Impact of the El Niño-Southern Oscillation on Atmospheric Conditions within Tropical Pro-Glacial Valleys

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Abstract

El Niño-Southern Oscillation (ENSO) is known to be the primary modulator of inter-annual weather patterns in the Andes, but its impact in the Cordillera Blanca (White Range) is not fully understood. Starting in 2004, an autonomous sensor network (ASN) was installed in the Llanganuco Valley in the Cordillera Blanca, Peru consisting of two automatic weather stations (AWS) located at the base and upper ridge of the valley connected by four air temperature/humidity micro-loggers at equal elevation intervals. The ASN permits high resolution evaluations of the micro-scale meteorology within the valley. Twenty-four hour composites and monthly averages of wind, air temperature, and precipitation obtained from the ASN were analyzed for the historical wet and dry seasons between the years of 2005 and 2015. The evidence suggests that teleconnections exist between eastern equatorial Pacific Ocean sea surface temperatures and meteorological forcing within the Valley. Warm ENSO phases promote wetter than normal dry seasons and dryer than normal wet seasons and visa versa for cold phases of ENSO. Air temperature is strongly positively correlated to warm ENSO phases during the wet season and depends on elevation during the dry season. The observed seasonality is, in part, attributed to interactions between channeled synoptic flow and thermally driven valley winds. Although the sporadic availability of data prevents definitive conclusions at this time, recent improvements in the ASN infrastructure will facilitate deeper understanding of how pro-glacial valley microclimates interact with synoptic scale systems such as ENSO.
1. Introduction

1.1 Background

The glaciers of the Cordillera Blanca, Peru (9°S) have been on a track of persistent decline since the mid-20th century (e.g. Vuille et al., 2008b, 2008a; Mark and Seltzer, 2005; Kaser and Georges, 1997). Glacial meltwater is an integral water resource for populations in the Santa River Valley adjacent to the Cordillera Blanca as it provides a year round supply of water for purposes such as agriculture, city services, and domestic use (e.g. Bury et al., 2011; Mark et al., 2010; Vuille et al., 2008b, 2008a). The melt is being caused by a destabilization of the glacier mass balance which, under conditions of equilibrium, maintains a glacier’s mass over a long period through the cancelling of melting and accumulation (Vuille et al., 2008a). A glacier is balanced when the mass of ice lost from sublimation and melt equals the mass gained by accumulation of snow and ice. An inequity of mass loss and gain shifts the balance either negative when loss is greater than gain or positive when gain exceeds the loss. For the latter half of the century the mass balance in the Cordillera Blanca has been perpetually negative leading to the decline that is now being seen as a trend in tropical glaciers worldwide (Vuille et al., 2008a).

The mass balance of the glaciers in the Cordillera Blanca is being disrupted in part due to the warming effects of climate change, but most significantly through the resultant changes in the patterns of atmospheric humidity, cloud cover, and precipitation (Wagnon et al., 1999; Francou et al., 2003; Vuille et al. 2008a, 2008b, 2003; Mark and Seltzer, 2005; Hellström et al., 2010). Humidity, through its contributions to latent heat transfer, sublimation, and melt, is a dominant force for affecting the mass balance (Vuille et al. 2008a, Hellström et al, 2010). Likewise, precipitation and cloud cover patterns play a critical role by governing surface albedo and all-wave radiation (Wagnon et al., 1999; Francou et al., 2003; Vuille et al. 2008a, 2008b,
2003; Mark and Seltzer, 2005; Hellström et al., 2010). The documented lack of measurements of these critical variables in the Cordillera Blanca has hindered many efforts to evaluate the teleconnection between the glaciers and regional climate (Vuille et al., 2008a; Hellström et al., 2010).

In 2004 an Autonomous Sensor Network (ASN) was installed in the Llanganuco Valley of the Cordillera Blanca to provide insight into the atmospheric moisture flux within a pro-glacial valley microclimate. The impact of pro-glacial valley microclimates on glacier mass balance in the tropics has been largely disregarded in prior research, in part, due to the technical difficulty of establishing a reliable dataset in such remote areas (Hellström et al., 2010). A key finding of Hellström et al. (2010) indicates that atmospheric moisture from valley-sourced evapotranspiration may play a more significant role in the glacier mass balance than previously thought due to a thermally driven microscale valley wind system. The winds, caused by un-even heating of the surface of the valley, could plausibly act as a mechanism to transport atmospheric moisture to the glaciated mountain peaks and thus contribute to cloud formation and nocturnal precipitation (Hellström et al., 2010). Overall, the study revealed the need to better understand the interactions of pro-glacial valley microclimates on glacier mass balance.

It is well known that glacier mass balance changes inter-annually according to synoptic scale fluctuations such as El Nino-Southern Oscillation (ENSO) (e.g. Vuille et al., 2008a; Francou et al. 2003; Francou et al., 1995; Andreoli and Kayano, 2005). The term synoptic is used to describe atmospheric processes that occur on a scale of hundreds to thousands of kilometers over a period of days to weeks. Microscale systems, on the other hand, describe phenomena that occur on a scale of around 1 kilometer or less and are short lived, such as the Llanganuco valley wind system which shifts diurnally. Limited data availability at the time of the Hellström et al.
(2010) study precluded further analysis into inter-annual changes of air temperature, precipitation, and winds within the valley. With increased data availability since 2010, including that from an additional weather station, it is worth re-evaluating the findings reported by Hellström et al. (2010) and documenting inter-annual fluctuations seen in the Llanganuco Valley microclimate to reveal how it interacts with synoptic scale fluctuations such as ENSO.

1.2 The El Niño-Southern Oscillation

ENSO is a fluctuation of sea surface temperature (SST) and upper tropospheric winds in and over the eastern equatorial Pacific Ocean that impacts weather on a global scale (e.g. Andreoli and Kayano, 2005; Trenberth, 1997). The waters of the eastern equatorial Pacific are characterized by relatively cold ocean temperatures and high atmospheric pressure. The cold SSTs relative to the western and central pacific are caused by an ocean current which upwells cold water from the deep sea to the surface (e.g. Vuille and René, 2011). Every three to seven years easterly trade winds weaken near the equator causing the current to slow thus reducing the cold upwelling and allowing warmer waters to penetrate farther east (e.g. Vuille and René, 2011). The result is warmer than average SST in the east and anomalous westerly winds aloft (e.g. Vuille and René, 2011). The phenomenon is often referred to as an El Niño event, or warm phase of ENSO, in the case when the 5 month running mean SST anomalies are greater than plus 0.5°C for at least 6 months (Trenberth, 1997). In the cases where trade winds are stronger than usual, the opposite effect can be observed where colder than average water temperatures dominate in the east and easterly winds aloft are anomalously high. Such events with SST anomalies less than minus 0.5°C for the same criteria are referred to as La Niña events, or cold phase of ENSO (Trenberth, 1997).
The impact of ENSO in South America has been extensively documented primarily as a modulator of precipitation (Andreoli and Kayano, 2005). In the northern Andes Mountains, including the Cordillera Blanca, ENSO regulates precipitation, humidity, and air temperature and is therefore the most significant player in inter-annual changes to glacier mass balance (Vuille et al., 2008a). Studies using glacial runoff records and the available, albeit scarce, climate datasets in the Cordillera Blanca have concluded that warm phases of ENSO tend to be attributed to warmer and dryer wet seasons whereas cold phases have the opposite effect (Mcglone and Vuille, 2012; Vera and Silvestri, 2009; Vuille et al., 2008a, Kaser et al., 2003; Garreaud et al., 2009; Vuille, 1999). The synoptic wind anomalies associated with ENSO serve as a teleconnection mechanism between SST anomalies and the glaciated mountains (Vuille et al., 2008a). The westerly wind anomalies that occur during warm ENSO phases block moist Amazonian air from reaching the leeward side of the Cordillera Blanca causing reduced precipitation by creating less snowfall and less accumulation, warmer temperatures, and increased glacial melt. The strong easterly winds associated with cold phases tend to push the moist air over the range supporting increased precipitation, cooler temperatures, and glacial accumulation. More comprehensive studies of the Zongo Glacier in the Bolivian Altiplano region have found similar impacts however caution should be exercised when attempting to compare the two regions due to an occasional latitudinal shift in the ENSO teleconnection mechanism (Francou, 1995; Francou et al., 2003; Vuille et al., 2008a).

1.3 The Llanganuco Valley Microclimate

Supported by data from the ASN, Hellström et al. (2010) documented a unique microclimate in the pro-glacial Llanganuco Valley by evaluating diurnal patterns of meteorological forcing for one annual wet and dry season cycle in 2004 and 2005. Air
temperatures are fairly homogeneous throughout the year but humidity, precipitation, and wind direction vary greatly depending on the season. Eighty-five percent of the annual rainfall in the valley falls in between the months of November and April. The wet season is characterized by frequent rainfall, high humidity, and persistent up-valley winds from the west. At higher elevations within the valley, precipitation may fall as snow or ice pellets at any time throughout the year, but frozen accumulation is usually nominal and short lived. During the dry season months of June, July, and August, little to no precipitation falls, humidity is low, and winds shift diurnally from down-valley in the night to up-valley during the day. Meteorological forcing in the dry season has a more pronounced diurnal cycle due to the lack of atmospheric moisture and hence cloud cover, which encourages strong solar heating throughout the daylight hours and strong loss of heat at night.

When valley wind conditions were evaluated against NCEP reanalysis data it became clear that synoptic flow often opposed the flow measured within the valley, particularly during the wet season (Hellström et al., 2010). This finding indicates a decoupling of the wind systems demonstrating that the flow being measured within the valley is not the result of channeled synoptic winds (Hellström et al., 2010). The pattern is indicative of the valley wind system observed that could serve as a transportation mechanism for moisture to the glaciated peaks thus impacting glacier mass balance.

This study will present data from two automatic weather stations in the Llanganuco Valley which have been logging hourly meteorological data since 2004 as part of the ASN utilized by Hellström et al. (2010). Monthly averages of air temperature, precipitation, and solar radiation will be evaluated for correlations to pacific sea surface temperature anomalies to identify
connections to ENSO. Further evidence for the valley wind system will be presented and interconnections to synoptic winds will be discussed.

2. Methods

2.1 The Autonomous Sensor Network

The ASN serves as the primary source for in-situ data during the course of this study. In July, 2004 the first automatic weather station (AWS) was installed at the Lower Lake in the Llanganuco Valley at 3835 m (a.s.l.). The station rests on a surface of natural grasses and shrubbery and faces minimal wind obstruction from vegetation. NE (~50°) of the station points up valley and SW (~230°) points down valley. To the north and south of the station are the steep rock walls of the valley which exceed 1000 meters in height. The station continues to measure and log hourly wind speed, wind direction, air temperature, relative humidity, solar irradiance, and soil temperature. The hardware and sensors are sourced from Onset Computer (onsetcomp.com) and are maintained and downloaded on a yearly basis.

![Fig. 1. (a) A regional map of the Cordillera Blanca, Peru. (b) A satellite image of the Llanganuco Valley with overlaid elevation contours and AWS locations. Note the glaciers and steep elevation gradient. Map (a) is republished from Hellstrom et al. 2010 with permission.](image)
In July 2006, a second AWS (referred to as Portachuelo), as shown in Figure 1, was installed at the upper pass (4767 m a.s.l.) of the valley. The station has the same sensors as the Lower Lake station minus an air temperature/humidity sensor and radiation shield which was not installed until July, 2015. Prior to the upgrade, temperature and relative humidity were logged hourly via a Lascar USB-2 micro-datalogger (lascarelectronics.com) shielded from solar radiation by a thin tin cone insulated by two Styrofoam plates. The station rests on a rocky knife-edge ridge separating the east and west valley. It is still within the valley walls, but is high enough in elevation to be impacted directly by synoptic winds. There are no wind obstructions to the south, east, and west. An underrepresentation of northerly winds can be expected due to the obstruction of a rock wall to the north. Between the Portachuelo and Lower Lake AWS stations, at approximately 200 meter intervals, are four Lascar dataloggers with identical setups to the one installed at Portachuelo. Effort was made to locate the loggers in discrete, shaded locations at two meters above the ground.

2.2 Data Acquisition and Synthesis

Hourly meteorological data from the ASN were compiled for all years available starting in 2004 and integrated onto a single continuous timestamped Microsoft Excel file. In many cases, the station dataloggers were not logging on the hour. In such cases, the timestamp for air temperature, relative humidity, accumulated precipitation, solar irradiance, wind speed, and soil temperature was rectified using the following method:

\[ V + \frac{T_{offset}(V_{next} - V)}{T_{interval}} \]  

(1.)

\( V \) indicates the meteorological data value temporally closest to the rectified hour on the hour and \( V_{next} \) indicates the next data value in the time series. \( T_{offset} \) indicates the time difference in minutes between the rectified hour and the datalogger timestamp. For example, the rectified hour of a
data value logged at 15:44 is 16:00 and it has a 16 minute $T_{offset}$. The value at +1 hour (16:44) will be considered $V_{next}$. If the data is hourly, the $T_{interval}$ becomes 60 minutes. For cases in which data was exactly 30 minutes off of the hour, the same principle would apply and the output value would be exactly half way in between the $V_{next}$ and $V$.

Wind direction was rectified by initially converting wind speed ($S$ in m/s) and wind direction ($D$ in degrees) to vector components using the following methods and then applying formula 1 to the vectors.

\[ Y \text{ vector} = -S \times \sin\left(\frac{D\pi}{180}\right) \]  \hspace{1cm} (2.)
\[ X \text{ vector} = -S \times \cos\left(\frac{D\pi}{180}\right) \]  \hspace{1cm} (3.)

The resultant vectors can be converted back into wind direction degrees using the logic in formula 4.

\[ IF \ y < 0 \ then \ 90 - \tan\left(\frac{y}{x}\right) \times \frac{180}{\pi} else \ 270 - \tan\left(\frac{y}{x}\right) \times \frac{180}{\pi} \]  \hspace{1cm} (4.)

Where $x$ and $y$ represent their corresponding wind vectors calculated using formulas 2 and 3.

2.3 Analysis and Quality Control

Data from the Lower Lake and Portachuelo AWS units were averaged for the full months of January and July. The two months were chosen as points of analysis in this study because they had relatively complete data records and fall in the middle of the wet and dry season respectively. Correlation analysis was applied to the monthly averages of the two stations and ENSO SST anomalies from region 3.4 (5°N-5°S 170-120°W). Correlations with $r$ values less than 0.3 were considered negligible. The methods described in section 2.2 with formulas 2-4 were used to obtain a monthly average wind direction in order to build the wind vector charts used in this analysis.
All data were evaluated for accuracy and removed if there were unrealistic deviations from the normal conditions within the valley. Certain data were also omitted if there was a documented concern with the sensor’s integrity. Full days of data were used as a metric for quantifying the quality of the monthly averages (see Appendix A). For precipitation accumulation, wind speed, and wind direction, any month with less than 31 days of data was omitted. For air temperature, the month was considered acceptable if it had greater than 10 days of data to represent the monthly average. At the Lower Lake AWS, 39% of the months included in this study for air temperature were based on less than 31 days of data. At the Portachuelo AWS, 25% of the months sampled has a record less than 31 days.

3. Results and Discussion

3.1 Inter-annual meteorological variability and correlation to ENSO

The graphs shown in Figures 2 and 3 provide a visualization of ENSO SST anomalies with relation to meteorological forcing within Llanganuco Valley. Each variable is broken down into monthly averages for January representing the wet season and July representing the dry season. Each graph is further broken down to show differences of elevation using data collected from the Lower Lake and Portachuelo AWS units. Years without displayed data values either have no data available or have had data omitted for quality control concerns. It is important to

![Fig. 2](image_url). Graphs depicting Niño region 3.4 monthly mean SST anomalies versus total precipitation accumulated at elevation for the wet (January) and dry (July) season within the Llanganuco Valley (Lower Lake and Portachuelo stations).
note that the dashed line connecting SST anomalies is a visual aid for correlation and does not represent the actual values between years.

During the wet season of 2009, ENSO was in a weak-moderate cold phase with a SST anomaly of minus 1.0 °C. Precipitation, as shown in figure 2, was fairly equal between the two stations and was anomalously high overall. In 2010 a moderate warm phase of plus 1.5°C contributed to significantly less, although normal, precipitation amounts during the wet season. During the dry season of 2009, the SST anomaly was plus 0.7°C indicating a weak warm ENSO phase which produced above normal precipitation for both stations. During the dry season of 2010, a moderate cold phase with an anomaly of minus 1.1 °C contributed to a decrease in precipitation. While the limited data prevents definitive conclusion at this time, the evidence suggests that there is a positive correlation between precipitation and SST anomalies during dry season and a negative correlation during the wet season. The results indicate that precipitation variability within the valley is similar to that of the rest of the Cordillera Blanca with relation to ENSO (e.g. Mcglone and Vuille, 2012; Vuille et al. 2008a).

Fig.3. Graphs depicting Niño region 3.4 monthly mean SST anomalies versus monthly mean air temperatures at elevation for the wet (January) and dry (July) season within the Llanganuco Valley.
Figure 3 demonstrates a strong positive correlation, regardless of elevation, between SST anomalies and air temperatures within the valley during the wet season. The upper station correlated the closest to SST with a nearly perfect r value of 0.94. The two stations correlate very strongly (r=0.99) with each other. The results verify the findings of Hellström et al. (2010) and align with the findings of other prior research indicating that El Niño phases tend to produce warmer than average air temperatures during the wet season. For the dry season, figure 3 presents a slightly different dynamic. Air temperature at the upper station correlates moderately to SST with an r value of 0.48, but the lower station sees no such significant correlation. There appears to be a teleconnection mechanism between the two valley stations during the wet season that is absent during the dry season. This disconnect is likely caused by increased solar heating of valley walls during the dry season due to a lack of cloud cover and, most notably, by the seasonal shift of valley winds. During the wet season, clouds block a significant percentage of incoming solar radiation that causes the surface to warm. The reduced cloud cover during the dry season would allow for increased solar heating of the valley walls which would cause the valley to warm to greater levels than what would be present under the typical conditions brought on by ENSO.

The poor correlation of air temperature among the two AWS units in the dry season combined with the seasonal shift of valley winds provides evidence for a teleconnection mechanism between the two stations. Figure 4 breaks down the wind vectors for the wet and dry seasons at the lower and upper stations. The dry season shown in Figure 4 is ENSO neutral and the wet season occurs during a weak cold phase. During the wet season, up-valley winds prevail at both stations whereas during the dry season the up-valley wind is only recorded at the upper station. During the dry season, the lower station experiences a consistent down-valley flow. The
seasonal reversal of wind at the lower elevations in the valley likely contributes to the lacking correlations seen between station temperatures during the dry season. The up valley wind can serve as a transportation mechanism for the warm air sourced from daytime solar heating within the valley. During periods in which there is a down-valley wind, the transportation mechanism is not present and the air temperatures at the two stations do not align as they would if an up-valley wind was in place. The upper station, unlike the lower station, is exposed to synoptic winds year round so it can be more directly regulated by ENSO. The closer connection to ENSO explains why it reports higher correlations to SST anomalies than the lower station regardless of the season.

**Lower Lake [3835 m]**

**Portachuelo [4767 m]**

![Wind vector charts](image)

**Fig. 4.** Wind vector charts broken down by station and season.
3.2 Inter-annual, seasonal, and diurnal intra-valley wind patterns

As one would expect, the south-easterly component is the strongest at the upper station where there can be a greater influence of synoptic scale easterlies. The south westerly component observed at Portachuelo in January (Fig. 4) is particularly interesting as it demonstrates that winds flow about half the time from within the valley during the wet season. As shown in Figure 5, graph B, winds shift slowly from west to east and then to back to west throughout the day. This evidence of a diurnal cycle indicates that Portachuelo is impacted, at least partially, by valley winds during the wet season unlike during the dry season. It is also notable that winds do not respond similarly between the two stations. At the Lower Lake, the wind direction remains steady during the day and evening and becomes variable at night. The shift to the WSW at Portachuelo in the evening aligns temporally to the diurnal precipitation maxima in the valley documented by Hellström et al. (2010). Based on this data, it could be plausibly assumed that moist air originating at lower elevations within the valley is being transported to the upper elevations. The flow is likely, at least partially, thermally driven as it changes diurnally (Hellström et al., 2010). The interaction of moist valley winds from the west and strong synoptic easterlies could be a precursor to cloud formation and perhaps convection at the ridge which would explain the typical occurrence of precipitation in the evening.

The winds shown in the 24-hour composite graphs C and D of Figure 5 show very consistent easterly winds during the dry season unlike what was found by Hellström et al. (2010) who identified a distinct diurnal wind shift in the 2005 dry season. Diurnal patterns are identifying traits of a valley wind but do not appear to be common to all dry seasons. Unlike valley winds, synoptic winds do not fluctuate diurnally. The consistency of wind direction shown in Figure 5 during the 2013 dry season implies that the dominant flow is from synoptic
channeling rather than valley winds such as those that were present in 2005. The cause for the differences between the two dry seasons is likely ENSO. In July 2013, there was a minus 0.3°C anomaly of SST which would have supported a modest anomaly of stronger easterly winds aloft which could plausibly channel down the valley and overcome the valley wind system. In 2005 ENSO was in a weak warm phase of plus 0.3°C which would have contributed to a slight westerly wind anomaly in the upper troposphere. That anomaly could plausibly block the synoptic easterlies from channeling down the valley at least to a degree that was enough to allow the valley wind system to be the dominant source of wind for the month.

Fig. 5. Graphs showing diurnal wind direction and wind speed for the Portachuelo and Lower Lake stations with seasons compared.
4. Conclusion

The results reveal a valley microclimate which is impacted by ENSO similarly to the regional climate in the Cordillera Blanca. It is clear, however, that the microclimate is distinct from the regional climate as some impacts within the valley are reduced or muted. Warm ENSO phases contribute warmer and dryer wet seasons and wetter dry seasons. Cold ENSO phases have the opposite effect as is seen throughout the Cordillera Blanca. During the dry season, the correlation of ENSO to air temperature is dependent on elevation which indicates that the intra-valley teleconnection mechanism between upper and lower elevations of the valley seasonally breaks down. The breakdown of the teleconnection mechanism is likely attributed to the seasonal shifting of valley winds and increased thermal radiation from the rocky valley walls during the dry season. An evaluation of winds in the valley from both stations indicates that winds shift seasonally at lower elevations but less so at the higher elevations. The difference is attributed to the interaction of synoptic and valley wind systems which could plausibly converge at the ridge of the valley causing the formation of clouds and increased precipitation. The patterns observed provide increased evidence for the valley winds observed in prior studies. Though it is beyond the scope of this study, the results presented, will be beneficial for describing inter-annual trends of glacial melt. The evidence will also help to improve the understanding of how pro-glacial valleys interact with synoptic scale systems and thus affect glacier mass balance.

5. Acknowledgements

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Research at Bridgewater State University and the Adrian Tinsley Program Summer Grant for making this research possible.

6. References


7. Appendix

Appendix A. Data quality chart; values represent full days with usable data

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