PROYECTO
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GROWS

Quantifying the controls of Peruvian glacier response to climate

PEGASUS
PRODUCCIÓN DE ENERGÍA PREVENCIÓN DE PELIGROS

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Introduction

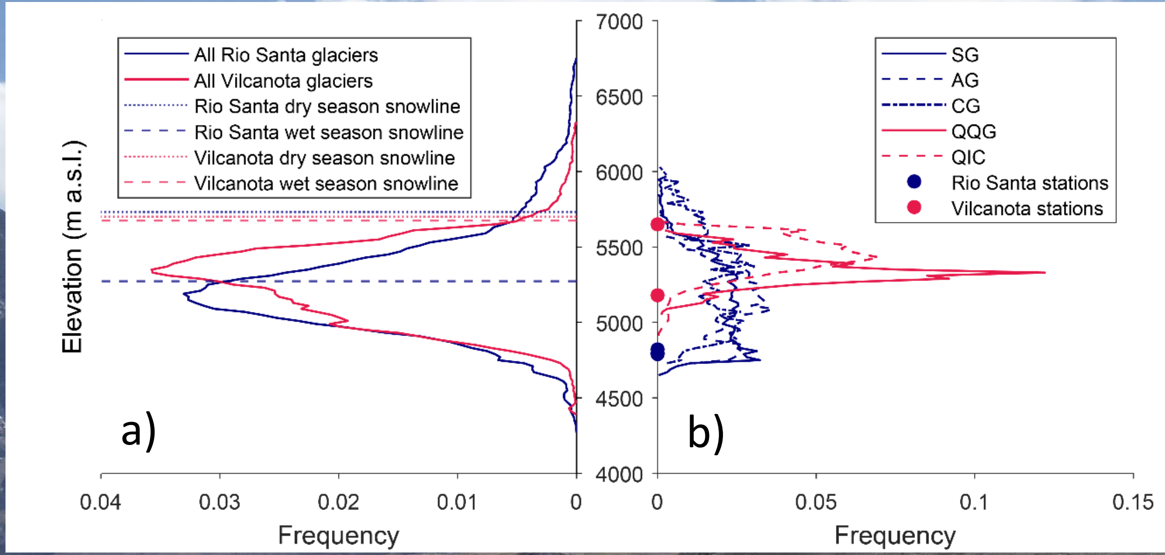
Aim:

To understand the key drivers of the energy and mass balance of five Peruvian glaciers, and to determine differences between the Cordillera Blanca and Cordillera Vilcanota

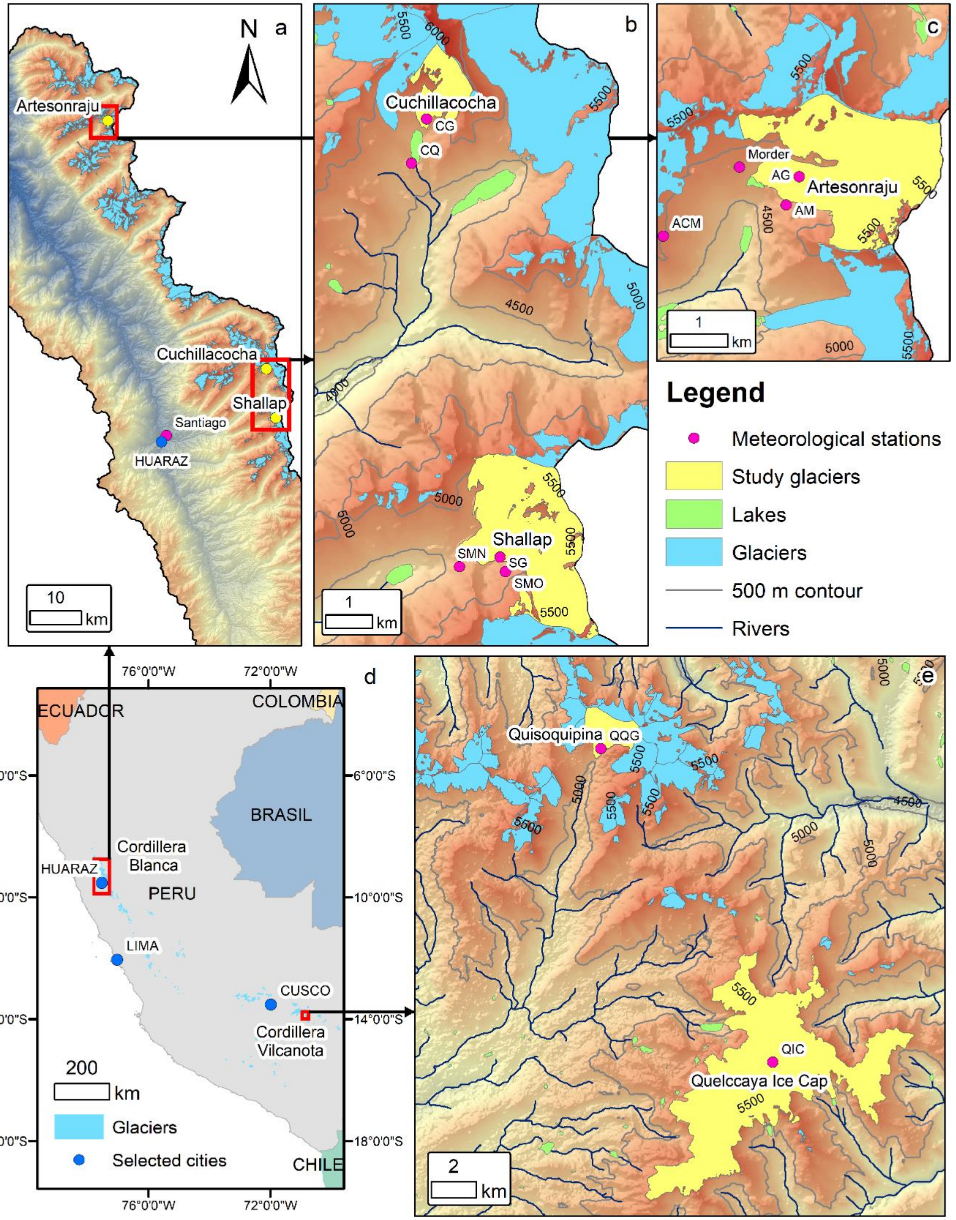
Objectives:

1. Determine the relative importance of each of the energy fluxes on melt rates of the five glaciers.
2. Determine the temporal variability and spatial differences between sites in the magnitude of ice melt, snow melt and sublimation.
3. Quantify the sensitivity of the energy and mass balance of the glaciers to changes in air temperature and precipitation.
4. Determine the key differences between the Cordillera Blanca and Cordillera Vilcanota glaciers

Study sites and glaciers



Right Panel a) is the elevation distribution of the glaciers within the Rio Santa and Vilcanota catchments with the mean catchment snowline in both seasons shown as a horizontal line. Panel b) is the elevation distribution of the study glaciers, including points showing the elevation of the on-glacier meteorological stations.

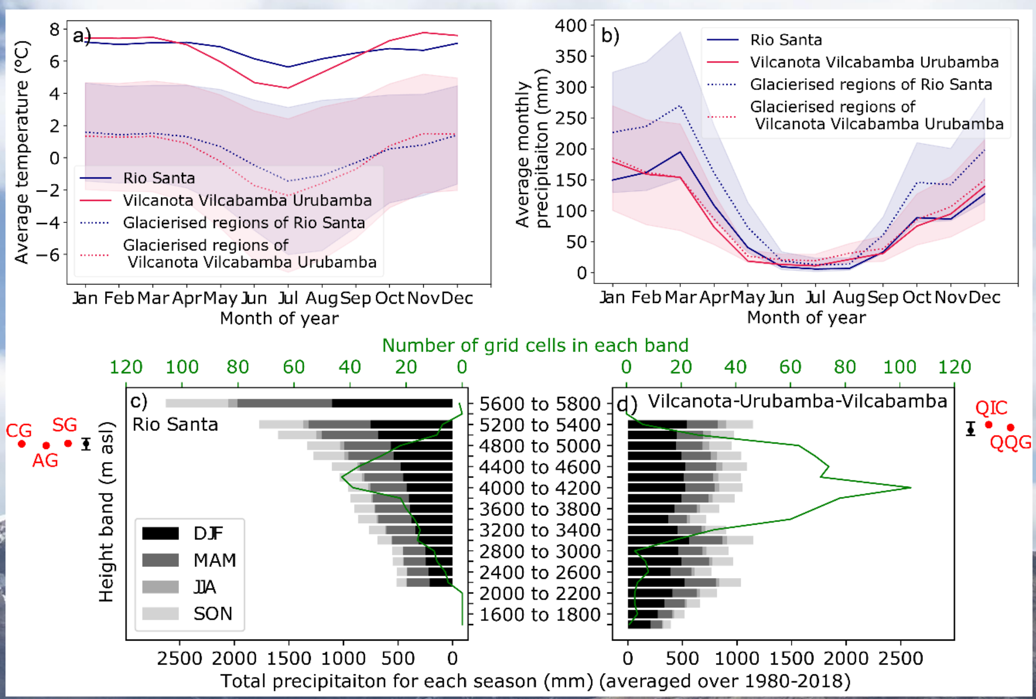


Above Glaciers and meteorological stations. The elevation data and underlying hillshade are from ASTER GDEM v.3 which is a product of METI and NASA. The glacier and lake outlines are from the National Peruvian Glacier and Lake Inventories, respectively.

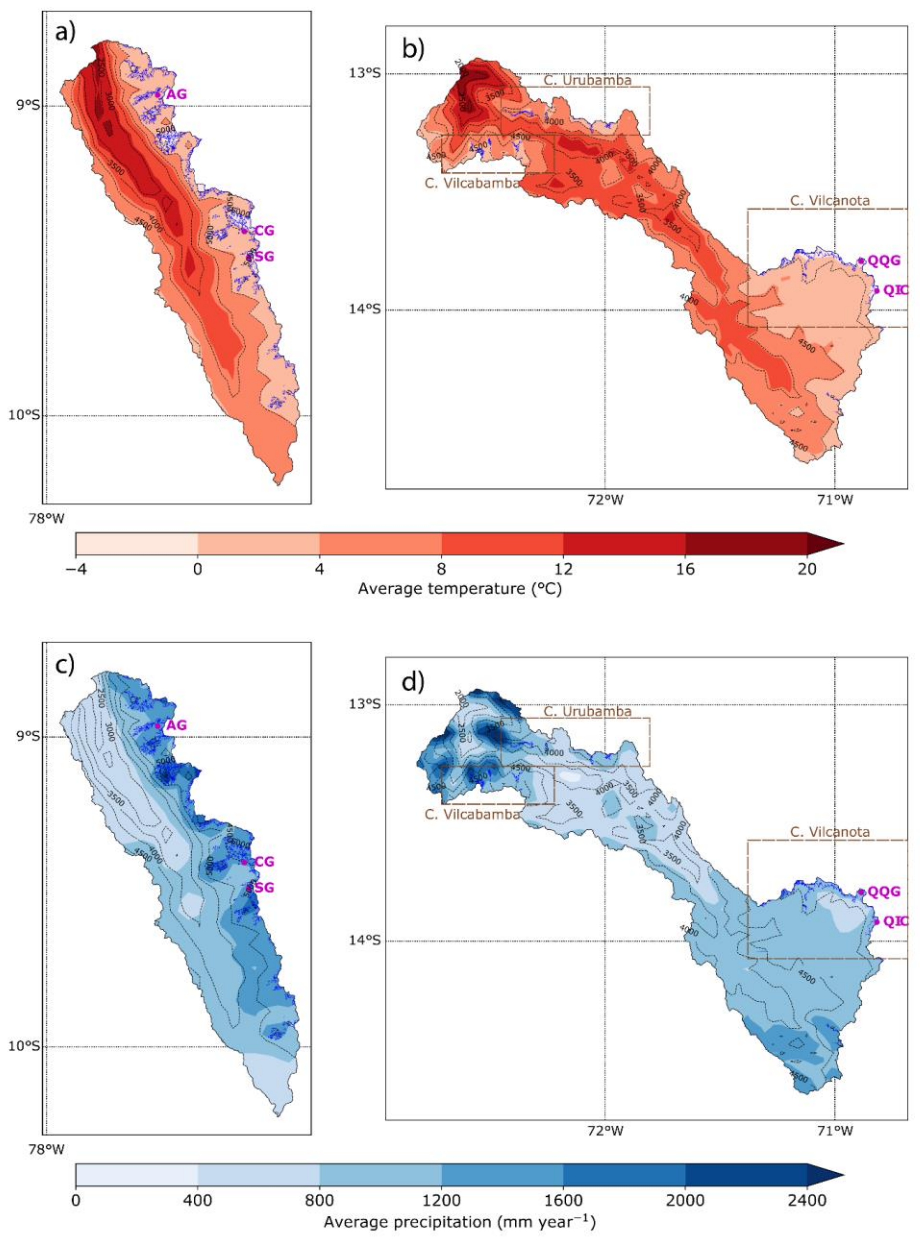
- Focus on two Peruvian catchments: Rio Santa (Cordillera Blanca) and Vilcanota (Cordilleras Vilcabamba, Urubamba and Vilcanota and the Quelccaya Ice Cap)
- Five on glacier weather stations: Artesonraju (AG), Shallap (SG), Cuchillacocha (CG) (all Rio Santa), Quisoquipina (QQG) and Quelccaya Ice Cap (QIC) (both Vilcanota)
- Minimum and median glacier elevations and the wet season snowline are higher in Vilcanota compared to Rio Santa: the climate of the Vilcanota catchment is less favourable for glaciers, mainly due to lower precipitation rates here (see 'Regional Climate').

Regional climate

Right Panel a) average annual cycle in temperature (monthly averaged) over the Rio Santa (blue) and Vilcabamba, Urubamba and Vilcanota regions (red). The dotted lines show the average temperature over the glacierised areas. Shaded areas represent +/- 2 standard deviations of the mean. Panel b) is the same as a) but for monthly averaged precipitation. Panels c) and d) are the average total precipitation varying with elevation for each season over the upper Rio Santa and the Vilcanota-Urubamba-Vilcabamba region.



- Peruvian climate has distinct wet and dry seasons: summer (Nov-Apr) is much wetter than winter (May-Oct)
- Dry season runoff is composed of glacier/snow melt and groundwater
- Climate assessed from bias-corrected, high-resolution (4km) Weather Research and Forecasting (WRF) outputs, run 1980-2018
- Mean Ta is only slightly cooler in the dry compared to wet season, with the difference greater in Vilcanota than Rio Santa, but due to the higher glacier elevations in Vilcanota, wet season on-glacier Ta is similar
- Precipitation increases with elevation in Rio Santa, but not in Vilcanota; here precipitation is predominantly from the north-west leading to a strong north-south precipitation gradient



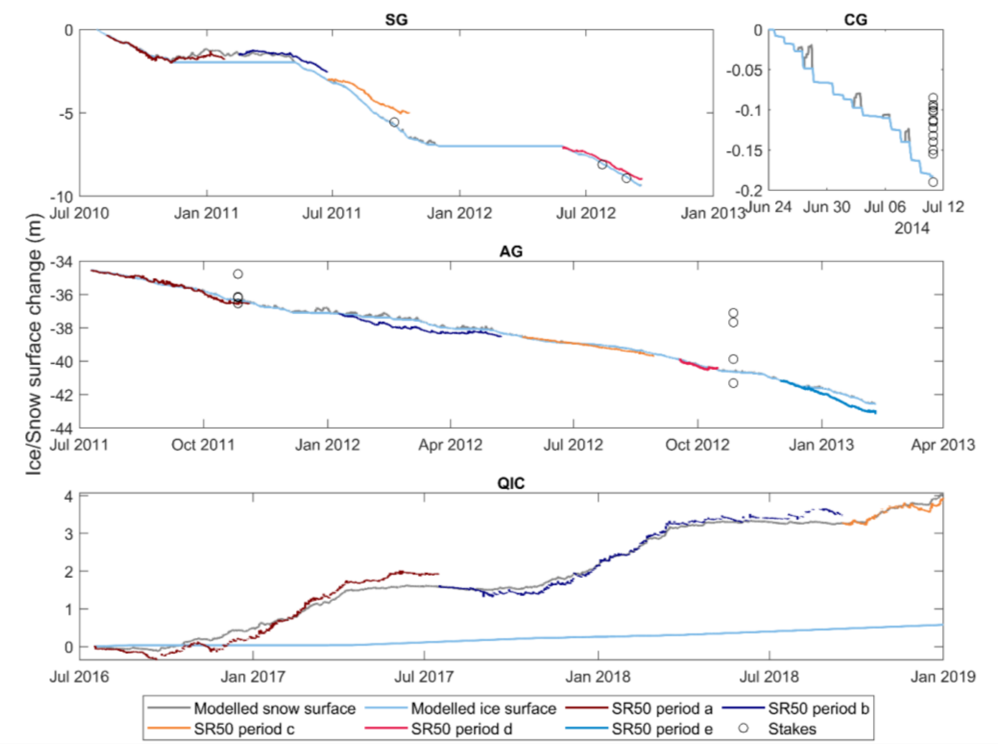
Above Average daily temperature at 2 m (red shading) across the upper Rio Santa River Basin (**a**), and the Vilcanota region, encompassing the Cordilleras Vilcabamba, Urubamba and Vilcanota (**b**). Glaciers are outlined in blue. Model elevation contours are also shown (black dashed lines), along with the locations of the automatic weather stations (maroon circles). Panels **c**) and **d**) are the same as **a**) and **b**) but for average yearly precipitation (blue shading).

Methods

$$dQ(T_s) = R_n(T_s) + Q_v(T_s) + Q_{fm}(T_s) + H(T_s) + \lambda E(T_s) + G(T_s)$$

dQ = energy flux into the ice/snow, Rn = net radiation, Qv = sensible heat due to precipitation, Qfm = heat flux due to melting/freezing, H = sensible heat flux, λE = latent heat flux, G = conductive heat flux (Fatichi et al., 2012). Fluxes positive downward.

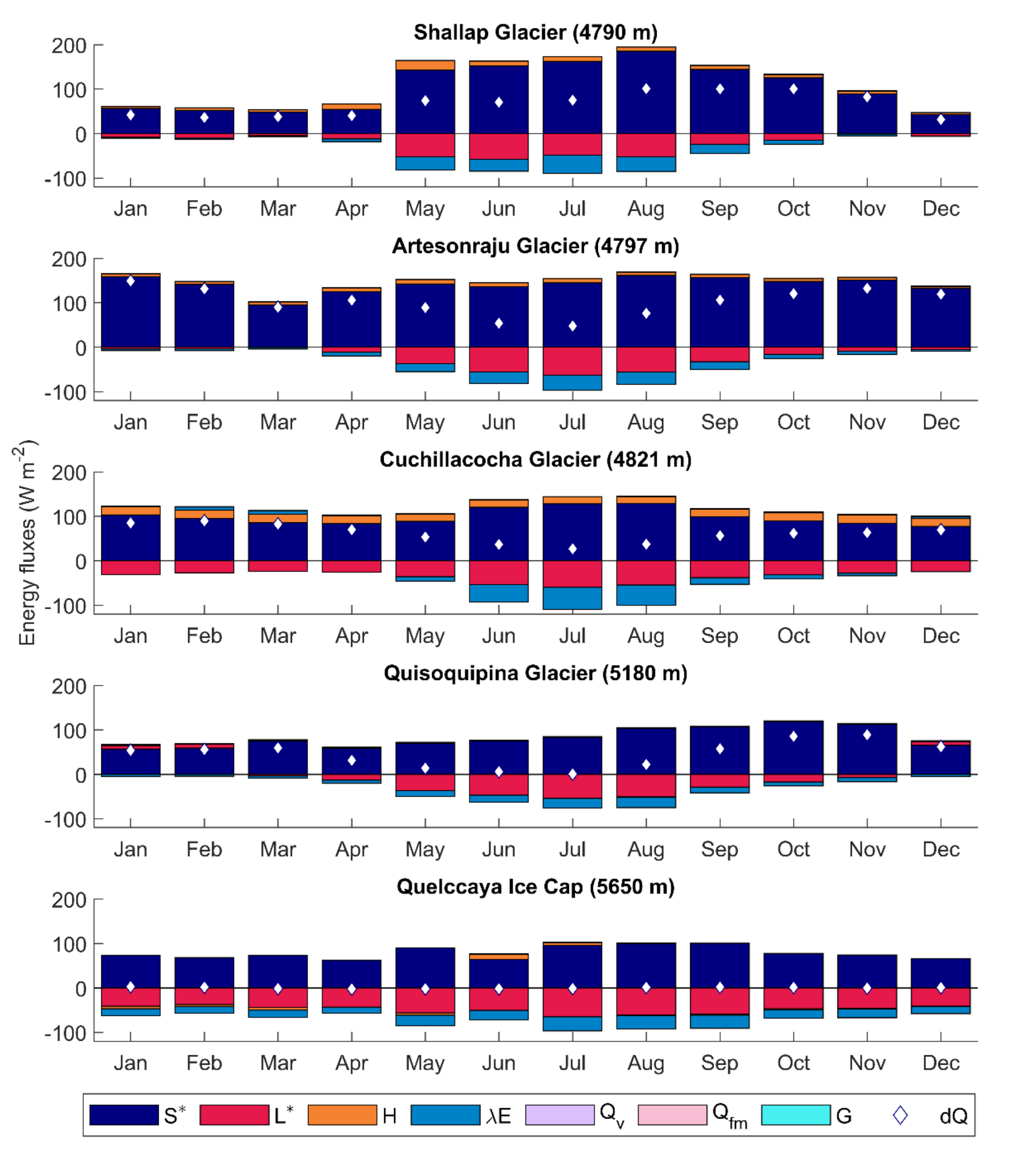
- Tethys-Chloris energy balance melt model ran at the point scale
- Ice and snow energy and mass balance calculated
- All input data relevant to on-glacier, but sometimes data were filled from off-glacier data corrected to on-glacier, or from WRF
- Modelling periods differ but assessment of their climatology compared to the 1980-2018 mean showed that they were very representative, except at Shallap which was cooler due to La Niña
- When no measurements used Brock et al. (2000) albedo parameterization and an incoming longwave parameterization based on Dilley O'Brian (1998) and Unsworth and Monteith (1975).
- Snow density calibrated for QIC.
- Validation with ablation stakes, SR50 (snow depth) and albedo



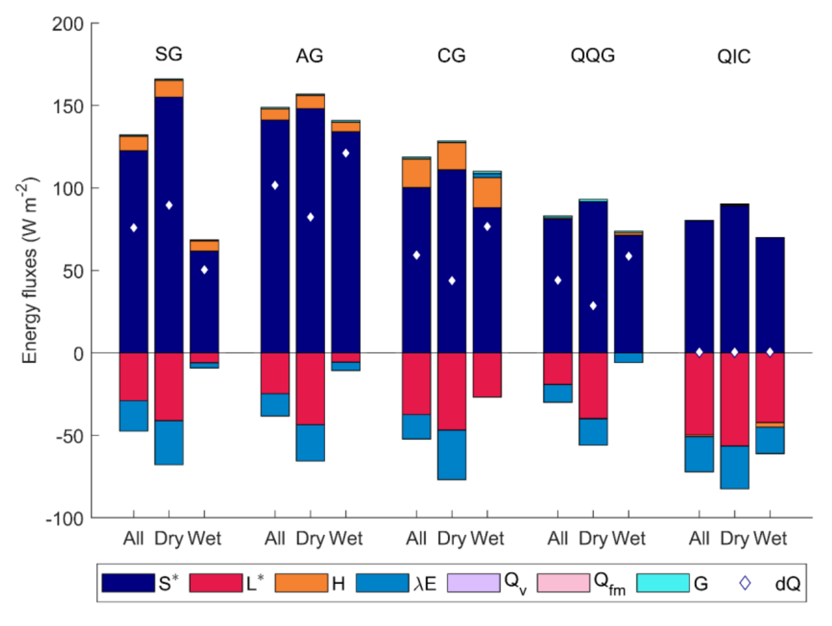
Above Comparison of modelled ice/snow surface against validation data from SR50 and stake measurements. Note that the Artesonraju and Cuchillacocha modelling periods are longer than shown, only the period with validation data is represented. Stake data at Quispquipina (not shown) only available for different years than modelled, but comparison was favourable.

Glacier	Start	End	Notes on inputs
SG	26/07/2010	18/09/2012	Measured but filling from off-glacier required. Gap without data.
AG	20/15/2006	12/05/2013	Measured with filling from off-glacier. Small period modelled SWout and LWin.
CG	24/06/2014	05/08/2016	Derived from off-glacier. SWout and LWin modelled.
QIC	17/07/2016	31/12/2018	Measured on glacier, except Pr, from WRF.
QQG	27/10/2011	25/08/2018	Measured on glacier, SWin from WRF, SWout and LWin modelled.

Energy fluxes



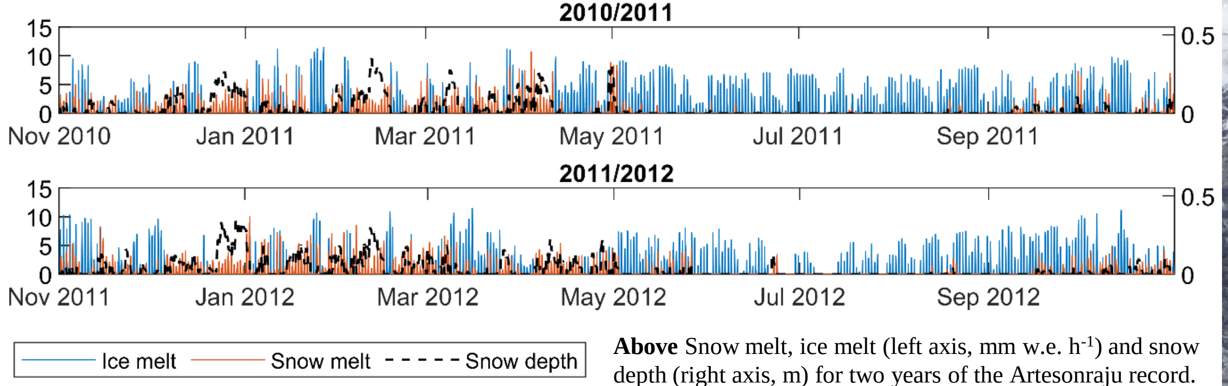
Left Monthly mean energy fluxes (per hour) for each site. **Right** Mean energy fluxes averaged per hour over the whole record and the wet and dry seasons. dQ (energy available for melt) is shown as a point on top of the bar graphs. Positive fluxes are towards the surface. S* is net shortwave radiation and L* is net longwave radiation.



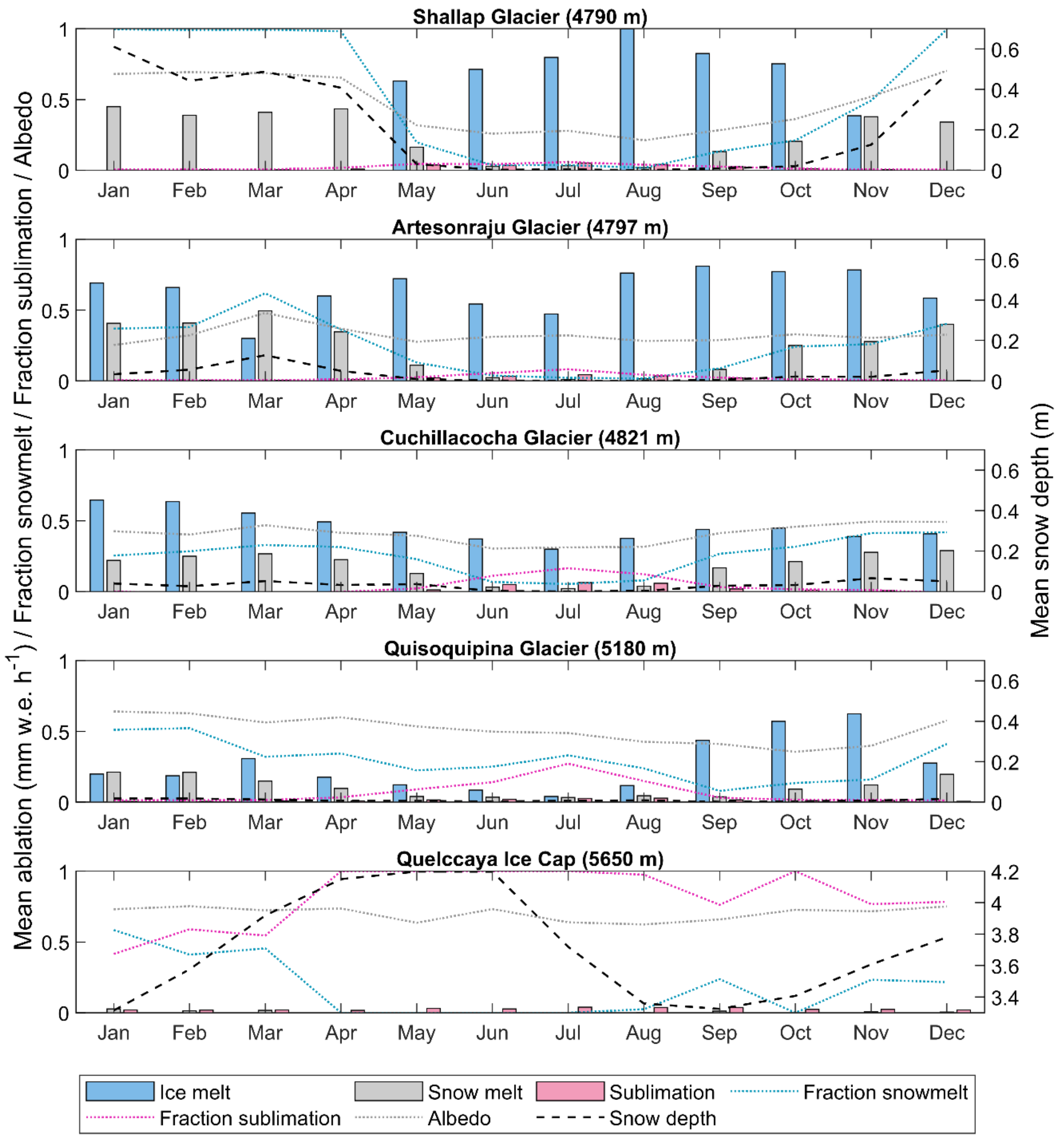
- Net shortwave radiation (S*) clearly largest flux, tends to be largest in late winter/spring, due to a combination of low albedo ice surface combined with increasing radiation receipts
- Wet season S* lower than dry season S* due to higher snow albedo and cloudiness counteracting higher top-of-atmosphere SWin
- Sensible heat flux (H) generally small, but highest at CG, due to higher wind speeds and relatively high Ta, and smallest at QIC (even negative in wet season)
- Greatest energy losses due to net longwave radiation (L*), which is most negative in the dry season due to reduced cloud cover
- The latent heat flux (λE) also results in energy loss, being most negative in the dry season due to low relative humidity

Ablation

- Most snowmelt in wet season, with ice melt predominating in dry season. Rates of ice melt higher than snow melt due to high snow albedo.
- Mixture of ice and snowmelt occurs throughout wet season at Artesonraju, Cuchillacocha and Quisoquipina; indicating the snowpack is thin and ephemeral, forming and melting in days to weeks.
- But there is a continuous snowpack at Shallup over 2010/2011 wet season, due to anomalously cold El Niña conditions. Wet season ablation is then less than dry.
- Sublimation occurs in the dry season at all sites, being most important at the higher sites, accounting for 4% of ablation at Quisoquipina and 81% at Quelccaya Ice Cap



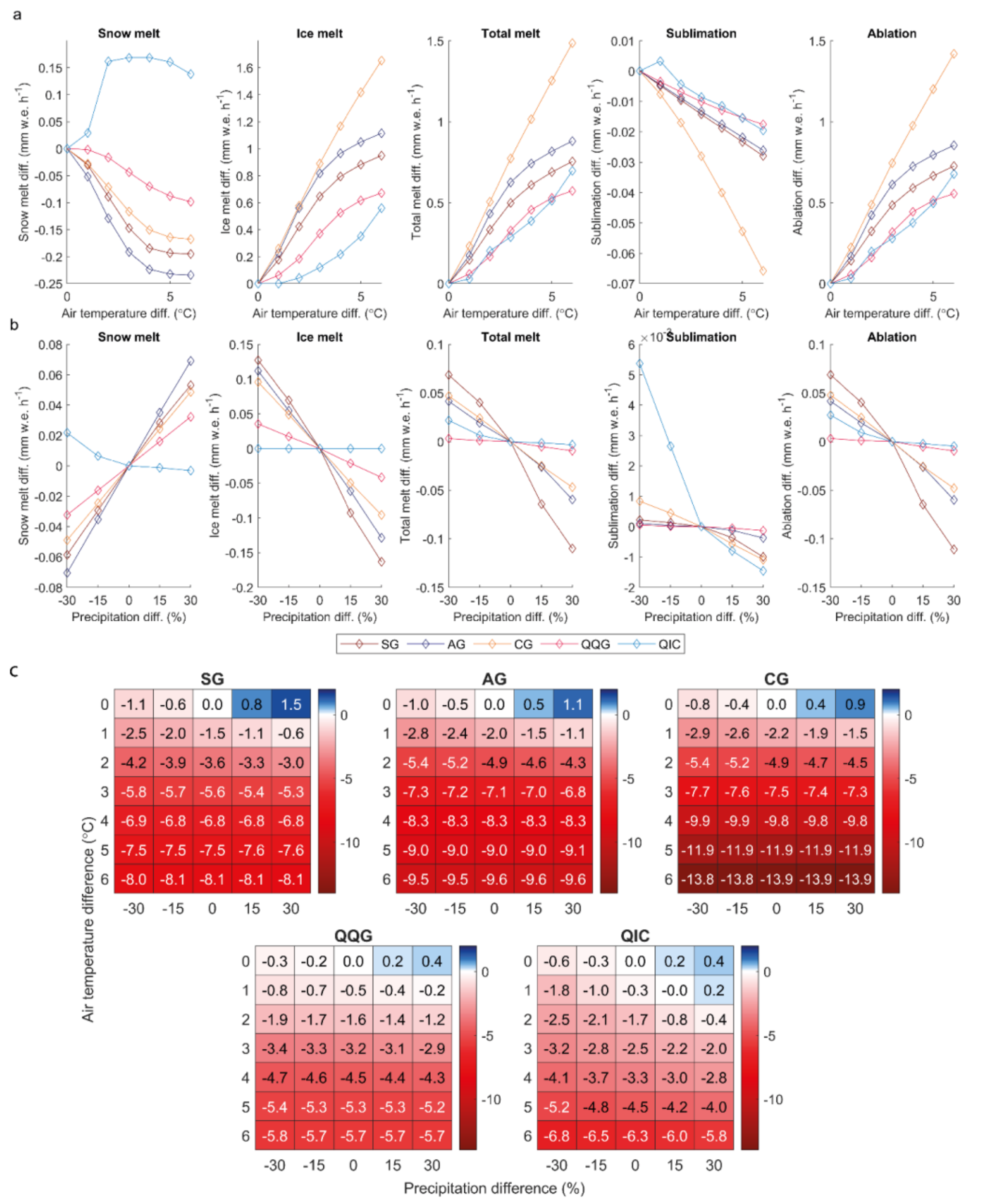
Above Snow melt, ice melt (left axis, mm w.e. h^{-1}) and snow depth (right axis, m) for two years of the Artesonraju record.



Above Ablation split into mean monthly ice melt, snow melt and sublimation for each month. The averages are applied over the whole record. Also shown is the fraction of snowmelt and sublimation of total ablation, the albedo and on the right y-axis the mean monthly snow depth.

Climate change

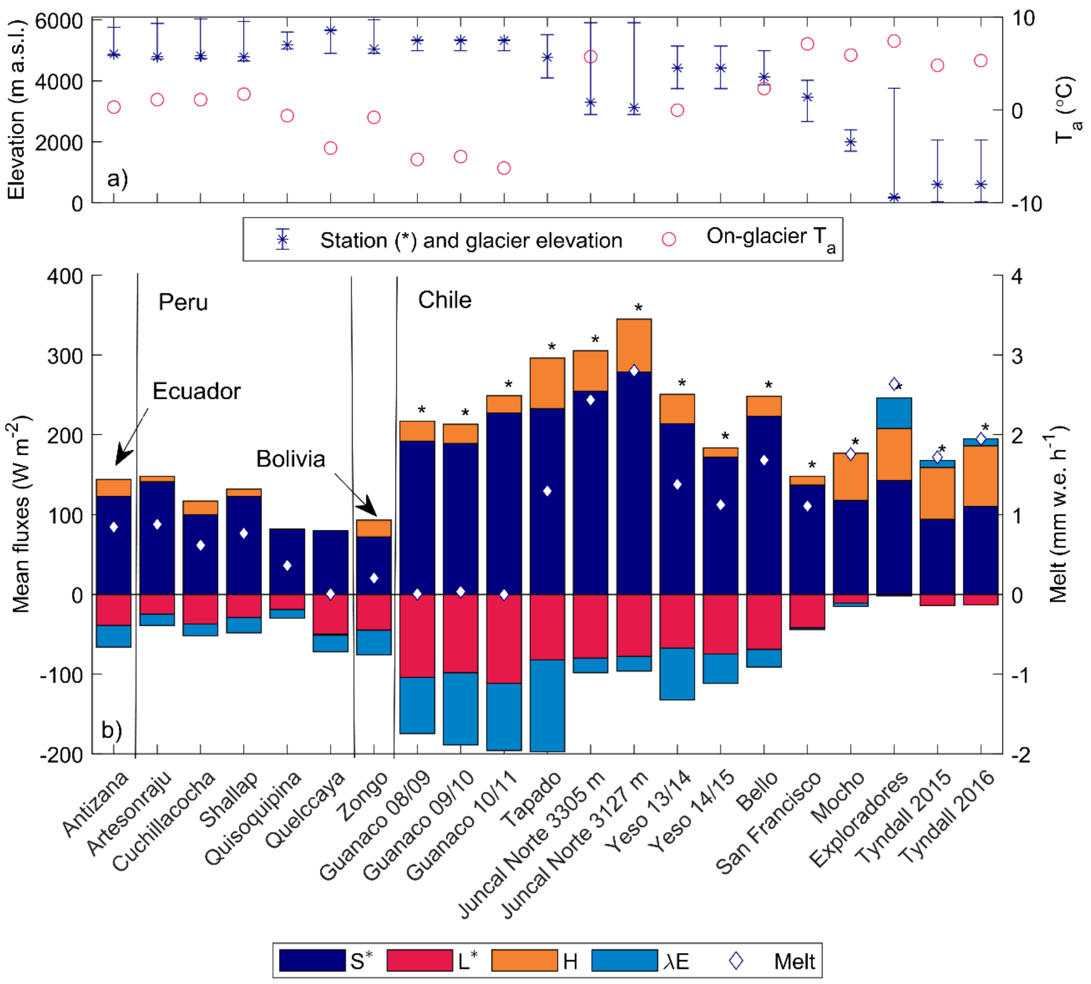
- Applied changes of +0 to +6°C to air temperature and -30% to +30% to precipitation, both individually and combined. All runs used modelled albedo and the vapour pressure and dew point temperature were recalculated.
- Under SRES A2 warming of 4.5-5°C expected over tropical Andes (Vuille et al., 2008)
- Warmer air temperatures result in increased ice melt at the expense of snow melt at the four lower sites (SG, AG, CG, QQG); mainly due to warming decreasing the percentage snowfall of total precipitation. At SG, AG and CG snowfall is *less than 10% of total precipitation* when Ta is enhanced by 4°C or more.
- This reduced % snowfall means increasing precipitation has little impact on mass balance at high air temperatures
- Sublimation switches to melting with a Ta increase between 1 and 2°C at Quelccaya Ice Cap (*sublimation is reduced from 81% of total ablation for the standard run to 9.7% with +2°C*), resulting in a non-linear increase in ablation with increasing Ta
- With +2°C specific mass balance at QIC is negative



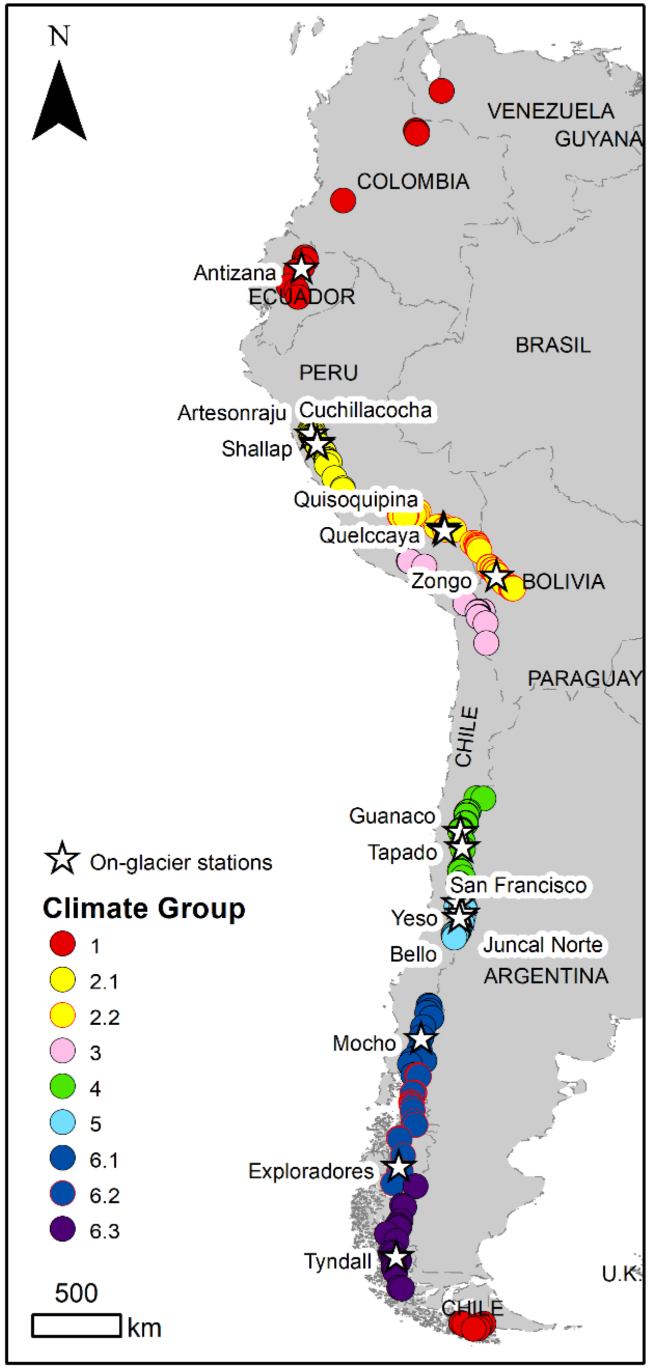
Above Influence of the increase in air temperature (row **a**) and precipitation (row **b**) on snow melt, ice melt, total melt, sublimation and ablation. For Quelccaya, ice melt corresponds to the melt of firn, which was not represented as a separate compartment in the model. Row **c**) difference in the mass balance (in m w.e. per year) between the standard runs and each scenario.

Peruvian glaciers in a South American Context

- Our Peruvian sites are similar to the glaciers in Ecuador (Antizana 15) and Bolivia (Zongo) and to a certain extent central Chile (Guanaco to Bello)
- At these glaciers net shortwave radiation dominates the energy balance and therefore drives ablation, with the sensible heat flux small and net longwave radiation and the latent heat flux negative.
- In southern Chile glaciers exist at lower elevations and warmer air temperatures due to higher precipitation rates. Here the sensible heat flux is higher and latent heat flux positive.



Above Comparing South American on-glacier meteorology, with sites ordered by latitude (north-south). Panel **a**) station elevation in context of the glacier maximum and minimum elevation, and the mean on-glacier air temperature. Panel **b**) radiation and melt. Sites marked * were averaged over a few months or less, the data for the other sites were averaged over at least a year. Data from locations other than Peru from Favier et al. (2004), Sicart et al. (2002), Ayala et al. (2017), Schaefer et al. (2020), Schaefer et al. (2017) and Barcaza et al. (2017). **Right** Station locations. The climate group is as given in Sagredo and Lowell (2012).



Conclusions

What is the importance of each of the energy fluxes?
Net shortwave radiation is the greatest contributor to melt energy, it is highest in the dry season due to clear skies and low ice albedo. Sensible heat flux is small in comparison. Both net longwave radiation and the latent heat flux are usually negative and act to reduce ablation, especially in the dry season.

What's the temporal and spatial variability in ice melt, snow melt and sublimation?
Importantly ice melt occurs throughout the year at most sites (Artesonraju, Cuchillacocha and Quisoquipina), due to a thin, ephemeral wet season snowpack which forms and melts over days to weeks. The snowpack is still very important since it protects the ice and reduces melt rates. Mass loss by sublimation is especially important at the highest sites.

What's the sensitivity of the glaciers' energy and mass balance to changes in air temperature and precipitation?
Increases in air temperature at the lower sites changes the precipitation phase from snow to rain, increasing ablation via the switch from snow to ice melt. This also means increased precipitation has little affect on mass balance under warmer conditions. On Quelccaya Ice Cap warmer temperatures result in a switch from sublimation to melting, so that ablation increases non-linearly with air temperature and mass balance in the accumulation zone becomes negative with Ta +2°C.

What's the difference between the glaciers in the Rio Santa and Vilcanota regions?
The Vilcanota region is less favourable to glacier existence due to lower precipitation rates compared to the Rio Santa. Minimum and median glacier elevations are therefore higher in the Vilcanota compared to the Rio Santa catchment.

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