Supplementary Information for

Detection and attribution assessment of climate change impacts in coupled human-natural systems in the Andes

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A. Detailed description of the detection and attribution assessment for each natural and human system

Cryosphere

The Andes hold widespread glacierized regions including small and high-altitudinal glaciers of the Tropical Andes (1540 km²) [1–5] and subtropical Dry Andes (2180 km²) [6], and large low-lying glaciers and icefields in North and South Patagonia (23,100 km²) and the Fuegian Andes (8500 km²) [6–8]. Andean glaciers exhibit some of the fastest shrinkage rates worldwide with an estimated area reduction of 1-2%/year in the last 3-5 decades [7,9,10] and a negative mass balance of about 0.7 m w.e./year on average for the period 2000-2017 [6]. While the Tropical Andes and Patagonian Andes have strong negative mass balances (~0.8 m w.e./year), the lowest loss rates are in the Dry Andes (~0.3 m w.e./year for the period 2000-2017) [6]. Currently, Venezuela (0.1 km² glacier area left) is on the verge of transforming into the first deglaciated Andean country [5]. Our results indicate very high confidence in glacier area reduction and high confidence in negative mass balance, with high confidence in anthropogenic forcing.

Glaciated and snow-dominated headwaters play an important role for sustaining human livelihoods and ecosystems along the Andes Cordillera from the inner-tropical to the Southern Patagonian Andes. Particularly in the outer-tropical and Dry Andes, glacier meltwater represents a crucial source for downstream water use in dry months, and sustained glacier shrinkage already threatens human water security [10–12]. Sustained melting of ice leads to a peak water followed by meltwater reductions and potentially increasing river flow variability. In several smaller basins with reduced ice-cover fraction, such as in the Tropical Andes [13] or Dry Andes, peak water has most likely been reached or is close to being passed [14]. In turn, large glacier areas, such as some parts of the Patagonian icefields, could still provide substantial glacier contribution to streamflow for several more decades [14]. Further field-based evidence is needed particularly in often ungauged headwaters to further confirm these findings and improve systematic understanding of changes in glacier-fed basins. Therefore, our results indicate high confidence in detected impacts on glacier hydrology and the role of anthropogenic forcing.

Across all Andean countries, the cryosphere system is strongly affected by climate change impacts and the growing body of evidence supports high detection and attribution confidence levels for the occurrence of glacier shrinkage. However, for related processes, such as snow cover changes, and impacts, like the incidence of peak water and GLOF events, more systematic studies and clear evidence are missing (medium-high detection and attribution confidence levels) (Figures 3-4).

Water

Impacts on water systems are widely spread across all Andean regions and include (1) a higher frequency in floods, (2) droughts, and (3) a lower water quality (Table 1). Changes in precipitation and rising temperatures have been related with an increase in the frequency of floods during the last three decades [15,16]. Trends in droughts and water scarcity have impacted the Andes, influenced by climate drivers such as precipitation decrease, precipitation seasonality changes and temperature increase and by non-climate drivers such as mining and population growth [14,17–23]. Several Andean settlements have perceived decreases in water availability and water supply, shorter rainy seasons and disappearance of local streams [24–29].

Across all Andean countries, the water system is strongly affected by climate change impacts (medium to high detection and attribution confidence levels) with highest confidence in Peru (Figure 3). There are more detected impacts in comparison with other systems, with assessments of an anthropogenic role ranging from medium to high confidence (Figure 4).

Terrestrial and aquatic ecosystems

Impacts in terrestrial ecosystems have been found in all Andean countries and include (1) augmented fires, (2) changes in species abundance and diversity, and (3) ecological succession and changes in species distribution (Table 1). Rising temperatures have caused changes terrestrial and aquatic ecosystems, such as changes in avifauna [30], tree mortality and diversity loss [31,32], and increases in abundance of *Cladocera* and *Plankton* species [33,34]. Climate changes and glacier retreat have been related with upward plant [35,36] and animals [37] colonization and changes in plant richness, cover and abundance [38]. Increases in precipitation extremes and glacier retreat correlate with an increase in the number of wetlands and their total area over thirty years of monitoring in *Cordillera Real* in Bolivia [39]. These measured changes are supported by perceptions studies carried out for the Colombian and Chilean areas, which report occupation by butterflies common to colder levels, new pests affecting crops, and plant colonization of higher altitudes [28,40]. Most of the observed ecological succession are related to global warming and only in a few cases, evidence suggests other predominant drivers, such as changes in precipitation patterns [39].

Across all Andean countries, changes in terrestrial and aquatic ecosystems have been detected and attributed with medium to very high confidence levels (Figure 3). Our results show medium confidence in a role of anthropogenic climate change with the main driver of change being rising temperatures (Figure 4).

Food security

Agriculture is an important aspect of Andean livelihood and culture. Native crops are cultivated at different altitudinal stages in the Andean hillslopes, and together with livestock are organized and maintained according to millennia of knowledge and cultural rituals [41]. In the last decades, although adaptation strategies such as shifting plantations to higher altitudes have been implemented, increasing temperature (mean, maximum

and minimum) and changes in precipitation seasonality have affected agriculture in some Andean communities [42–46]. In Peru, the quantity of harvested crops and their farm gate prices has declined, due to warming, precipitation decrease and a combination of social, political, and economic issues [47]. Several perception studies have registered reduction in agricultural production in Bolivia, Peru and Chile [27,28,46,48], increase in crops damages in Peru [25], loss of agrobiodiversity in Colombia [40], and negative impacts to soils and livestock in Peru [27]. In Ecuador, changes in agriculture have been perceived by communities due to heavy windstorms, drought periods, heat waves, and cold periods, heavy hail events and decrease in rainfall events[49].
Most of the detected impacts on agriculture are found in Peru with medium to high confidence levels in detection and attribution (Figure 3 and 4).

Disasters

The Andes is one the most disaster-prone regions of the world, being frequently affected by floods (50% of total registered events in global mountainous region databases) and landslides (29%) [15]. The frequency of these disasters has increased in Argentina [16] and Bolivia [26]. Furthermore, glacier detected hazards have increased in Cordillera Blanca, Peru [50–52]. With ongoing glacier retreat and permafrost degradation, hazards develop from destabilizing mountain flanks due to de-buttressed slopes, over steepened rocks and ice, and increasing rock-slope failures [53,54]. This situation leads to disastrous events, when e.g., rock falls, ice detachments or snow avalanches reach rapidly developing lakes in subjacent deglaciating areas and trigger glacier lake outburst floods (GLOF). These process chains of combined mass movements have already threatened downstream populations and assets in the Tropical Andes [55–60], Dry Andes [61] and Patagonian Andes [62]. At Lake Palcacocha (Cordillera Blanca, Peru), Stuart-Smith et al. [63] demonstrate that observed increasing outburst flood hazard would be clearly attributable to anthropogenic climate change. However, incomplete and inconsistent statistics, regional aspects combined with complex cascading effects (e.g. glacier-lake geometries, peak water, sedimentology) and lagged response times of glacier shrinkage and lake development make the attribution of single events to anthropogenic climate change far more challenging [50,51].
Drivers of disasters include climate extremes and exposure and vulnerability of human systems [64]. The disaster frequency reviewed in mountainous systems from 1985–2014 indicated an increasing trend of weather- and climate-related disasters for the most disaster-prone regions [15]. In the Andes, precipitation changes and phenomena like ENSO act as climate drivers. ENSO is particularly responsible for damages to health, infrastructure, loss of lives, agriculture and livestock. El Niño has occurred more frequently since the 1970s, but any connection to anthropogenic forcing is unclear [65]. On the other hand, the Andean region has a high exposure and vulnerability to disasters due to steep slopes, land use changes, and settlements in landslide risk sites caused by lack of planning and poverty. Disasters, as defined in [66], have a cascading effect, threatening ecosystems, human lives, infrastructure and influencing the economy in the region.
We have detected disaster-related impacts in all Andean countries, except Venezuela with an overall medium confidence in detection and attribution to anthropogenic climate change (Figure 3 and 4) due to the agreement among studies and their attribution to raising temperatures, precipitation changes, ENSO phenomena and high vulnerability of the Andean region.

Energy

The Andean region receives 60% of its total primary renewable energy supply from hydropower [67]. Hydro power contributes significantly to the economy of Andean countries, and provides energy for Andean cities as well as for coastal and Amazonian regions. A decreasing trend in hydropower potential (25 – 47 MW/year) has been detected in Chile [68], finding correlation with increasing trends in global sea surface temperature that are attributed to anthropogenic climate change with high confidence, as well as with interannual to decadal large-scale climate controls (i.e., ENSO events, the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation and the Southern Annular Mode). Another study found a reduction of hydro-energy inflow in the last decade related to temperature increase [69]. Besides these studies, there is a lack of information of documented impacts on this system in the Andean region.

Our results show a medium confidence in detection and attribution assessment for energy system in the Andes. However, few evidence was found and noting the potential and importance of hydropower in the region, there is the need for further information on the impacts of climate change in this system.

Tourism

Andean tourism includes cultural festivals, ski, hiking and extreme mountain sports. The disappearance of glaciers has impacted all these sectors. The Chacaltaya glacier in Bolivia is an example of vanished tourism due to the disappearance of the glacier in 1987 [70]. The Pastoruri glacier in Peru, is a similar case [71]. Adaptation strategies such as sightseeing and hiking at the location of vanished glaciers are, therefore, emerging [70]. Drivers include raising temperatures that have caused glacier retreat, and as a consequence, tourism loss [72,73].

Our results show high confidence in the detection of decreasing trends in tourism in Peru with medium confidence in the role of anthropogenic warming (Figure 3 and 4).

Migration

Experts and inhabitants of Andean communities in Bolivia and Peru have described an increase in migration, especially of young people, to coastal or nearby cities [47,74–76]. Drivers of migration include raising temperatures, precipitation changes, glacier retreat that impacts on water availability, decline in agricultural production and social conflicts. However, non-climate drivers such as unfavorable market set-up, families abandoning farming for more stable income, the need of people to look for better education and work in the cities, and desire to pursue urban lifestyle have also increased migration.

We have found medium to high confidence in an increase in migration in Peru and Bolivia (Figure 3) due to high consistency between studies, even though some studies covered short periods or small study sites. Migration is partly attributed to anthropogenic climate change (medium confidence, Figure 4).

Human health

Climate change can impact human health directly (e.g. heat waves), through natural systems (e.g. increase in air pollution via wildfire) and through socioeconomic systems (e.g. food and water insecurity). Impacts have been observed in human health in the Andes via each of these methods, even though research is currently thin. Long-term changes in climate variables in the last three decades such as precipitation decrease, higher solar radiation, heavier winds and lower relative humidity have made conditions more conducive to air pollution events in urban zones, causing problems for human health in the Andes of Chile [19,77]. Other climate changes, such as temperature and precipitation increase, have been suggested as drivers of the increase of malaria [78] and dengue incidence rates in Colombia, although other factors such as reduced immunity and ENSO events need to be considered [79,80]. Increases in health problems in Peru have been perceived by communities and linked to warming and increases in extreme rainfall events in the last two to three decades as well as to climatic impacts on other systems such as water and agriculture [25,48].

Human health impacts have been detected in Colombia, Peru and Chile (Figure 3). Detection and attribution are assessed to be of high and medium confidence overall, respectively (Figure 4).

Community changes and cultural values

Mountain landscape features are a fundamental part of the Andean cosmovision as they represent living beings and sacred places [81–83]. The current vanishing and transformation of glacier areas deeply shape culture, beliefs and narratives, and often mean a disruption of people and nature and thus a loss of cultural, spiritual and socioeconomic values [70,83–87]. For instance, glacier shrinkage is perceived as an indicator of illness of the mountain deities due to irresponsible human behavior and a growing imbalance between natural and human systems. Therefore, ice harvesting for local markets [84] and traditional ritual practices [83] which were an inherent part of the Andean culture, have been modified by the communities in order not to further harm the glaciers. Decreasing water availability has produced a conflict in Peruvian peasants, who are used to presenting offerings to deities in exchange for water for agriculture and now perceive these practices as no longer sustainable [85]. However, there is increasing evidence of some opportunities using current landscape transformation. These include adapting local economic practices by e.g. establishing vanishing glacier sites as sentinels of climate change and environmental education, new hiking routes and emerging glacier lake sites as new tourist attractions. Such changes can contribute to a revalorization of rapidly changing mountain environments and, to some extent, offset perceived cultural and spiritual losses associated with glacier retreat and landscape transformation [70,71,87].

Since most of these cultural changes are related to temperature increase and associated glacier disappearance, this impact on the human system can be attributed to anthropogenic climate change. However, other drivers such as changes in community structures, marginalization of rural communities, mining, access to resources and social conflicts, can also play an important role shaping Andean communities and their cultural values.

Community changes and affectation to cultural values have been found in Ecuador, Peru and Chile (Figure 3) with an overall high detection confidence (Figure 4). Although there is a fairly good link to temperature-related impacts on human culture (high confidence attribution, Figure 4), other socioeconomic and cultural stressors might have overlapped and interfered.

B. Detection and attribution assessment of observed changes in coupled natural and human systems of the Andes

Table B1 is organized by impacts (one impact per row). The reference column contains the articles where the impacts have been registered. There are cases in which the same article shows more than one impact, and therefore, more than one row has the same reference. When the same impact was found in the same study site and reported in different articles, only one row was filled in.

Table B1. Detection and attribution assessment using information extracted from documents that were chosen after a systematic review. Detection and attribution assessment of local impacts in Andean human and natural systems.

The full table is available at: https://doi.org/10.6084/m9.figshare.28243337.v2

C. Assessment of the attribution of climate trends to anthropogenic influence

The core of the assessment of the attribution to anthropogenic climate change is a multiple linear regression of the form [88] of Eq 1.

$$X_{obs,i}(t)=\beta_{ant,i,j}\cdot X_{ant,j}(t)+\beta_{nat,i,j}\cdot X_{nat,i}(t)+\varepsilon_{i,j}(t) \quad (1)$$

where $X_{obs,i}(t)$, $X_{ant,j}(t)$, and $X_{nat,i}(t)$ are time series of 5-year mean temperature or precipitation averaged over a region. $X_{obs,i}(t)$ is the time series calculated from observational data set *i*. $X_{ant,j}(t)$ is the time series calculated from the average across multiple simulations of climate model *j* run under historical variations in anthropogenic (greenhouse gas concentrations, aerosol precursor emissions, ozone depletion, land use/cover change) drivers, and $X_{nat,i}(t)$ is the time series calculated from the average across multiple simulations of climate model *j* run under variations in natural drivers (solar brightness, volcanic eruptions). The regression coefficients $\beta_{ant,i,j}$ and $\beta_{nat,i,j}$, for the anthropogenic and natural signals respectively, are evaluated for inconsistency with zero (i.e. required to account for the observed variations) and for consistency with one (i.e. consistent in magnitude with observed variations), while the variance of the residuals $\varepsilon_{i,j}(t)$ is evaluated for consistency with the variance in "noise" simulations of the climate models with no changes in anthropogenic or natural drivers. The evaluation is performed separately for the combination of each of the 4 observational products listed in Table C1 (precipitation) or Table C2 (temperature) and each of the 12 climate models with historical simulations listed in Table C3. The noise simulations from all climate models listed in Table C3 are used in all cases. A linear transformation is performed as part of the regression process to isolate the anthropogenic signal in the historical simulations (which are driven by variations in both anthropogenic and natural drivers) using the signal from the natural historical simulations.

The tests on the regression coefficients and residuals across the multiple observations-climate model combinations, along with evaluation of diversity and quality of the data sources, are combined into an overall assessment of confidence using a modified version of the algorithm described in Stone and Hansen [89]. The modification involves incorporation of the spatial resolution of the data set, in comparison to the region size, as part of the evaluation of the data sources, and the addition of weightings applied to the multiple regression combination tests which are derived from that evaluation.

The code for the regional climate detection and attribution assessment is available at https://climate.web.runbox.net/idl_lib/index.html#Regional_D-and-A_Confidence

Table C1. List of observational climate data products used for analysis of the anthropogenic role in historical precipitation changes.

Product	Version	Source
CRU TS	v4.064	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.064/
GPCC	v2022 (0.5°x0.5°)	https://opendata.dwd.de/climate_environment/GPCC/html/gpcc_normals_v2018_doi_download.html
NOAA PRECL	v1.0 (0.5°x0.5°)	https://psl.noaa.gov/data/gridded/data.precl.html
UDel	v5.01	http://climate.geog.udel.edu/~climate/html_pages/download.html#P2017

Table C2. List of observational climate data products used for analysis of the anthropogenic role in historical temperature changes.

Product	Version	Source
BEST	2021/03/11 (1°x1°)	https://berkeleyearth.org/data/
CRU TS	v4.064	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.064/
GHCN-CAMS	v3.01	https://psl.noaa.gov/data/gridded/data.ghcncams.html
UDel	v5.01	http://climate.geog.udel.edu/~climate/html_pages/download.html#T2017

Table C3. List of climate model simulations used for detection and attribution analysis of the anthropogenic role in observed precipitation and temperature changes. All data are from the Detection and Attribution Model Intercomparison Project and the Coupled Model Intercomparison Project Phase 6 [90,91] (https://esgf-node.llnl.gov/search/cmip6/).

Model	Historical simulations (number)	Natural historical simulations (number)	Noise segments (55 years)
ACCESS-CM2	5	3	9
ACCESS-ESM1-5	40	3	27
BCC-CSM2-MR	3	3	15
CanESM5	65	50	55
CESM2	11	3	30
CNRM-CM6-1	29	10	9
FGOALS-g3	6	3	12
GFDL-ESM4	3	3	9
GISS-E2.1G	15	15	22
HadGEM3-GC31-LL	45	104	36
IPSL-CM6A-LR	33	10	-
MIROC6	50	50	14
MRI-ESM2.0	10	5	20
NorESM2-LM	3	3	9
Total	278 (14 models)	171 (14 models)	267 (13 models)

Our assessments are performed on 5-year regional averages of temperature and precipitation during the 1961-2015 period, with the regions corresponding to political divisions averaging ~500,000 km^2 as described in Stone[92],. Final assessments are shown in the bottom panels of Figure 2, expressed as confidence in the attribution of at least a minor role of human influence. These are based on the multiplication of the various contributing factors listed in Tables C4 (temperature) and C5 (precipitation).

We have compared our assessments to the available literature on observed climate trends and the attribution of those trends. The available literature, the method of assessing how evidence in the literature translates into confidence in attribution, and the resulting confidence for both methods are described in Supplementary Table C6 (separate file). The results are summarised in Figure C1. Even though the general conclusions of human-induced warming are the same, confidence based on previous studies is lower than as assessed through our algorithm at least in part because of the lack of formal attribution analysis in those previous studies For precipitation, the assessed pattern of wetting and drying trends is similar, except for southern Patagonia in Argentina (assessed as “low confidence” with both methods) and for the large number of regions without attribution information in any prior studies.

Table C4. Contribution of the various tests in the climate attribution evaluation to the overall assessment for regional temperature shown in Figure 2. An additional step of “Physical representation in climate models” contributes a factor of 1.0 for temperature.

WRAF v4.1 region ID and name	Diversity and quality of observational sources (0.0 to ∞)	Diversity and quality of climate models (0.0 to ∞)	Match of observed and simulated anthropogenic signal pattern (0.0 to 1.0)	Match of observed and simulated magnitude of anthropogenic signal (0.6 to 1.0)	Match of observed and simulated magnitude of nature signal (0.9 to 1.0)	Consistency of observed and simulated endogenous variability (0.5 to 1.0)
3.X.X.1 Venezuela: northern	2.00	2.83	1.00	0.60	0.92	0.96
3.X.X.2 Venezuela: Amazonas and Bolivar	1.99	2.77	0.99	0.60	0.94	1.00
X.1.1.1 Colombia (western)	1.99	2.83	1.00	0.60	0.90	0.50
X.1.1.2 Columbia: eastern	1.98	2.98	0.99	0.60	0.90	0.50
X.1.1X.1, X.1.1.X.2, X.1.1.X.3 Ecuador	1.88	2.51	1.00	0.60	0.90	0.50
X.1.2.1 Peru: southwestern	1.98	3.04	0.99	0.60	0.90	0.52
X.1.2.2 Peru: northeastern	1.97	2.91	0.93	0.60	0.90	0.50
X.1.2.3 Bolivia: northeastern	1.94	2.97	0.73	0.60	0.90	0.77
X.1.2.4 Bolivia: southwestern	1.98	2.79	0.62	0.60	0.90	0.92
X.X.X.2 Chile	1.99	3.04	0.99	0.60	0.91	0.50
3.3.1.1 Argentina: (northwestern)	2.00	2.86	0.97	0.60	0.90	0.78
3.3.1.3 Argentina: western central	2.00	2.99	0.98	0.60	0.90	0.99
3.3.1.5 Argentina: southern Patagonia	1.99	2.83	0.94	0.60	0.99	1.00

Table C5. Contribution of the various tests in the climate attribution evaluation to the overall assessment for regional precipitation shown in Figure 2. An additional step of "Physical representation in climate models" contributes a factor of 0.8 for precipitation.

WRAF v4.1 region ID and name	Diversity and quality of observational sources (0.0 to ∞)	Diversity and quality of climate models (0.0 to ∞)	Match of observed and simulated anthropogenic signal pattern (0.0 to 1.0)	Match of observed and simulated magnitude of anthropogenic signal (0.6 to 1.0)	Match of observed and simulated magnitude of nature signal (0.9 to 1.0)	Consistency of observed and simulated endogenous variability (0.5 to 1.0)
3.X.X.1 Venezuela: northern	1.56	2.83	0.36	0.60	0.90	0.87
3.X.X.2 Venezuela: Amazonas and Bolivar	1.08	2.78	0.40	0.60	0.91	0.52
X.1.1.1 Colombia (western)	1.50	2.83	0.39	0.60	0.90	0.50
X.1.1.2 Columbia: eastern	1.09	2.98	0.47	0.60	0.97	1.00
X.1.1X.1, X.1.1.X.2, X.1.1.X.3 Ecuador	1.32	2.51	0.33	0.60	0.90	0.50
X.1.2.1 Peru: southwestern	1.59	3.04	0.48	0.60	0.90	0.50
X.1.2.2 Peru: northeastern	1.29	2.91	0.39	0.60	0.91	0.50
X.1.2.3 Bolivia: northeastern	1.18	2.97	0.6	0.60	0.90	0.50
X.1.2.4 Bolivia: southwestern	1.64	2.79	0.74	0.60	0.90	0.50
X.X.X.2 Chile	1.60	3.04	0.67	0.60	0.90	0.50
3.3.1.1 Argentina: (northwestern)	1.82	2.86	0.68	0.70	0.90	0.50
3.3.1.3 Argentina: western central	1.90	2.99	0.60	0.60	0.90	0.50
3.3.1.5 Argentina: southern Patagonia	1.64	2.83	0.66	0.60	0.90	0.50

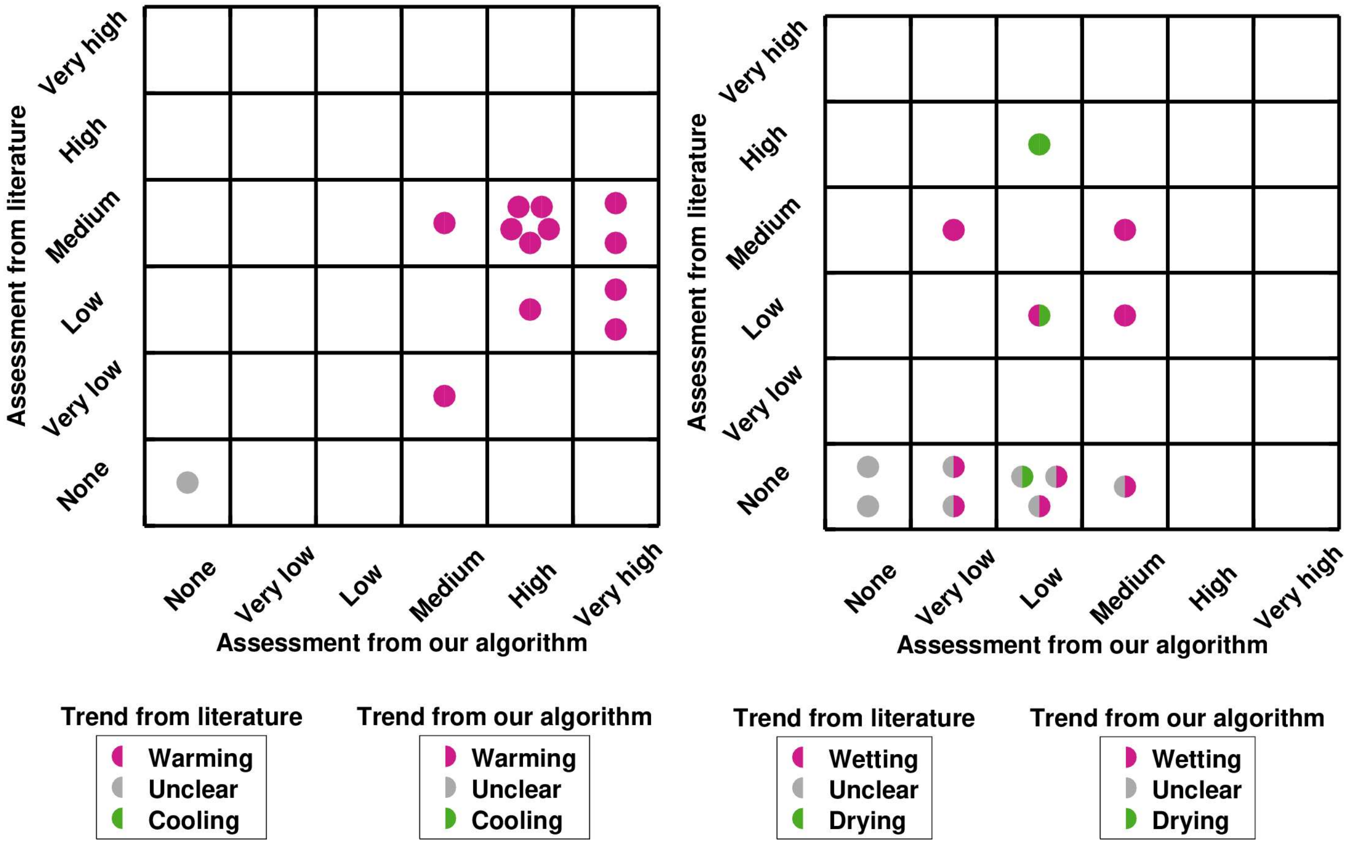

Figure C1. Comparison of two different ways of assessing confidence in the attribution of a human influence of observed climate trends. Details on the assessments are provided in the Supplementary text and in Supplementary Table C6 (separate file). Assessments are on the 1960-2015 variations in a) temperature and b) precipitation over 500,000 km2 regions in the Andes. Each disk represents a separate region, with the left half indicating the assessment based on a review of previous studies and the right half the assessment based on our regression-based algorithm.

Supplementary Table C6

This table contains a comparison of two different methods of assessing confidence in attribution of at least a minor anthropogenic role in observed climate trends for the manuscript
"Detection and attribution of climate change impacts in coupled natural-human systems in the Andes"
by Ana Ochoa-Sánchez (aeochoa@uazuay.edu.ec), Dáithí Stone (daithi.stone@niwa.co.nz), Fabian Drenkhan, Daniel Mendoza, Ronald Gualán, Christian Huggel

WRAF v4.1 ID	WRAF v4.1 name	Precipitation				Temperature			
		Observed precipitation trends	Precipitation attribution	Confidence in attribution of at least minor role in precipitation based on literature	Confidence in attribution of at least minor role in precipitation based on our analysis	Observed temperature trends	Temperature attribution	Confidence in attribution of at least minor role in temperature based on literature	Confidence in attribution of at least minor role in temperature based on our analysis
3.X.X.1	Venezuela (northern)	*** Negligible trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004)		none	low (wetting)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	very high (warming)
3.X.X.2	Venezuela: Amazonas and Bolivar	*** Robust wetting trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015) * Unclear trend: de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004)		none	very low (wetting)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); de Barros Soares et al., 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	very high (warming)
X.1.1.1	Colombia (western)	*** Robust wetting trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015) * Unclear or mixed trends: de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004); Carmona and Poveda 2014 (stations, various periods)		none	none	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); Carmona and Poveda 2014 (various periods) *** Negligible trend:** de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming expected from anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	high (warming)
X.1.1.2	Colombia (eastern)	*** Negligible trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015) *** Unclear trend:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004)		none	none	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015) *** Negligible trend:** de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming expected from anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	low (warming)	high (warming)
X.1.1X.1, X.1.1X.2, X.1.1X.3	Ecuador	*** Robust wetting trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004) *** Mixed trend:** Morán-Tejeda et al., 2016 (stations, 1966-2011)	*** Wetting inconsistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, CMIP5, 1955-2004)	none	very low (wetting)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); Morán-Tejeda et al., 2016 (stations, 1966-2011) *** Unclear trend:** de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming expected from anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	medium (warming)
X.1.2.1	Peru (southwestern)	*** Robust wetting trend:** Schauwecker et al., 2014 (stations, NCEP/NCAR, ERA-Interim, 1980-2012, Cordillera Blanca) *** Negligible trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004); Imfeld et alii 2020 (stations, PISCO gridded, 1965-2018, southern Peruvian Andes)		none	low (drying)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004); Schauwecker et al., 2014 (stations, NCEP/NCAR, ERA-Interim, 1969-2012, Cordillera Blanca); Imfeld et alii 2020 (stations, PISCO gridded, 1965-2018, southern Peruvian Andes)	*** Warming consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	high (warming)
X.1.2.2	Peru (northeastern)	*** Negligible trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004); Lavado Casimiro et alii 2013 (stations, 1965-2007)		none	low (wetting)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004); Lavado Casimiro et alii 2013 (stations, 1965-2007)	*** Warming consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	high (warming)
X.1.2.3	Bolivia (northeastern)	*** Robust wetting trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004)	*** Wetting consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, CMIP5, 1955-2004)	medium (wetting)	very low (wetting)	*** Warming trend:** Seiler et alii 2013 (stations, 1965-2004) *** No clear trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming expected from anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	very low (warming)	medium (warming)
X.1.2.4	Bolivia (southwestern)	*** Robust wetting trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004)	*** Wetting inconsistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, CMIP5, 1955-2004)	none	medium (wetting)	*** Warming trend:** López-Moreno et alii 2016 (stations, 1965-2012); Seiler et alii 2013 (stations, 1965-2004) *** Cooling trend:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004) *** Unclear trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015)	*** Cooling inconsistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	none	none
X.X.X.2	Chile	*** Robust drying trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); Rivera and Arnould 2020 (CRU TS 4.03, 1901-2014); Boisier et alii 2016 (stations, 1979-2014, central Chile); Boisier et alii 2018 (stations, 1960-2016) *** Unclear trend:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004)	*** Drying requires anthropogenic forcing:** Boisier et alii 2018 (stations, CMIP5, 1960-2016) *** Drying consistent with anthropogenic influence:** Rivera and Arnould 2020 (CRU TS 4.03, CMIP6, 1901-2014); Boisier et alii 2016 (stations, CMIP5, NOAA-FACTS, 1979-2014, central Chile)	high (drying)	low (drying)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); Burger et alii 2018 (stations, 1979-2015, central Chile) *** Negligible trend:** de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming expected from anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	high (warming)
3.3.1.1	Argentina (northwestern)	*** Robust wetting trend:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004) *** Negligible trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015)	*** Wetting consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, CMIP5, 1955-2004)	low (wetting)	medium (wetting)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015); de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	medium (warming)	high (warming)
3.3.1.3	Argentina (western central)	*** Robust wetting trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015); de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004)	*** Wetting consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, CMIP5, 1955-2004)	medium (wetting)	medium (wetting)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015) *** Negligible trend:** de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming expected from anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	low (warming)	very high (warming)
3.3.1.5	Argentina (southern Patagonia)	*** Robust wetting trend:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, 1955-2004) *** Negligible trend:** Gutiérrez et alii 2021 (CRU TS 4.04, GPCC v2020, 1961-2015)	*** Wetting consistent with anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, GPCC v.6, CMIP5, 1955-2004)	low (wetting)	low (drying)	*** Robust warming trend:** Gutiérrez et alii 2021 (Berkeley Earth, CRU TS 4.04, 1961-2015) *** Negligible trend:** de Barros Soares et alii 2017 (CRU TS 3.22, UDelaware v2.01, 1975-2004)	*** Warming expected from anthropogenic influence:** de Barros Soares et alii, 2017 (CRU TS 3.22, UDelaware v2.01, CMIP5, 1975-2004)	low (warming)	very high (warming)

Method for "Confidence in attribution of at least minor role in precipitation based on literature"

Observed trends	Attribution	Confidence
	No attribution analysis	none
Observational data sets with "robust" trends of opposite signs		none
At least one observational data set with "robust" trend of certain sign, none with opposite sign	Attribution analysis is for trend opposing observed sign	none
At least one observational data set with "robust" trend of certain sign, less than half of data sets/studies with that robust trend, none with opposite sign	Observed trend consistent with historical simulations of climate model, using no more than one observational data set and no more than one climate model	very low
At least two observational data sets with "robust" trend of certain sign, at least half of data sets with that robust trend, none with opposite sign	Observed trend consistent with historical simulations of climate models, using 2+ observational data sets and 2+ climate models	low
At least two observational data sets in at least two studies with "robust" trend of certain sign, at least half of data sets with that robust trend, none with opposite sign	Observed trend consistent with historical simulations of climate models, using 2+ observational data sets and 2+ climate models	medium
At least two observational data sets in at least two studies with "robust" trend of certain sign, at least half of data sets with that robust trend, none with opposite sign	Observed trend only possible with anthropogenic forcing in climate models, using 2+ observational data sets and 2+ climate models	high

Method for "Confidence in attribution of at least minor role in precipitation based on our analysis"

Taken from from bottom panels of Figure 2, but also accounting for consistency of signs of observed trends in the top two panels of Figure 2.

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D. Systematic review

Search terms were elaborated in a general form (i.e., without considering specific words for each natural and human system) to avoid missing suitable documents (Table D1). We collected the information from these search terms in February 2020 and updated that review in July 2022. Furthermore, we searched for grey literature, especially on the web pages of National Institutions in each Andean country and the reports of the Intergovernmental Panel on Climate Change. We also scanned the reference list of articles that met all the inclusion criteria and we peruse key Journals. We avoided picking articles that authors were familiar with, instead we did a manual search in the Journals of those articles. These search terms were selected after trying multiple options.

Table D1. Search terms for retrieving scientific articles that detect an observed change in a natural or human system.

Database	Search terms
Scopus	TITLE-ABS-KEY (((climat* PRE/3 change*) OR ("warming")) W/15 (impact OR effect OR contribut* OR measure* OR observation OR threat)) AND TITLE-ABS-KEY ("Tropical Andes" OR andean OR andes OR ecuador* OR peru* OR bolivia* OR colombia* OR venezuela* OR chile* OR argentin*) AND (LIMIT-TO (LANGUAGE , "English") OR LIMIT-TO (LANGUAGE , "Spanish"))
Web of Science	(TS = (((climat* NEAR/3 change*) OR ("warming")) SAME (impact OR effect OR contribut* OR measure* OR observation OR threat) AND ("Tropical Andes" OR andean OR andes OR ecuador* OR peru* OR bolivia* OR colombia* OR venezuela* OR chile* OR argentin*))) AND LANGUAGE: (English OR Spanish)

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