	5.3	5.9	0.90
0°C Elevation (m)	5377	5033	1.07

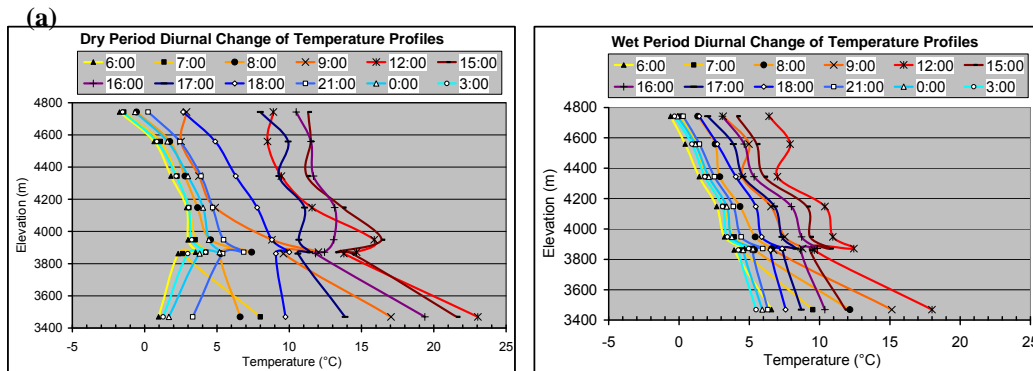


Figure 13. Diurnal variability of near-surface air temperature profiles, “lapse rate,” for dry (a) and wet (b) periods.

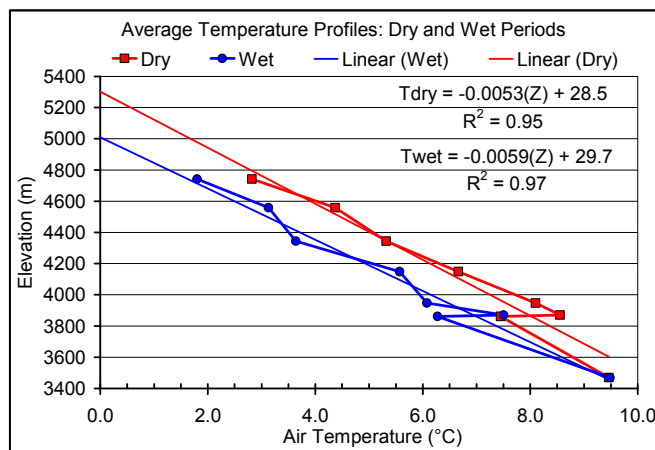


Figure 14. Composite iButton temperature profiles for dry (a) and wet (b) periods.

Model Results

We report on the (preliminary) results from the FAO and BROOK90 model simulations of ET_0 and actual ET, respectively, during the same dry and wet composites created for the meteorological data analysis. Input from the HOBO weather station and measurements of site parameters in the field were made at one central location within the valley. The resulting hydrological components for the dry and wet composite days are compared in Table 3 and Figs. 15 and 16. The magnitude of ET_0 was much greater, about two times, for the dry period, which agrees with the lack of precipitation during the dry period (Table 1).

Table 3 breaks down the hydrological components of ET based on the BROOK90 model runs for the composite hourly dry and wet periods. The BROOK90 estimate of actual ET from the wet period is 2.63 mm d^{-1} , which is 88 times that of the dry period, 0.03 mm d^{-1} . ET is 33% of daily precipitation for the dry period and 37% of the daily precipitation for the wet period, which are both significant portions of the hydrologic balance in the Llanganuco Valley. Transpiration is the greatest contribution to ET, 33% for the dry and 78% for the wet period.

Table 3. BROOK90 Estimated Moisture Fluxes Dry & Wet Periods (assuming 50% true veg. cover)

Period	Pre* (mm)	Inf (mm)	SEv (mm)	Trs (mm)	IEv (mm)	ET (mm)
Dry	0.09	0.09	0.02	0.01	0.00	0.03
% of Precip.	100	99	22	11	0	33
Wet	7.06	6.82	0.35	2.06	0.22	2.63
% of Precip.	100	97	5	29	3	37
Wet/Dry	78	76	18	206	n/a	88

*Pre = precipitation; Inf = infiltration; SEv = surface evaporation; Trs = transpiration; IEv = intercepted evaporation; ET = evapotranspiration

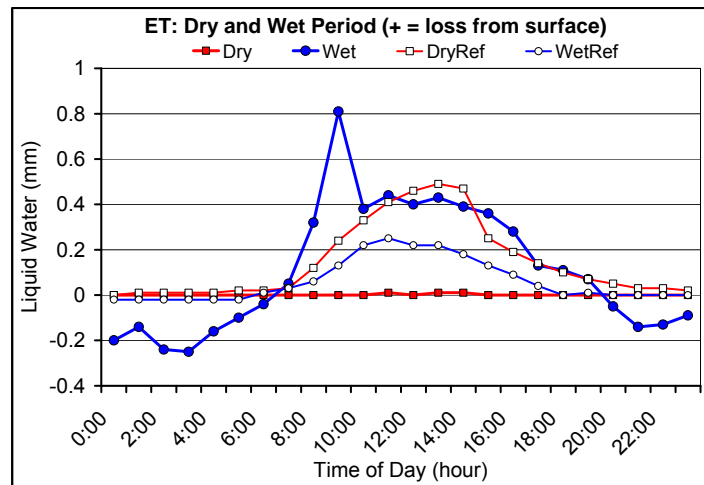


Figure 15. Penman-Monteith FAO and BROOK90 modeled ET for composite diurnal cycle for dry (a) and wet (b) periods.

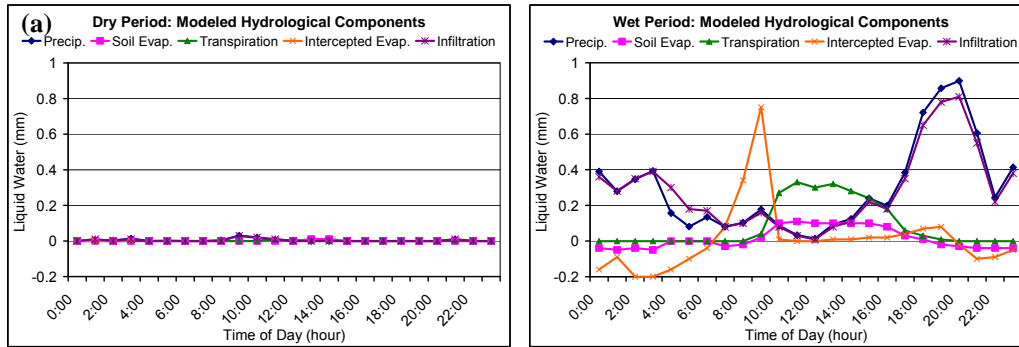


Figure 16. BROOK90 modeled components of ET for composite diurnal cycle for dry (a) and wet (b) periods.

DISCUSSION

Field and model results were interpreted and compared to explain the processes controlling ET within a pro-glacial valley.

Meteorological Measurements

The new sensor network initiated by this project permitted high resolution, discrete monitoring of air temperature at different elevations within a pro-glacial valley. Calibration of iButton temperature logger with the shielded temperature sensor on the HOBO weather station suggested a strong correlation, $r^2=0.988$, and this gave us high confidence in our interpretation of the measurements. As expected, analysis of hourly data from 2005 revealed evidence for a strong diurnal and wet versus dry seasonal dependence of meteorological forcing within the valley. The dry/wet ratio of 1.27 for daily insolation is smaller than we expected given the absence of precipitation during the dry period and much high precipitation total for the wet period. The hourly composite of precipitation for the wet period (Fig. 9) clearly shows the nocturnal tendency for precipitation and hence convective cloud formation at night, and strong solar forcing during daylight hours.

However, solar forcing was surprisingly similar for both the dry and wet periods, since most convection (rainfall) during the wet season occurs an hour or two prior to sunset and dissipates prior to sunrise. This strong diurnal convective cycle coupled with a persistent up-valley wind and a strong daytime lapse rate during the wet season suggests the plausible influence of daytime surface heating west and down slope of the pro-glacial valley. Furthermore, since clouds accompany precipitation, we concluded that nocturnal cloud cover strongly influences interseasonal and diurnal cycles of net radiation. Furthermore, this may establish a connection between cloud cover (and precipitation) and anthropogenic development in the Santa River valley, which receives most of its water from pro-glacial valleys along the western Cordillera Blanca, such as Llanganuco (Fig. 1). As demonstrated by Vuille et al. (2003), it is the western slope of the Cordillera Blanca that is experiencing the highest rate of warming based on weather station records. If this warming trend continues, we would expect to find drier and stronger up valley winds during both seasons. Forced by orographic uplift of the western slope, these near-surface winds would promote stronger nocturnal convection during the wet season.

This is one of our arguments for continued expansion of ground-based meteorological networks within tropical proglacial valleys. We are also interested in more accurately estimating the evapotranspiration rate within the valleys. Our model results are preliminary and we will require additional field measurements to verify and more accurately initiate the BROOK90 model.

Importance of diurnal cycles in the Tropics

Diurnal variation is related to the large and well-defined cycle in solar heating during a 24-hour period, and it represents one of the most fundamental components accounting for the variability of the climate system. Numerous observation studies have documented diurnal variation of deep convection, precipitation, cloudiness, and outgoing longwave radiation over the tropics (e.g., Gray and Jacobson, 1977; Duvel and Kandel, 1985; Hendon and Woodberry, 1993; Chen and Houze, 1997; Yang and Slingo, 2001; Nesbitt and Zipser, 2003; among many others). Mapes *et al.* (2003) observed an afternoon maximum rainfall over most of South and Central America that is typically composed of relatively small convective cloud systems. Furthermore, Mapes *et al.* found a nocturnal maximum of rainfall over some large valleys in the Andes, and this would include the larger hanging valleys, such as Llanganuco. Poveda *et al.* (2005) use hourly records from 51 rain gages in the Tropical Andes of Columbia to find clear diurnal cycles in precipitation, with minima between 0900 and 1100 local time, and nocturnal maxima on the western flank of the Central Andes. In addition, Poveda concluded no relation between the timing of the strong seasonal variability of rainfall maxima and elevation.

Bendix *et al.* (2006) used K-band rain-radar to study convection in a valley with east-west orientation between the southern Equadorean Andes and the Amazon basin. Results revealed that a great portion of rainfall is of stratiform character, and discovered the existence of embedded convection and/or showers produced by local heating for the overall amount of rainfall. Bendix *et al.* (2006) further suggests that cold air drainage flow from the Andes and low-level confluence due to the concavity of the Andean chain in this area leads to convective instability in the nocturnal Amazonian boundary layer, which is extended to the east-west oriented Andean valley the predominant easterlies in the mid-troposphere. Rain clouds with at least embedded shallow convection can overflow the bordering ridges of the San Francisco valley providing rains of higher intensity at the ECSF research station. On the contrary, Bendix *et al.* found that afternoon convective precipitation can be caused by locally induced thermal convection at the bordering slopes (up-slope breeze system) where the ECSF station profits from precipitation off the edge of these local cells due to the narrow valley. Recent remote sensing studies demonstrate pronounced diurnal variability of tropical rainfall intensity at synoptic and regional scales (Sorooshian *et al.*, 2002; Bowman *et al.*, 2005). Hence, evidence from various scales of observation suggest a strong influence of diurnal cycles in tropical regions, including the Andes Mountains.

CONCLUSION

From our meteorological and model results, we make the following conclusions for this proglacial valley. Additional years and observations of nearby valleys are anticipated. It is important to note that we are using the term lapse rate in an unconventional sense, not the free atmosphere, but rather the effects within the surface boundary layer up the valley floor. First, the steepest lapse rates occur below the lakes for both wet and dry seasons, and the lapse rate is significantly smaller above the glacial lakes. We partially attribute this elevation effect to the heterogeneous vegetation and topographic characteristics of pro-glacial valleys. Furthermore, the dry season nocturnal inversion below the lakes is not evident during wet season. Most precipitation (and cloud cover) occurs between sunset and sunrise during the wet season, hence insolation at the ground is strong during both seasons. Up-valley winds dominate during sunlight hours in both wet and dry seasons, but abruptly shift to katabatic winds during the dry season at sunset. The combination of valley winds and steep lapse rate below the lakes suggest local warm air advection within the surface boundary layer will contribute to evapotranspiration and lower glacial melt. Furthermore, the up-slope winds may enhance convective precipitation, particularly during the wet season after sunset. The BROOK90 output suggests that transpiration is a significant source of ET when soil moisture is available during the wet season. The model results suggest that the predominance of cloud-free daylight conditions and relatively high solar input enhance ET during the wet season. ET was insignificant throughout the dry season.

Future Work

We are installing additional humidity, wind, solar, and soil moisture sensors to evaluate spatial variation of ET. We plan to make direct measurements of ET using lysimeters and evaporation pans, and to use BROOK90 to perform a formal sensitivity analysis of ET to meteorological forcing. In addition to site-specific parameters, the meteorological input includes solar radiation, air temperature, vapor pressure, wind speed, and precipitation. Model output includes various hydrological balance components of the vegetation canopy and soil surface. We plan to evaluate the reliability and realism of estimated ET and to determine the sensitivity of ET to variables measured at the HOBO site in the Llanganuco valley. Future modeling will focus on more accurate measurements of parameters for BROOK90 and the elevation effects on ET and total ET for the valley.

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