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Supplementary Material

Glacial areas, lake areas, and snow lines from 1975 to 2012: Status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru

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Supplement A: Imagery Used

While lake extents can be outlined in any and all images (provided they are not occluded by clouds), glacierized regions, however, can only be outlined in images without local/regional snow (in addition to no cloud obstruction). As a result, this limits the number of images that can be used to create a glacial-area time series. Table S1 lists all the images used in this study, both for lakes (all images) and for glaciers (those mentioned). Specific thresholds for each image classification, in addition to which glacierized regions could be outlined in each image, are also mentioned. Note that images are dominantly from the cold dry season (May to September/October).

Supplement B: Detailed Classification Processes

The main manuscript describes the steps used to classify the lakes, glaciers, and the snowline. However, some additional information and clarifications on the processes are necessary and we provide them here.

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B1: Lake Classification

While the Normalized Difference Water Index (NDWI) successfully classified the majority of the lakes in the Landsat TM/ETM+ images, the similar (AST3-AST1)/(AST3+AST1) algorithm used for the ASTER images (given that ASTER images do not contain a 'blue' band, 0.45-0.52 μm) required more information to satisfactorily classify lakes of different sediment loads in the ASTER imagery. The ASTER NDWI version performed reasonably to classify the higher sediment loaded lakes, contrary to the other imagery used. For lakes with lower sediment concentrations, however, an additional threshold was applied to ASTER band 3 (DN $\leq$ 1000) to include the remaining lakes. Often in the ASTER imagery, only the larger lower sediment-laden lakes were present in the images used, and so only the ASTER B3 threshold was necessary. However, in these cases we still used the ASTER NDWI algorithm for consistency.

While glacier images required processing in chronological order, classification and identification of the lake outlines in the imagery did not. Due to the fact that the lake classification and hillshade shadow removal steps alone could not remove all the incorrectly classified polygons in the images, manual editing to remove these was required. Taking the time to get the first image accurately classified for the lakes eases this process for all subsequent images. Images with the least amount of incorrectly classified "shadow" pixels are those with high solar azimuth and elevation angles, and so using one of these we removed all polygons within 1 pixel of the hillshade shadow mask. This removes any lakes that may have their outlines obscured by shadows producing an incorrect outline. In some cases, these outlines can be visible in the imagery, and therefore can still be included and just manually altered to the "correct" outline. After this step, we validated the classification visually for any additional incorrect polygons, removing them if necessary. This first image classification then created the first lake outline dataset in a master lake file. To ease this somewhat manually intensive incorrectly-classified-polygons process, the master lake file is then used with subsequent images to extract only those lake polygons whose centroids fall within the polygons in this master lake file. After each additional image had been classified, the lake dataset for each additional image was also appended into the master lake file to be used for each subsequent image (as not every lake is classified in each image). This step aids in ensuring that at each step the most lakes possible are incorporated in each lake mask and used to clip the glacier masks most effectively.

Upon selection and identification of the 50 lakes in the first lake file, a similar process to the above was also applied; instead of manually selecting and keeping only the 50 selected lakes, a master 'selected' lake file was used to always extract the selected lakes in each image so that they could be easily assigned with ID numbers and manually quality controlled. The lake classification process is summarized visually in Figure S1 (a), (b) and (c).

B2: Glacier Classification

As mentioned in the manuscript, for our glacier classifications we followed the methodology outlined in Svoboda and Paul (2009). For the Landsat TM/ETM+ imagery, however, we added an additional 5x5 closing filter after their suggested 3x3 median filter. Initially, this additional filtering step appeared to work best with our imagery, however, pursuing this methodology on more imagery, the median filter alone appeared substantial enough. To maintain method consistency, we continued to apply the second filtering step to the remaining Landsat TM/ETM+ images.

One of the major assumptions we have made in this study is that the earliest image has the largest glacial extent, hence the use of processing glacier images in chronological order from earliest to latest. Having processed all 158 images over the 37 year time period of this study, we can say that this is correct at multi-annual timesteps. As each subsequent image is processed, the glacier polygon centroids for the current image are kept provided they fall within those polygons of the earlier images, each which has been continuously appended into a master glacier file upon completion of processing. Upon manual quality controlling of each image, if the location of a current image centroid was outside of the polygons of the previous years, yet the new ice patch (or old, depending on shape of the current polygon) was obviously a previous or new addition belonging to that glacierized region, these polygons were added to the glacierized polygons for that image, always being assigned the appropriate ID number. Upon completion of the classification for each image, each glacier dataset was appended into the master glacier file so that each subsequent image would always be using the master glacier dataset to ensure inclusion of all the glacierized areas of previous images. The glacier classification process is summarized visually in Figure S1 (d), (e) and (f).

B3: Snowline Classification

For the snowline classification, we used endmember Regions Of Interest (ROI) and the software ENVI add-on package "VIPER Tools" (Roberts et al., 2007) to create a spectral library of the ROIs for each image. These spectral libraries of ROIs for each image were then merged and analyzed to identify the optimum spectra for each endmember following the directions given in the VIPER Tools Manual (Roberts et al., 2007). The Multiple Endmember Spectral Mixture Analysis (MESMA) was then run using only the optimal spectra for each endmember (Figure S2).

Supplement C: Additional Results

C1: Glacier Area Changes

The following figures (Figure S3 through Figure S11) are the same as Figure 9 and Figure 10 of the main manuscript, but for the remaining glacierized areas throughout the Cordillera Vilcanota (CV) and just beyond. Note that each figure has a different y-axis, although the x-axis for all are the same. The locations and extents of each of these glacierized areas can be found in Figure 8 of the manuscript. Table S2 presents the non-normalized version of the decline rates shown in Table 3 of the manuscript. Figure S12 illustrates the intra-annual variability that even occurs when classifying multiple visually snow-free images per year. Additional glacier analyses are presented in Figure S13 (normalized decline rates against median aspect of glaciers within individual watersheds) and Figure S14 (normalized decline rates against hypsometric integral within individual glacier watersheds).

C2: Lake Area Changes

As mentioned in the manuscript, many lake areas do not change beyond their measurement uncertainties, whether they are large lakes or small lakes. We provide examples of such lake-area time series in Figure S15 (Figure S15a: Laguna Langui (Lake ID: 1), Figure S15b: Laguna Sibinacocha (Lake ID: 2), and Figure S15c: unnamed (Lake ID: 42)) so that this is more understandable (locations for all of these lakes are given in Figure 8). In Figure S16 we present the visual and graphical time series of a lake not connected to glacial watersheds which has been moderately declining (Laguna Janccoccota (Lake ID: 11)).

Additional analyses indicating the lake-area changes within 5-year time intervals for lakes connected and not connected to glacial watersheds are also presented in Figure S17 (Figure S17a and Figure S17b, respectively). Table S3 presents the data used to create Figure 16.

C3: Snowlines

Visual outlines of the MESMA classified snowlines for 1988, 1998, and 2009 are presented in Figure S18.

References for Supplementary Material

Roberts, D., Halligan, K. and Dennison, P.: VIPER Tools User Manual, UC Santa Barbara, Department of Geography, Version 1.7, 1–91, 2007.

Svoboda, F. and Paul, F.: A new glacier inventory on southern Baffin Island, Canada, from ASTER data: I. Applied methods, challenges and solutions, Annals of Glaciology, 50(53), 11–21, 2009.

Table S1: All imagery used in this study in a chronological list. All classification methods and thresholds used on each image are indicated, in addition to which images could be used (and were) for the area measurements of each glacierized region. NDWI is the Normalized Difference Water Index, and DS stands for Density Slice.

IMAGE INFORMATION			LAKES	GLACIERS	
Sensor	Date	Image ID	Method & Threshold Used	Method & Threshold Used	Regions ID'd
Landsat 2 MSS	11-Jul-1975	LM20020701975192AAA04	B7-B4/B7+B4 < -0.25		
Landsat 2 MSS	29-Jul-1975	LM20020701975210AAA05	B7-B4/B7+B4 < -0.25	DS 105-255 (B6)	- - - - - 6 - 8 - -
Landsat 2 MSS	28-Oct-1975	LM20030701975301AAA05	B7-B4/B7+B4 < 0.00	DS 150-255 (B6)	- 2 3 4 - - 7 - 9 10
Corona	3-Aug-1980	DZB1216-500232L008001	Manual	Manual	1 - - - - - - - - -
Landsat 4 MSS	13-Oct-1982	LM40030701982286AAA03	NDWI < -0.25		
Landsat 5 TM	6-May-1985	LT50030701985126AAA04	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	
Landsat 5 TM	25-Jul-1985	LT50030701985206AA008	NDWI < -0.60	TM3/TM5 ≥ 2 & TM1 > 25	
Landsat 5 MSS	10-Aug-1985	LM50030701985222AAA03	NDWI < 0.00		
Landsat 5 MSS	26-Aug-1985	LM50030701985238FFF03	NDWI < 0.00	DS 165-255 (B1)	- - - - - 6 - - 9 -
Landsat 5 TM	2-Aug-1988	LT50030701988215CUB00	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 - 9 10
Landsat 5 TM	18-Aug-1988	LT50030701988231CUB00	NDWI < -0.55		
Landsat 5 TM	3-Sep-1988	LT50030701988247CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 - 8 - -
Landsat 5 TM	5-Aug-1989	LT50030701989217CUB00	NDWI < -0.55		
Landsat 5 TM	6-Sep-1989	LT50030701989249CUB00	NDWI < -0.50		
Landsat 5 TM	22-Sep-1989	LT50030701989265CUB00	NDWI < -0.50		
Landsat 5 TM	18-Apr-1990	LT50030701990108XXX02	NDWI < -0.50		
Landsat 5 TM	4-May-1990	LT50030701990124CUB00	NDWI < -0.60	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - - 7 - 9 -
Landsat 5 TM	8-Aug-1990	LT50030701990220CUB00	NDWI < -0.55		
Landsat 5 TM	4-Mar-1991	LT50030701991063CUB00	NDWI < -0.50		
Landsat 5 TM	24-Jun-1991	LT50030701991175XXX02	NDWI < -0.60		
Landsat 5 TM	10-Jul-1991	LT50030701991191XXX01	NDWI < -0.55		
Landsat 5 TM	27-Aug-1991	LT50030701991239XXX01	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - - - - 9 10
Landsat 5 TM	14-Oct-1991	LT50030701991287AAA02	NDWI < -0.50		
Landsat 5 TM	17-Dec-1991	LT50030701991351XXX02	NDWI < -0.45		
Landsat 5 TM	10-Jun-1992	LT50030701992162CUB00	NDWI < -0.40	TM3/TM5 ≥ 2 & TM1 > 25	1 - 3 4 5 6 7 - 9 10
Landsat 5 TM	14-Sep-1992	LT50030701992258CUB00	NDWI < -0.40	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - 5 - - - - -
Landsat 5 TM	12-May-1993	LT50030701993132CUB00	NDWI < -0.50		
Landsat 5 TM	29-Jun-1993	LT50030701993180CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	- 2 - - - 6 - - - -
Landsat 5 TM	18-Jul-1994	LT50030701994199CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	- 2 - - - 6 - 8 - -
Landsat 5 TM	22-Aug-1995	LT50030701995234CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	7-Sep-1995	LT50030701995250CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	9-Oct-1995	LT50030701995282CUB00	NDWI < -0.40	TM3/TM5 ≥ 2 & TM1 > 25	1 - 3 4 5 - 7 8 9 10
Landsat 5 TM	21-Jun-1996	LT50030701996173XXX01	NDWI < -0.60	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - 6 - 8 9 -
Landsat 5 TM	23-Jul-1996	LT50030701996205XXX00	NDWI < -0.60	TM3/TM5 ≥ 2 & TM1 > 25	- 2 - - - 6 7 8 9 -
Landsat 5 TM	8-Aug-1996	LT50030701996221XXX02	NDWI < -0.55		
Landsat 5 TM	24-Aug-1996	LT50030701996237XXX03	NDWI < -0.60		
Landsat 5 TM	9-Sep-1996	LT50030701996253XXX02	NDWI < -0.55		
Landsat 5 TM	27-Oct-1996	LT50030701996301XXX01	NDWI < -0.50		
Landsat 5 TM	8-Jun-1997	LT50030701997159XXX01	NDWI < -0.55		
Landsat 5 TM	24-Jun-1997	LT50030701997175XXX02	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - 6 7 - - -
Landsat 5 TM	10-Jul-1997	LT50030701997191CUB00	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - 6 7 8 - -
Landsat 5 TM	26-Jul-1997	LT50030701997207XXX01	NDWI < -0.55		
Landsat 5 TM	27-Aug-1997	LT50030701997239AAA02	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - 6 - 8 - -
Landsat 5 TM	10-May-1998	LT50030701998130XXX01	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	26-May-1998	LT50030701998146XXX01	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	13-Jul-1998	LT50030701998194XXX01	NDWI < -0.55		
Landsat 5 TM	29-Jul-1998	LT50030701998210XXX00	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	14-Aug-1998	LT50030701998226XXX01	NDWI < -0.45		

IMAGE INFORMATION			LAKES	GLACIERS	
Sensor	**Date**	**Image ID**	**Method & Threshold Used**	**Method & Threshold Used**	**Regions ID'd**
Landsat 5 TM	30-Aug-1998	LT50030701998242XXX01	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - - - - - - -
Landsat 5 TM	15-Sep-1998	LT50030701998258XXX02	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - 5 - - - - -
Landsat 5 TM	27-Apr-1999	LT50030701999117CUB00	NDWI < -0.40		
Landsat 5 TM	29-May-1999	LT50030701999149XXX01	NDWI < -0.50		
Landsat 5 TM	14-Jun-1999	LT50030701999165XXX01	NDWI < -0.55		
Landsat 5 TM	30-Jun-1999	LT50030701999181XXX02	NDWI < -0.50		
Landsat 7 (SLC-on)	9-Aug-1999	LE70030701999221EDC01	NDWI < -0.40		
Landsat 5 TM	5-Nov-1999	LT50030701999309CPE01	NDWI < -0.45		
Landsat 5 TM	21-Nov-1999	LT50030701999325CPE01	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	1 - - 4 5 6 7 - 9 -
Landsat 5 TM	15-May-2000	LT50030702000136XXX02	NDWI < -0.55		
Landsat 7 (SLC-on)	23-May-2000	LE70030702000144EDC00	NDWI < -0.50		
Landsat 5 TM	31-May-2000	LT50030702000152XXX02	NDWI < -0.50		
Landsat 5 TM	16-Jun-2000	LT50030702000168XXX02	NDWI < -0.55		
Landsat 7 (SLC-on)	24-Jun-2000	LE70030702000176EDC00	NDWI < -0.40		
Landsat 5 TM	2-Jul-2000	LT50030702000184XXX02	NDWI < -0.50		
Landsat 5 TM	18-Jul-2000	LT50030702000200XXX02	NDWI < -0.40	TM3/TM5 ≥ 2 & TM1 > 25	- - - 4 - 6 7 - 9 -
Landsat 5 TM	4-Sep-2000	LT50030702000248XXX02	NDWI < -0.35		
Landsat 7 (SLC-on)	12-Sep-2000	LE70030702000256EDC00	NDWI < -0.30	ETM3/ETM5 ≥ 2 & ETM1 > 25	- - - - - 6 - - - -
Landsat 5 TM	19-Jun-2001	LT50030702001170CUB00	NDWI < -0.40		
ASTER-L1A (w/ SWIR)	13-Jul-2001	AST_L1A_003_07132001151224	NDWI < -0.20 OR B3 ≤ 1000		
Landsat 5 TM	21-Jul-2001	LT50030702001202CUB00	NDWI < -0.50		
Landsat 7 (SLC-on)	14-Aug-2001	LE70030702001226EDC00	NDWI < -0.40		
Landsat 7 (SLC-on)	4-Oct-2002	LE70030702002277EDC00	NDWI < -0.30		
ASTER-L1A (w/ SWIR)	4-Oct-2002	AST_L1A_003_10042002150525	NDWI < -0.15 OR B3 ≤ 1000		
ASTER-L1A (w/ SWIR)	30-Apr-2003	AST_L1A_003_04302003150425	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 7 (SLC-on)	30-Apr-2003	LE70030702003120EDC00	NDWI < -0.40		
ASTER-L1A (w/ SWIR)	8-Jun-2003	AST_L1A_003_06082003151047	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/ SWIR)	20-Aug-2003	AST_L1A_003_08202003150335	NDWI < -0.30 OR B3 ≤ 1000		
Landsat 5 TM	29-Sep-2003	LT50030702003272CUB00	NDWI < -0.40	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - - - 7 - - -
Landsat 5 TM	15-Oct-2003	LT50030702003288CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 - - 4 - - 7 - 9 -
ASTER-L1A (w/ SWIR)	8-Nov-2003	AST_L1A_003_11082003150436	NDWI < -0.20 OR B3 ≤ 1000	B3/B4 ≥ 1.6 & B1 > 47	- - - 4 - - 7 - - -
Landsat 5 TM	8-Apr-2004	LT50030702004099CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - - 6 - - - -
Landsat 5 TM	10-May-2004	LT50030702004131CUB00	NDWI < -0.55		
ASTER-L1A (w/ SWIR)	3-Jun-2004	AST_L1A_003_06032004150417	NDWI < -0.25 OR B3 ≤ 1000	B3/B4 ≥ 1.6 & B1 > 47	- - - - - 6 - - - -
Landsat 5 TM	11-Jun-2004	LT50030702004163CUB00	NDWI < -0.60	TM3/TM5 ≥ 2 & TM1 > 25	1 - 3 4 - - 7 - - -
ASTER-L1A (w/ SWIR)	21-Jul-2004	AST_L1A_003_07212004150403	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/ SWIR)	6-Aug-2004	AST_L1A_003_08062004150355	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/ SWIR)	6-Aug-2004	AST_L1A_003_08062004150404	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	26-Mar-2005	LT50030702005085CUB00	NDWI < -0.45		
Landsat 5 TM	11-Apr-2005	LT50030702005101CUB00	NDWI < -0.50		
Landsat 5 TM	29-May-2005	LT50030702005149CUB00	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 -
ASTER-L1A (w/ SWIR)	13-Jun-2005	AST_L1A_003_06132005150939	NDWI < -0.20 OR B3 ≤ 1000	B3/B4 ≥ 1.6 & B1 > 47	- - - 4 - - 7 - - -
Landsat 5 TM	14-Jun-2005	LT50030702005165CUB00	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	- - - 4 - - - - - -
Landsat 5 TM	30-Jun-2005	LT50030702005181CUB00	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 - 7 8 9 10
ASTER-L1A (w/ SWIR)	8-Jul-2005	AST_L1A_003_07082005150341	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	16-Jul-2005	LT50030702005197CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
ASTER-L1A (w/ SWIR)	24-Jul-2005	AST_L1A_003_07242005150342	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	1-Aug-2005	LT50030702005213CUB00	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - 5 - 7 8 - -
Landsat 5 TM	17-Aug-2005	LT50030702005229CUB00	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - 5 6 7 8 - -
Landsat 5 TM	16-May-2006	LT50030702006136CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - 6 - - - -
ASTER-L1A (w/ SWIR)	24-May-2006	AST_L1A_003_05242006150336	NDWI < -0.25 OR B3 ≤ 1000	B3/B4 ≥ 1.6 & B1 > 47	- - - - - 6 - - - -
Landsat 5 TM	17-Jun-2006	LT50030702006168CUB00	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - 5 6 - 8 9 -
ASTER-L1A (w/ SWIR)	25-Jun-2006	AST_L1A_003_06252006150357	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	19-Jul-2006	LT50030702006200CUB00	NDWI < -0.60	TM3/TM5 ≥ 2 & TM1 > 25	1 2 - - 5 6 7 8 9 -
ASTER-L1A (w/ SWIR)	27-Jul-2006	AST_L1A_003_07272006150413	NDWI < -0.25 OR B3 ≤ 1000	B3/B4 ≥ 1.6 & B1 > 47	- - - - - - - - 9 10
Landsat 5 TM	4-Aug-2006	LT50030702006216CUB01	NDWI < -0.50		
ASTER-L1A (w/ SWIR)	12-Aug-2006	AST_L1A_003_08122006150403	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	5-Sep-2006	LT50030702006248CUB00	NDWI < -0.50		
Landsat 5 TM	20-Jun-2007	LT50030702007171CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 - - -
Landsat 5 TM	6-Jul-2007	LT50030702007187CUB00	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	22-Jul-2007	LT50030702007203CUB00	NDWI < -0.55		
Landsat 5 TM	7-Aug-2007	LT50030702007219CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 - 5 6 7 - - -
Landsat 5 TM	23-Aug-2007	LT50030702007235CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	- - 3 4 5 6 7 8 - -
Landsat 5 TM	5-May-2008	LT50030702008126CUB00	NDWI < -0.50		
Landsat 5 TM	21-May-2008	LT50030702008142CUB00	NDWI < -0.50		
Landsat 5 TM	6-Jun-2008	LT50030702008158CUB00	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - - - - 9 -
Landsat 5 TM	24-Jul-2008	LT50030702008206CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - - - 7 - 9 10

IMAGE INFORMATION			LAKES	GLACIERS	
Sensor	Date	Image ID	Method & Threshold Used	Method & Threshold Used	Regions ID'd
ASTER-L1A (w/o SWIR)	1-Aug-2008	AST_L1A_003_08012008150435	NDWI < -0.25 OR B3 ≤ 1000	Manual	1 - - - - 6 - - - -
Landsat 5 TM	9-Aug-2008	LT50030702008222CUB00	NDWI < -0.50		
Landsat 5 TM	25-Aug-2008	LT50030702008238CUB00	NDWI < -0.55	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	26-Sep-2008	LT50030702008270CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - - - 7 - - -
Landsat 5 TM	12-Oct-2008	LT50030702008286CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - 5 - - - - -
Landsat 5 TM	8-May-2009	LT50030702009128CUB00	NDWI < -0.50		
Landsat 5 TM	24-May-2009	LT50030702009144CUB00	NDWI < -0.50		
Landsat 5 TM	9-Jun-2009	LT50030702009160CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	- - - - - 6 - - - -
Landsat 5 TM	25-Jun-2009	LT50030702009176CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 - - 4 5 6 7 - - -
ASTER-L1A (w/o SWIR)	3-Jul-2009	AST_L1A_003_07032009150439	NDWI < -0.25 OR B3 ≤ 1000	Manual	1 - - - 5 - 7 - - -
Landsat 5 TM	11-Jul-2009	LT50030702009192CUB00	NDWI < -0.50		
ASTER-L1A (w/o SWIR)	19-Jul-2009	AST_L1A_003_07192009150435	NDWI < -0.20 OR B3 ≤ 1000	Manual	1 - - - 5 - 7 - - -
ASTER-L1A (w/o SWIR)	4-Aug-2009	AST_L1A_003_08042009150436	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/o SWIR)	4-Aug-2009	AST_L1A_003_08042009150445	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	28-Aug-2009	LT50030702009240CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 - 8 - 10
Landsat 5 TM	13-Sep-2009	LT50030702009256CUB00	NDWI < -0.50		
Landsat 5 TM	15-Oct-2009	LT50030702009288CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 - - - - - 7 - 9 10
Landsat 5 TM	31-Oct-2009	LT50030702009304CUB00	NDWI < -0.40		
ASTER-L1A (w/o SWIR)	3-May-2010	AST_L1A_003_05032010150415	NDWI < -0.25 OR B3 ≤ 1000	Manual	- - - 4 - - - - - -
ASTER-L1A (w/o SWIR)	3-May-2010	AST_L1A_003_05032010150423	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	12-Jun-2010	LT50030702010163CUB00	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	1 - - 4 5 6 - 8 9 10
ASTER-L1A (w/o SWIR)	6-Jul-2010	AST_L1A_003_07062010150420	NDWI < -0.20 OR B3 ≤ 1000	Manual	1 - - - - 6 - - - -
ASTER-L1A (w/o SWIR)	22-Jul-2010	AST_L1A_003_07222010150413	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	30-Jul-2010	LT50030702010211CUB00	NDWI < -0.55		
ASTER-L1A (w/o SWIR)	7-Aug-2010	AST_L1A_003_08072010150403	NDWI < -0.25 OR B3 ≤ 1000	Manual	1 - - - - 6 - - - -
Landsat 5 TM	15-Aug-2010	LT50030702010227CUB00	NDWI < -0.45	TM3/TM5 ≥ 2 & TM1 > 25	1 2 - 4 5 6 7 8 9 10
ASTER-L1A (w/o SWIR)	23-Aug-2010	AST_L1A_003_08232010150404	NDWI < -0.25 OR B3 ≤ 1000	Manual	- - - - - 6 - - - -
Landsat 5 TM	16-Sep-2010	LT50030702010259CUB00	NDWI < -0.50	TM3/TM5 ≥ 2 & TM1 > 25	1 2 3 4 5 6 7 8 9 10
Landsat 5 TM	14-May-2011	LT50030702011134CUB00	NDWI < -0.50		
Landsat 5 TM	15-Jun-2011	LT50030702011166CUB00	NDWI < -0.55		
Landsat 5 TM	17-Jul-2011	LT50030702011198CUB00	NDWI < -0.50		
ASTER-L1A (w/o SWIR)	25-Jul-2011	AST_L1A_003_07252011150406	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/o SWIR)	10-Aug-2011	AST_L1A_003_08102011150405	NDWI < -0.25 OR B3 ≤ 1000		
Landsat 5 TM	18-Aug-2011	LT50030702011230CUB00	NDWI < -0.50		
ASTER-L1A (w/o SWIR)	2-Sep-2011	AST_L1A_003_09022011151005	NDWI < -0.20 OR B3 ≤ 1000		
Landsat 5 TM	3-Sep-2011	LT50030702011246CUB00	NDWI < -0.50		
Landsat 5 TM	21-Oct-2011	LT50030702011294CUB00	NDWI < -0.50		
Landsat 5 TM	6-Nov-2011	LT50030702011310CUB00	NDWI < -0.50		
ASTER-L1A (w/o SWIR)	2-Jul-2012	AST_L1A_003_07022012151021	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/o SWIR)	18-Jul-2012	AST_L1A_003_07182012151012	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/o SWIR)	18-Jul-2012	AST_L1A_003_07182012151021	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/o SWIR)	18-Jul-2012	AST_L1A_003_07182012151030	NDWI < -0.25 OR B3 ≤ 1000		
ASTER-L1A (w/o SWIR)	12-Aug-2012	AST_L1A_003_08122012150400	NDWI < -0.25 OR B3 ≤ 1000		

	1975 - 2010			1988 - 2010			1988 - 1999			2000 - 2010		
Glacier ID (increasing area ↓)	No. of Images	Decline Rate ± 95 % CI ($km^2 yr^{-1}$)	RMSE ($km^2 yr^{-1}$)	No. of Images	Decline Rate ± 95 % CI ($km^2 yr^{-1}$)	RMSE ($km^2 yr^{-1}$)	No. of Images	Decline Rate ± 95 % CI ($km^2 yr^{-1}$)	RMSE ($km^2 yr^{-1}$)	No. of Images	Decline Rate ± 95 % CI ($km^2 yr^{-1}$)	RMSE ($km^2 yr^{-1}$)
10 (NM)	12	0.16 ± 0.03	0.41	11	0.14 ± 0.06	0.40	5	0.34 ± 0.27	0.39	6	0.21 ± 0.10	0.07
7 (NCt)	18	0.07 ± 0.01	0.12	17	0.07 ± 0.02	0.12	8	0.11 ± 0.06	0.13	9	0.09 ± 0.05	0.08
9 (NCc)	18	0.08 ± 0.02	0.21	16	0.08 ± 0.02	0.17	8	0.12 ± 0.08	0.20	8	0.10 ± 0.05	0.09
4 (NI)	14	0.13 ± 0.02	0.29	13	0.10 ± 0.04	0.28	5	0.19 ± 0.17	0.29	8	0.11 ± 0.11	0.24
5 (NP)				11	0.11 ± 0.03	0.20	5	0.18 ± 0.08	0.15	6	0.15 ± 0.21	0.18
6 (NS)	19	0.31 ± 0.02	0.46	17	0.29 ± 0.04	0.40	9	0.27 ± 0.14	0.52	8	0.38 ± 0.06	0.16
8 (NAc)	13	0.45 ± 0.07	1.86	12	0.46 ± 0.14	1.94	6	0.51 ± 0.76	2.93	6	0.40 ± 0.43	0.85
3 (NA)	11	0.32 ± 0.08	1.51	10	0.32 ± 0.14	1.60	4	0.61 ± 0.89	1.71	6	0.66 ± 0.46	0.95
1 (QIC)	14	0.57 ± 0.09*	1.44	13	0.56 ± 0.11	1.49	5	0.73 ± 0.17	0.60	8	0.96 ± 0.32	1.03
2 (MGRCV)	13	2.87 ± 0.42	21.67	12	2.71 ± 0.70	22.24	6	3.06 ± 4.21	32.45	6	4.27 ± 1.96	8.56
CV (1-7, 9-10)				8	3.99 ± 1.15	35.94	3	5.66 ± 24.90	52.74	5	6.55 ± 4.76	20.11

* 1980 (not 1975) - 2010 for QIC

Table S2: Glacial decline rates (not normalized) using minimum areas for each year for each glacierized ID throughout the Cordillera Vilcanota (IDs 1-7, 9-10) and just beyond (ID 8) for four different time periods: 1975-2010 (the whole time series, including Corona and MSS imagery), 1988-2010 (the densest time series, Landsat TM/ETM+ and ASTER), 1988-1999 (which roughly represents the 1990s but with additional 1988 data points to strengthen the regression), and 2000-2010 (the 2000s). This table is the pre-normalized version of Table 3, with the addition of an RMSE column.

Group	Lake ID	Name (if known)	Easting	Northing	Earliest TM Area (km^2)	Earliest TM Area Date	Latest TM Area (km^2)	Latest TM Area Date	Area Change (%)	Summary of Change
Lakes CONNECTED to Glaciers	2	Laguna Sibinacocha	281807	8465689	25.193	07/25/85	28.202	10/21/11	11.9	Not Natural
	5		290564	8452268	0.730	07/25/85	0.724	11/06/11	-0.8	Stable
1st	6		272311	8480662	0.063	05/06/85	0.062	10/21/11	-2.5	Stable
	7	Laguna Huarurumicocha	271493	8481826	0.341	07/25/85	0.383	10/21/11	12.3	Moderate Growth
	39		268881	8484817	0.036	05/06/85	0.032	10/21/11	-10.1	Moderate Decline
	31		268004	8485559	0.219	05/06/85	0.209	10/21/11	-4.6	Stable
Last	32	Laguna Singrenacocha	266203	8488682	2.849	05/06/85	2.808	10/21/11	-1.5	Stable
	8		255485	8476568	0.009	05/06/85	0.194	10/21/11	2107.7	Significant Growth
	46	Laguna Pucacocha	256711	8471542	0.213	05/04/90	0.209	11/06/11	-1.9	Stable
	9		253688	8472565	0.098	05/06/85	0.090	11/06/11	-7.4	Minimal Decline
	20		348622	8459476	0.097	08/02/88	0.093	11/06/11	-4.4	Stable
	21		348598	8455665	0.221	07/25/85	0.229	11/06/11	4.0	Stable
	50		345177	8452149	0.233	05/06/85	0.309	11/06/11	32.4	Moderate Growth
	22		305368	8442352	0.011	08/18/88	0.010	09/03/11	-10.0	Moderate Decline
	23		298261	8455219	0.013	07/06/07	0.017	11/06/11	29.8	Moderate Growth
	24		300804	8461043	0.015	05/04/90	0.009	08/15/10	-39.7	Moderate Decline
	25		300517	8460427	0.011	08/14/98	0.061	11/06/11	472.3	Significant Growth
	26		299617	8459054	0.014	08/02/88	0.032	11/06/11	125.0	Significant Growth
	30	Laguna Armaccocha	263310	8485068	0.606	05/06/85	0.561	09/03/11	-7.4	Minimal Decline
	34		301702	8461358	0.027	08/02/88	0.025	11/06/11	-6.7	Minimal Decline
	33		300980	8461956	0.008	07/25/85	0.316	09/03/11	3745.2	Significant Growth
	35		299034	8458600	0.012	10/27/96	0.077	11/06/11	555.8	Significant Growth
	36		280549	8476358	0.142	05/04/90	0.128	10/21/11	-9.5	Minimal Decline
	37		281884	8475474	0.523	07/25/85	0.517	10/21/11	-1.2	Stable
	38	Laguna Amayuni	284433	8471893	2.109	05/06/85	2.124	11/06/11	0.7	Stable
	40		277876	8482943	0.317	05/06/85	0.337	08/18/11	6.1	Minimal Growth
	41		274034	8486443	0.077	05/06/85	0.129	09/03/11	66.8	Moderate Growth
	42		301008	8463877	0.011	07/25/85	0.012	11/06/11	8.3	Minimal Growth
	44		356155	8454809	2.312	08/02/88	2.282	11/06/11	-1.3	Stable
	45		301197	8477901	0.015	05/06/85	0.027	09/03/11	87.7	Moderate Growth
	48	Laguna Quillca	281816	8409695	0.241	08/02/88	0.246	11/06/11	2.0	Stable
					Mean: 1.186 Median: 0.098		Mean: 1.305 Median: 0.194		Mean: 230.9 Median: 0.7	
Lakes NOT CONNECTED to Glaciers	49		282171	8388617	0.344	08/18/88	0.331	11/06/11	-3.9	Stable
	1	Laguna Langui	260881	8397984	54.549	08/02/88	54.220	11/06/11	-0.6	Stable
	3	Laguna Cochachaca	275785	8455448	1.509	07/25/85	1.484	11/06/11	-1.7	Stable
	4	Laguna Cocha Uma	276792	8454254	1.464	07/25/85	1.437	11/06/11	-1.8	Stable
	10	Laguna Conoccotta	261248	8414392	0.871	07/25/85	0.827	11/06/11	-5.1	Minimal Decline
	11	Laguna Janccoccota	340198	8377507	3.154	07/25/85	1.828	09/03/11	-42.0	Moderate Decline
	12		352198	8376508	0.844	07/25/85	0.835	11/06/11	-1.0	Stable
	13		381829	8426559	1.238	07/25/85	1.130	11/06/11	-8.7	Minimal Decline
	14		372188	8441884	0.252	07/25/85	0.237	11/06/11	-5.9	Minimal Decline
	15		369908	8443332	0.302	07/25/85	0.276	11/06/11	-8.5	Minimal Decline
	16		359676	8443875	0.987	07/25/85	0.916	11/06/11	-7.2	Minimal Decline
	17		359572	8447310	0.604	07/25/85	0.579	09/03/11	-4.1	Stable
	18		358714	8448244	0.785	07/25/85	0.746	11/06/11	-5.0	Minimal Decline
	19		358015	8456141	0.327	07/25/85	0.327	11/06/11	-0.1	Stable
	27	Laguna Sacacanicocha	275861	8425772	2.374	07/25/85	2.304	11/06/11	-2.9	Stable
	28	Laguna Asnacocha	232508	8439237	3.040	05/06/85	2.823	11/06/11	-7.1	Minimal Decline
	29	Laguna Acopia	230652	8443674	0.480	07/25/85	0.458	11/06/11	-4.5	Stable
	47	Laguna Pomacanchi	227033	8448491	20.227	08/02/88	20.514	10/21/11	1.4	Stable
	43		357893	8451780	1.016	07/25/85	0.974	11/06/11	-4.1	Stable
					Mean: 4.967 Median: 0.983		Mean: 4.855 Median: 0.916		Mean: -5.9 Median: -4.1	

Table S3: Data from which Figure 16 in the main manuscript is derived. If one lake is the only lake investigated in a watershed, it is enclosed above and below by black lines. If lakes flow into each other, as in, if multiple lakes are within the watershed of the lake farthest downstream, these are those between the black lines, ordered by first lake in the watershed to last lake (for an example, please refer to Lake IDs 6, 7, 39, 31, and 32).

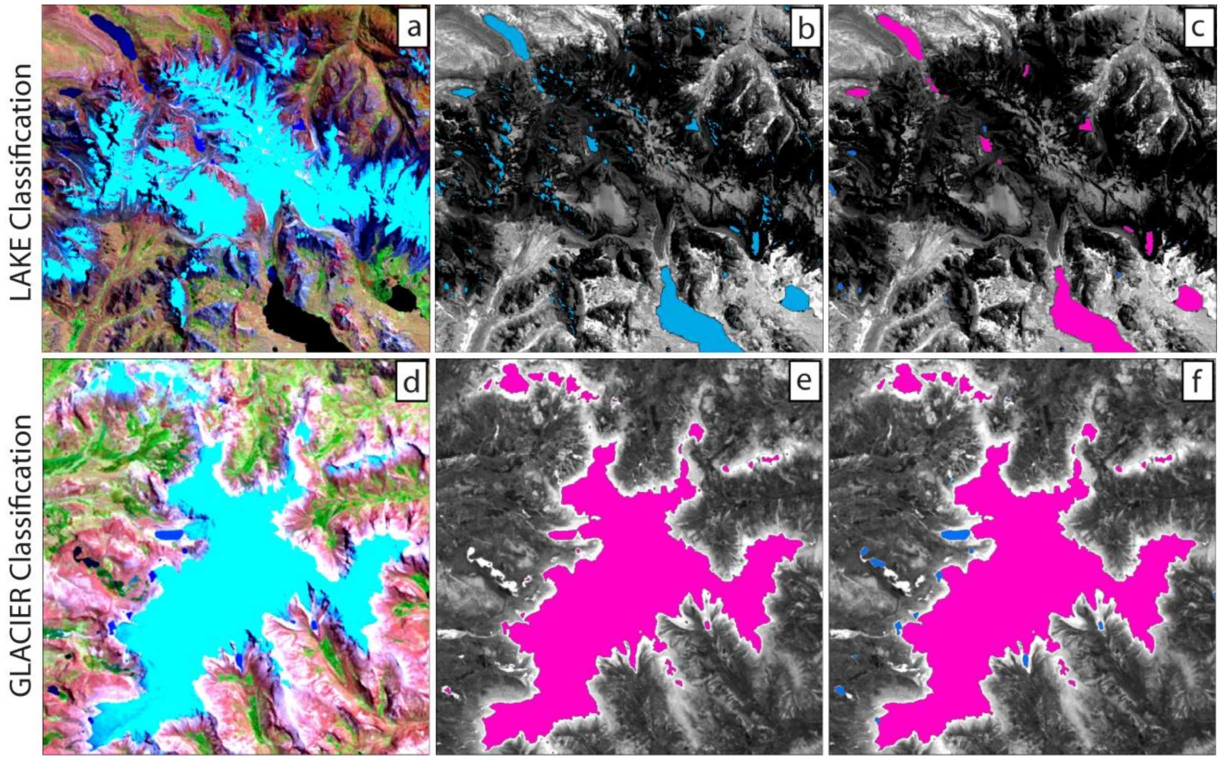

Figure S1: Images summarizing classification methods for lake (a, b, c) and glacier (d, e, f) outlines – (a) and (d) Landsat TM image for 09/16/2010 (Bands 742 RGB), (b) NDWI with threshold and 5x5 closing filter applied (resulting "lakes" colored blue). Note that many shadow areas are incorrectly classified as lakes. (c) Final lake mask, post-hillshade shadow removal and manual editing. Lakes colored in pink indicate some of the 50 lakes that were selected and identified to be followed through time. (e) TM3/TM5 with thresholds applied (resulting "glaciers" colored pink). Note that some lakes are incorrectly classified as glaciers. (f) Final glacier mask (for the Quelccaya Ice Cap), post-lake removal (lakes from lake mask are colored in blue) and manual editing.

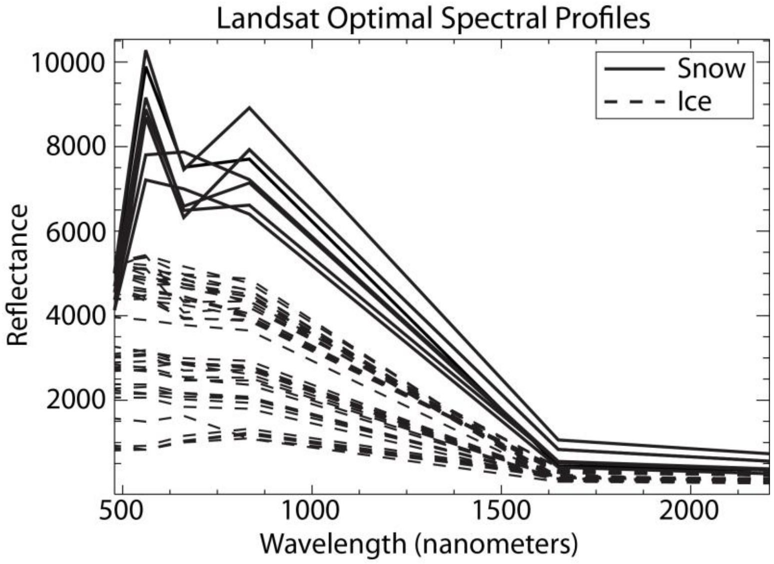

Figure S2: Optimal spectra used in MESMA analysis for Landsat imagery (3 images ranging from 09/03/1988-10/15/2009). Solid lines indicate snow spectra, and dashed lines indicate ice spectra. Note that there is a general greater variability within the ice spectra than in the snow spectra and we have thus relied on more endmembers for ice.

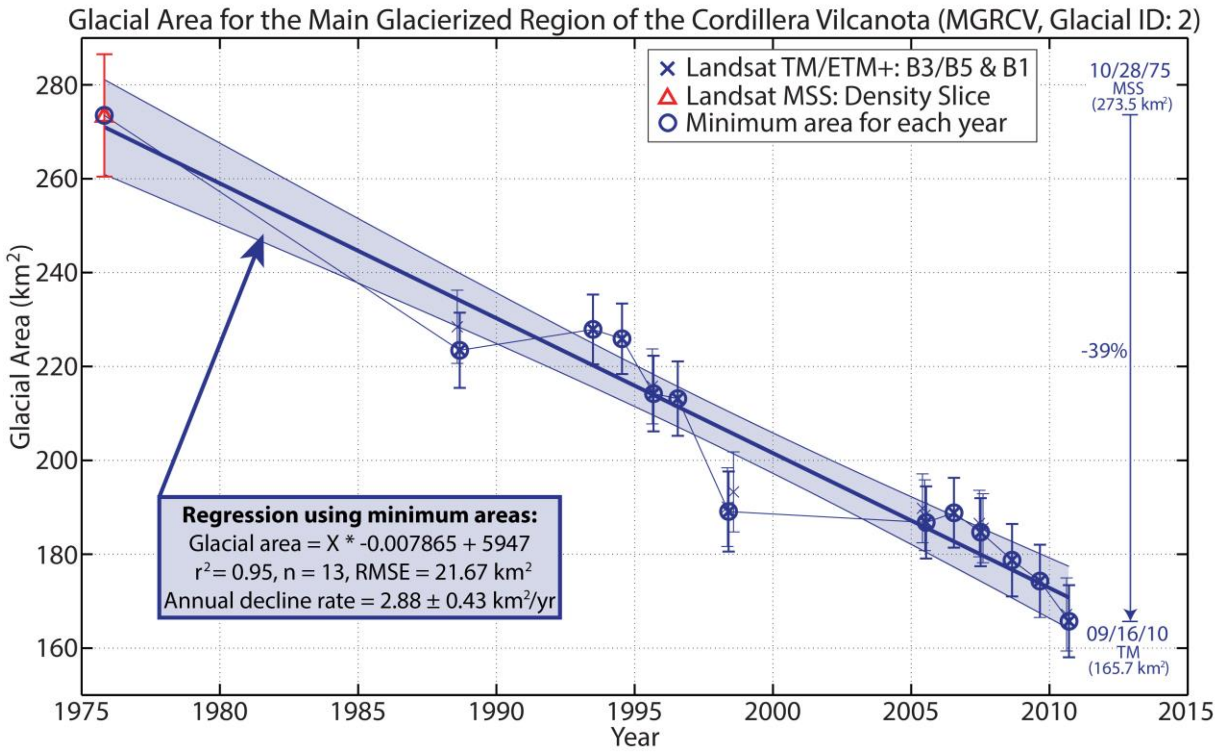

Figure S3: Glacial-area time series for the main glacierized region of the CV (Glacial ID: 2, Figure 8).

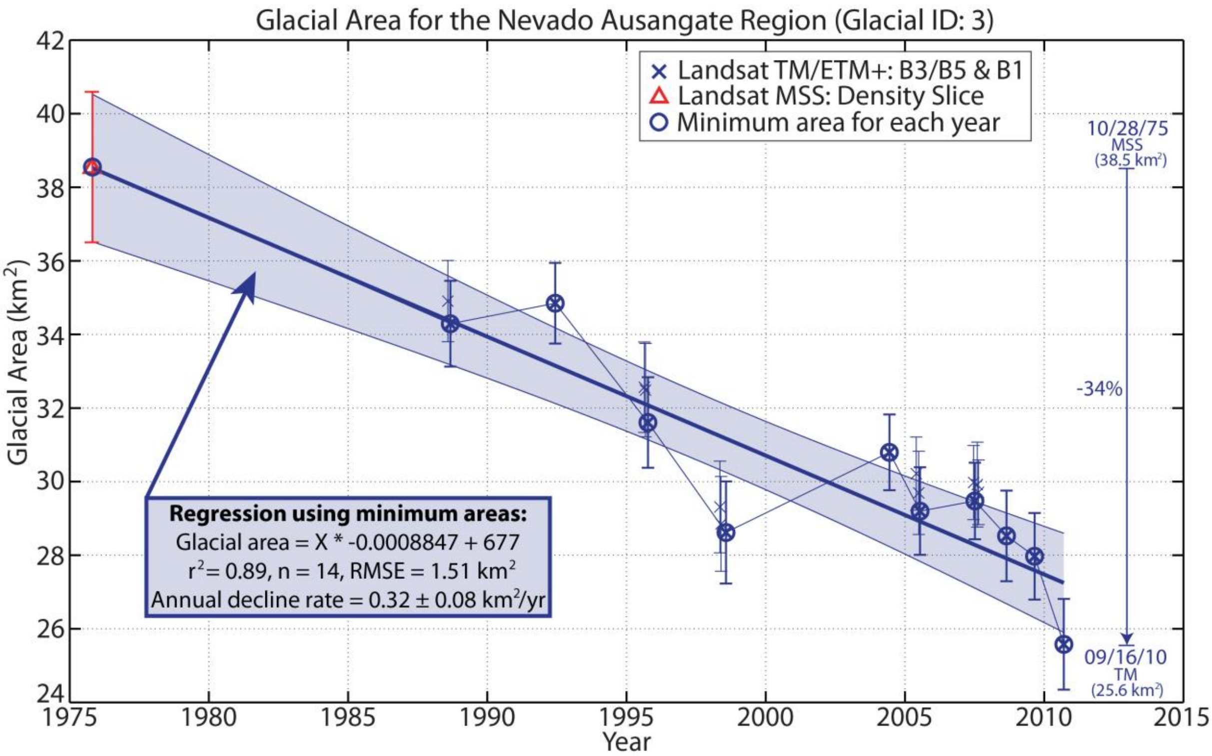

Figure S4: Glacial-area time series for the Nevado Ausangate region (Glacial ID: 3, Figure 8).

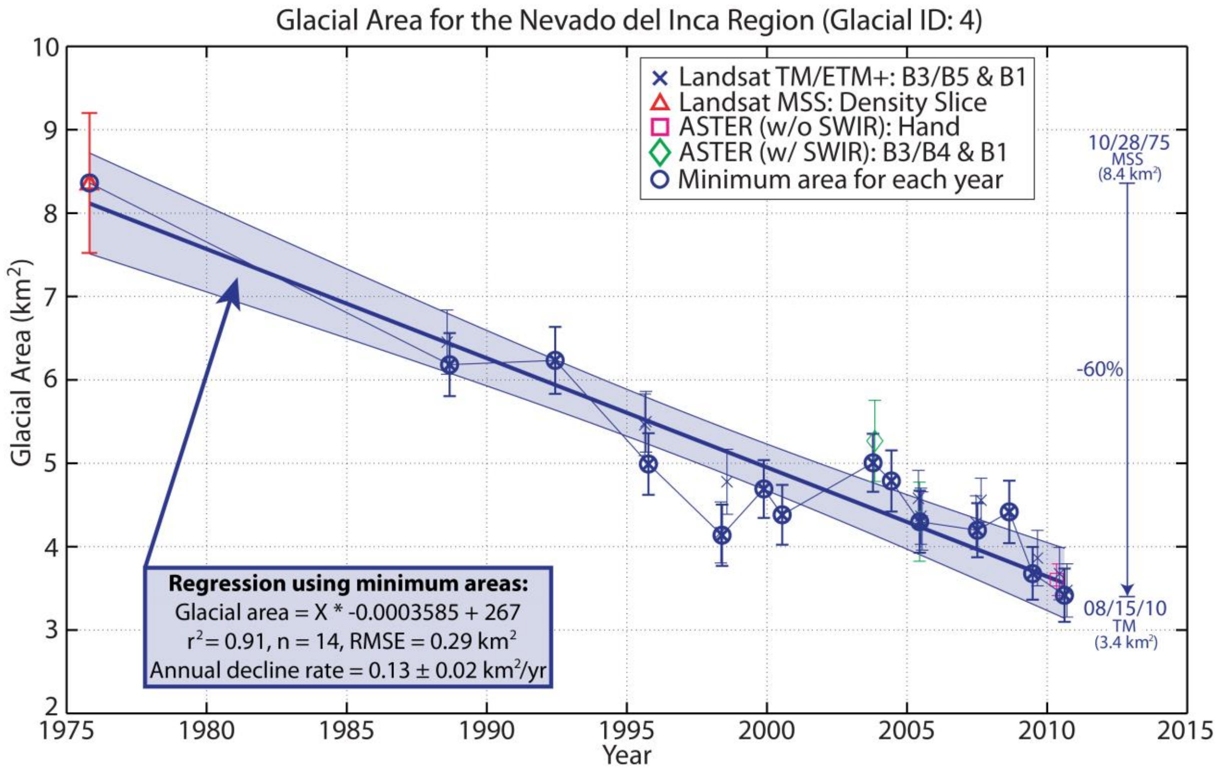

Figure S5: Glacial-area time series for the Nevado del Inca region (Glacial ID: 4, Figure 8).

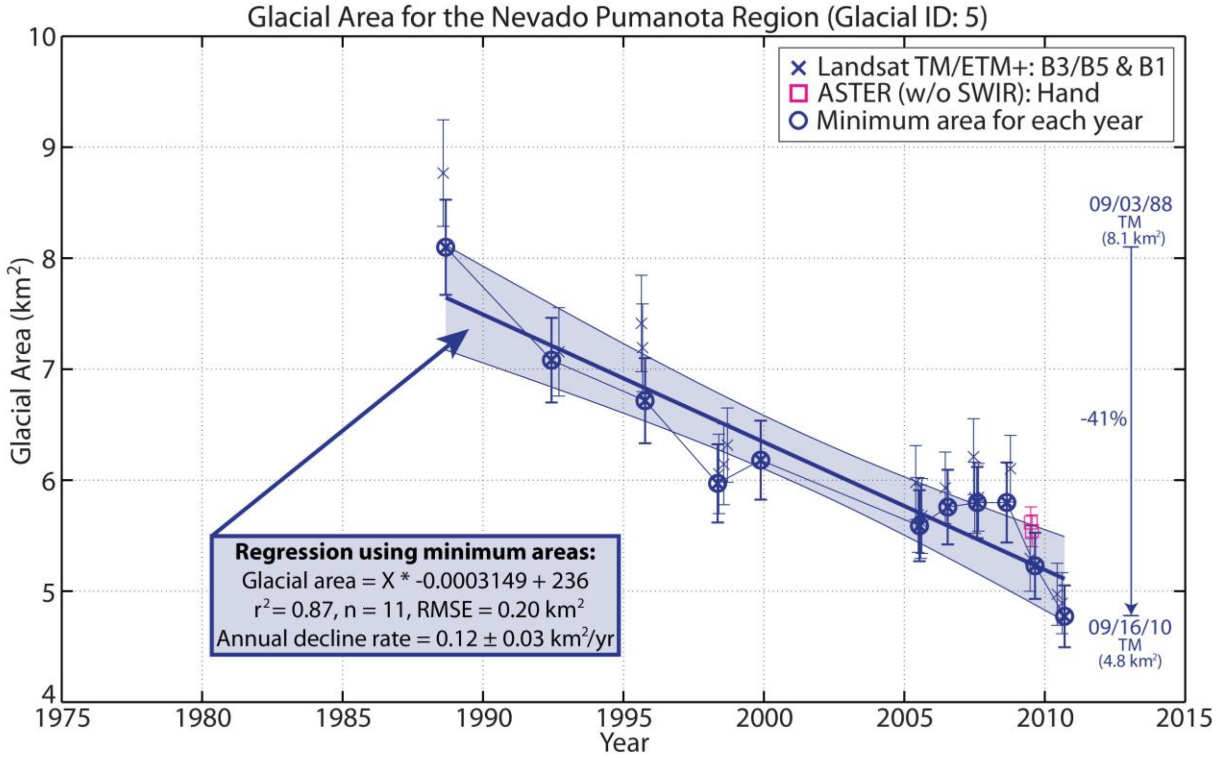

Figure S6: Glacial-area time series for the Nevado Pumanota region (Glacial ID: 5, Figure 8).

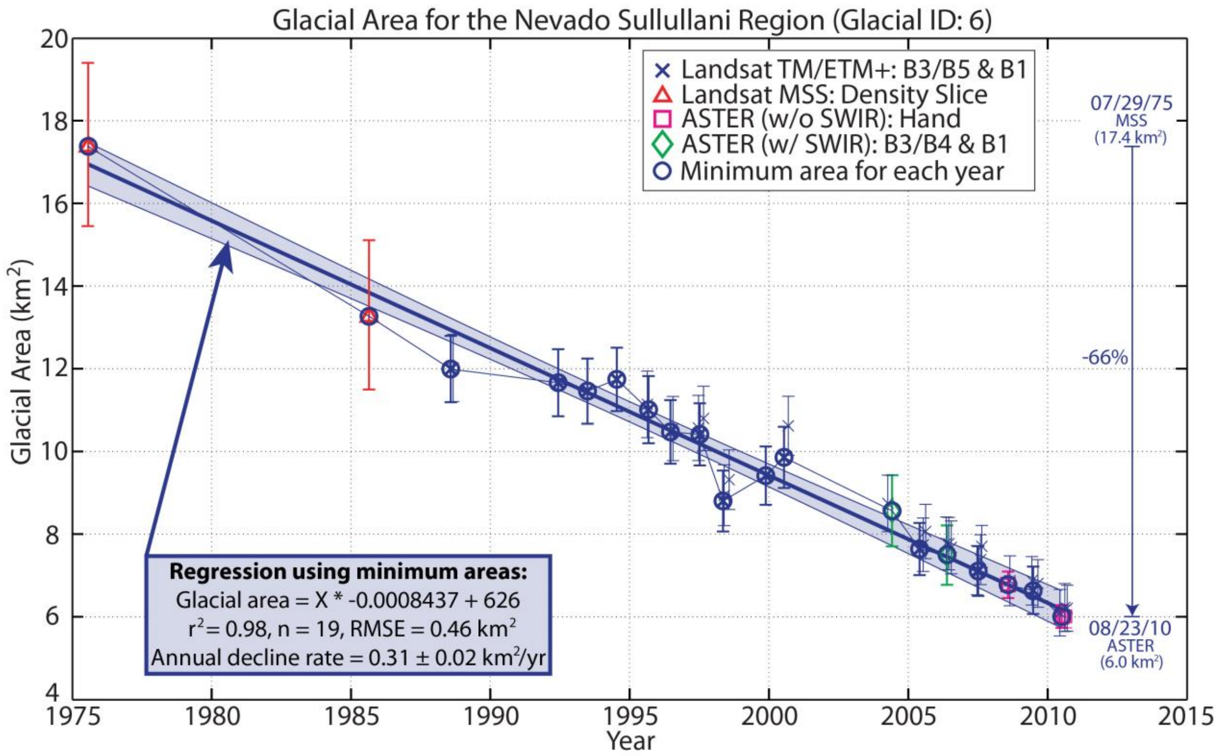

Figure S7: Glacial-area time series for the Nevado Sullullani region (Glacial ID: 6, Figure 8).

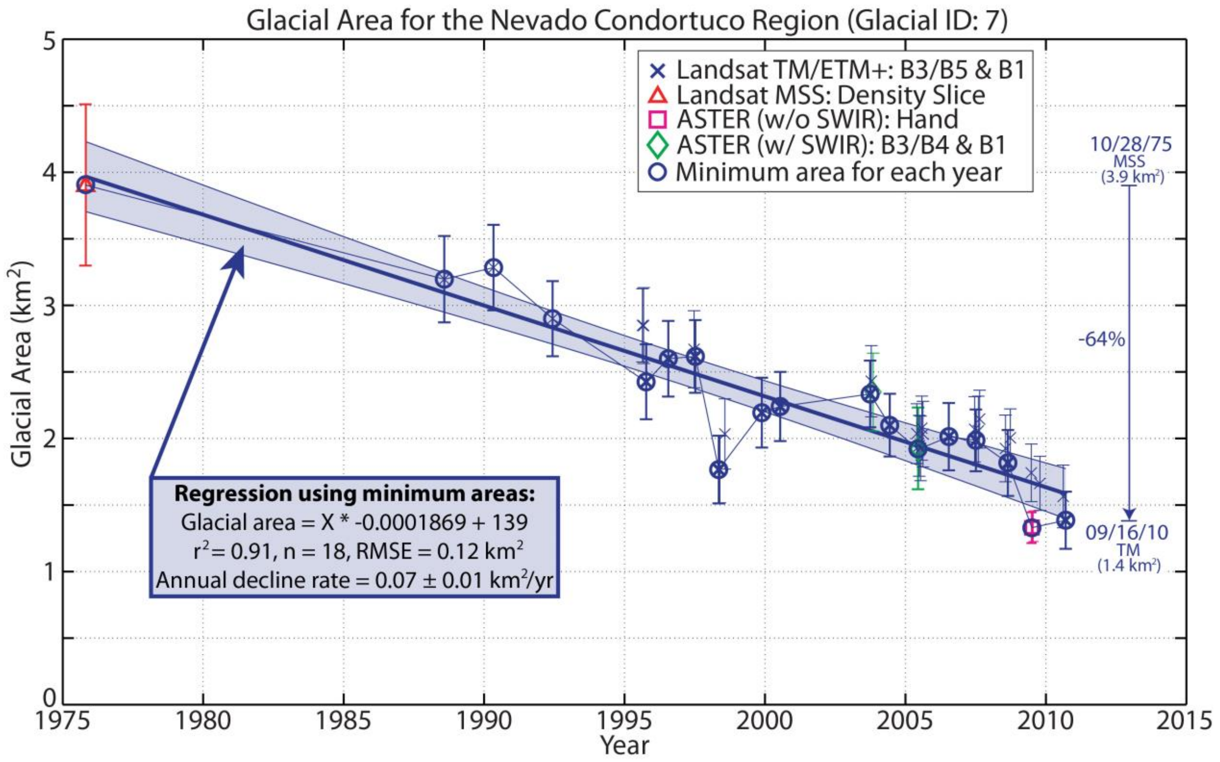

Figure S8: Glacial-area time series for the Nevado Condortuco region (Glacial ID: 7, Figure 8).

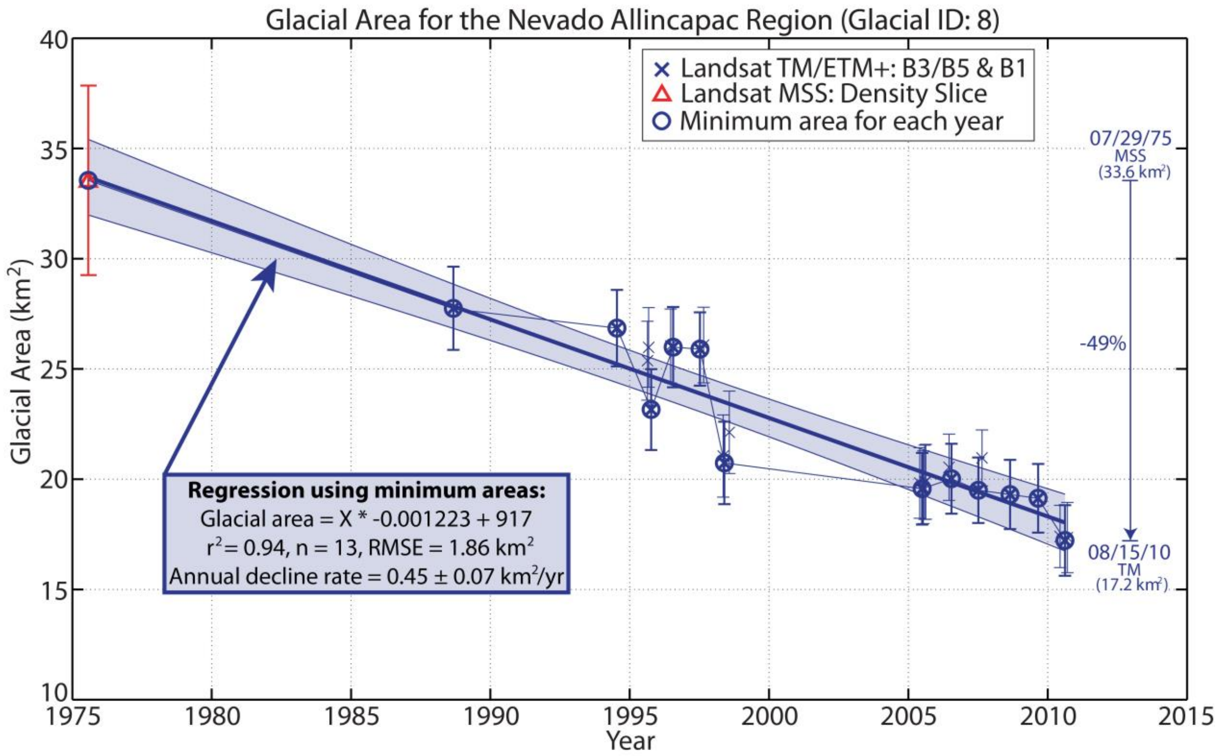

Figure S9: Glacial-area time series for the Nevado Allincapac region (Glacial ID: 8, Figure 8). This glacierized region is located just beyond the eastern boundary of the Cordillera Vilcanota.

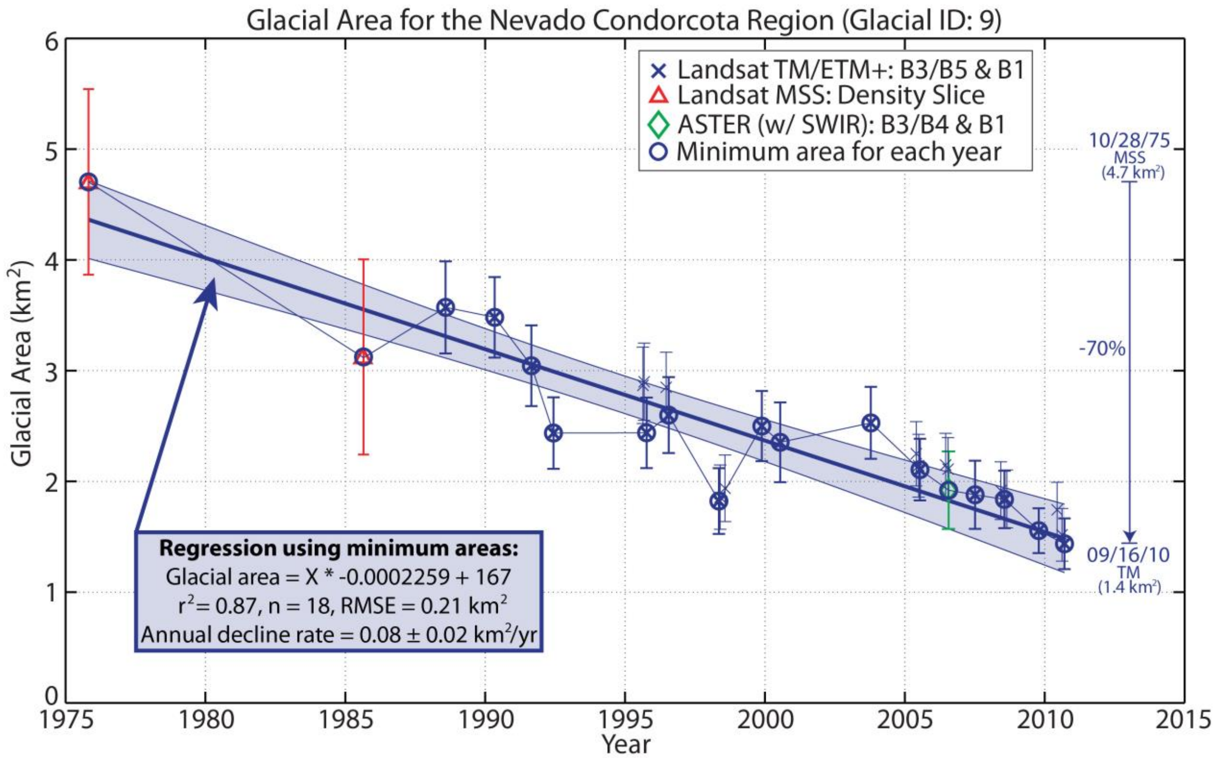

Figure S10: Glacial-area time series for the Nevado Condorcota region (Glacial ID: 9, Figure 8).

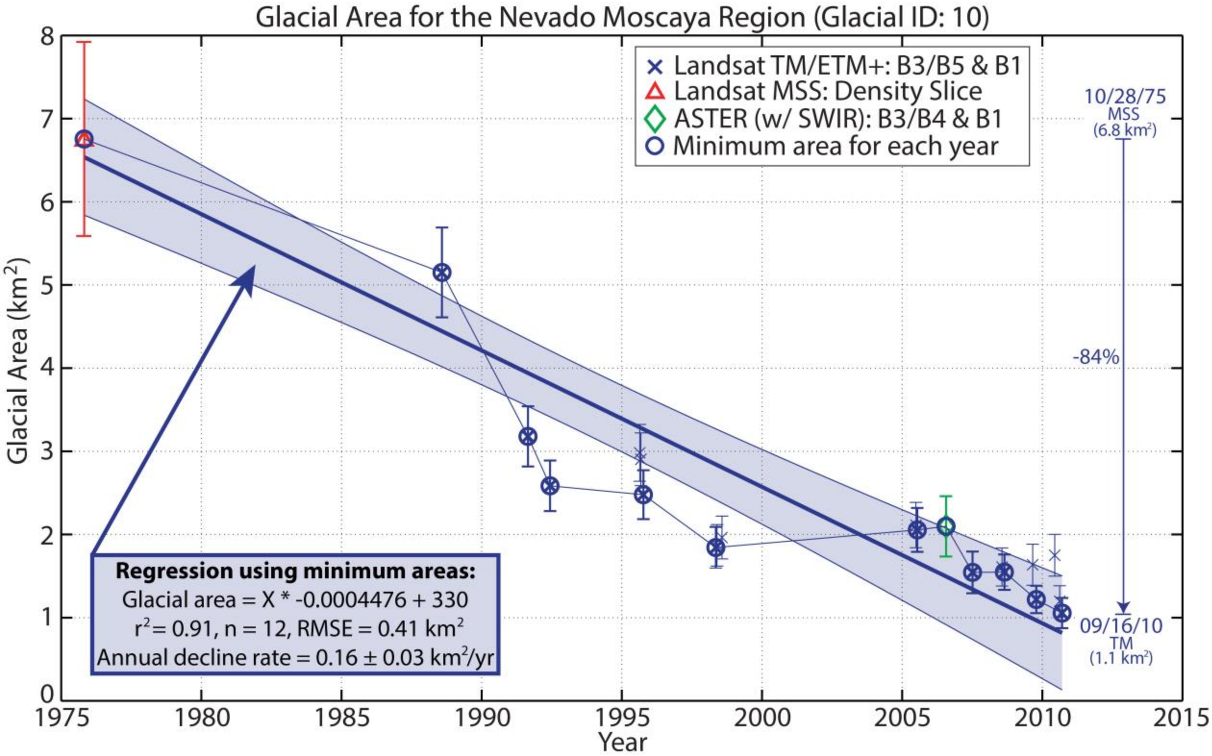

Figure S11: Glacial-area time series for the Nevado Moscaya region (Glacial ID: 10, Figure 8).

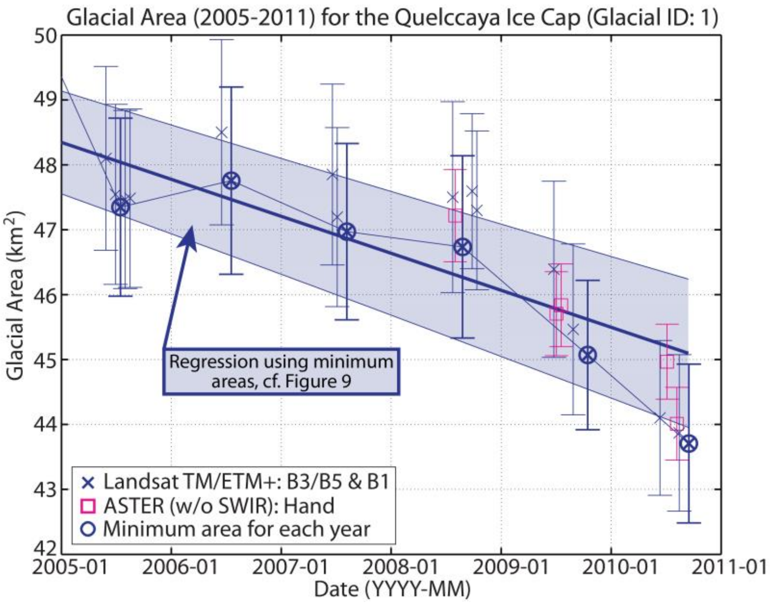

Figure S12: Focus on 2005-2011 of the glacial-area time series for the Quelccaya Ice Cap (the whole time series is shown in Figure 9). Notice the intra-annual variability, which exists even when using the same classifier, same methodology, and only classifying images that visually appear snow free. Within years, and between years, however, these measurements do overlap within their 1σ error bars.

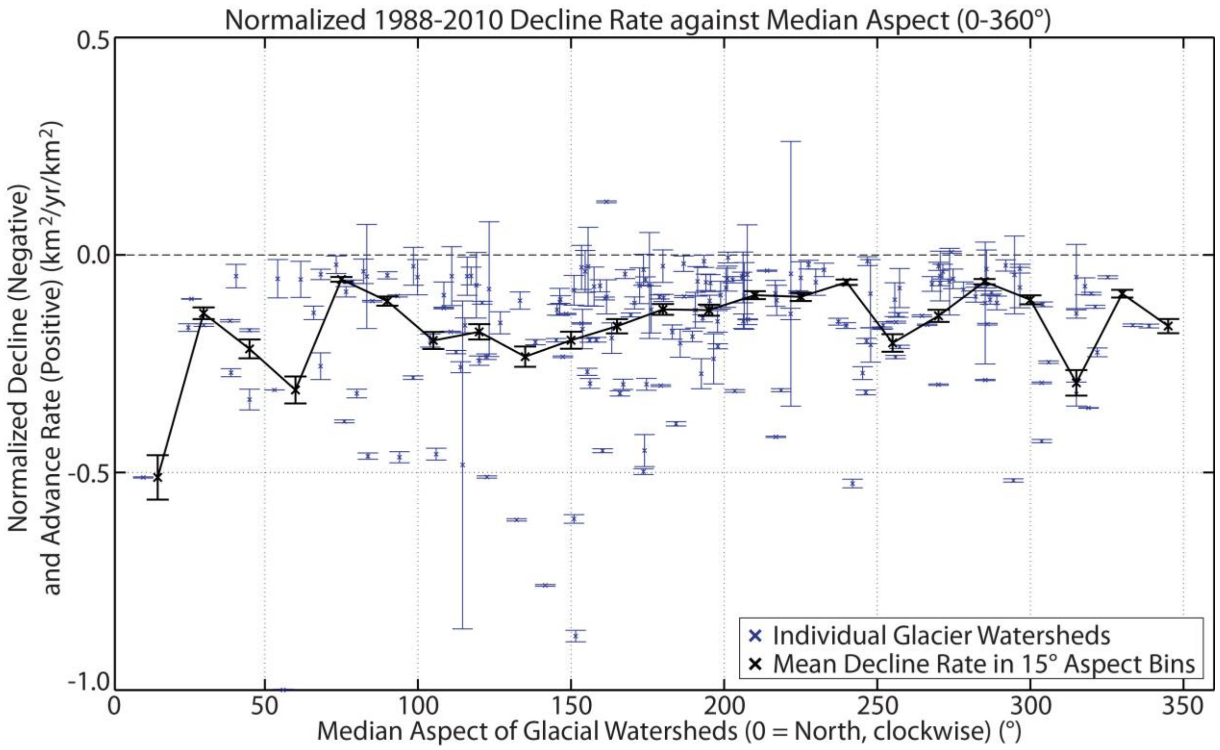

Figure S13: Normalized (against median area) decline rates against median aspect of glaciers within individual glacial watersheds. Error bars indicate 95 % CI.

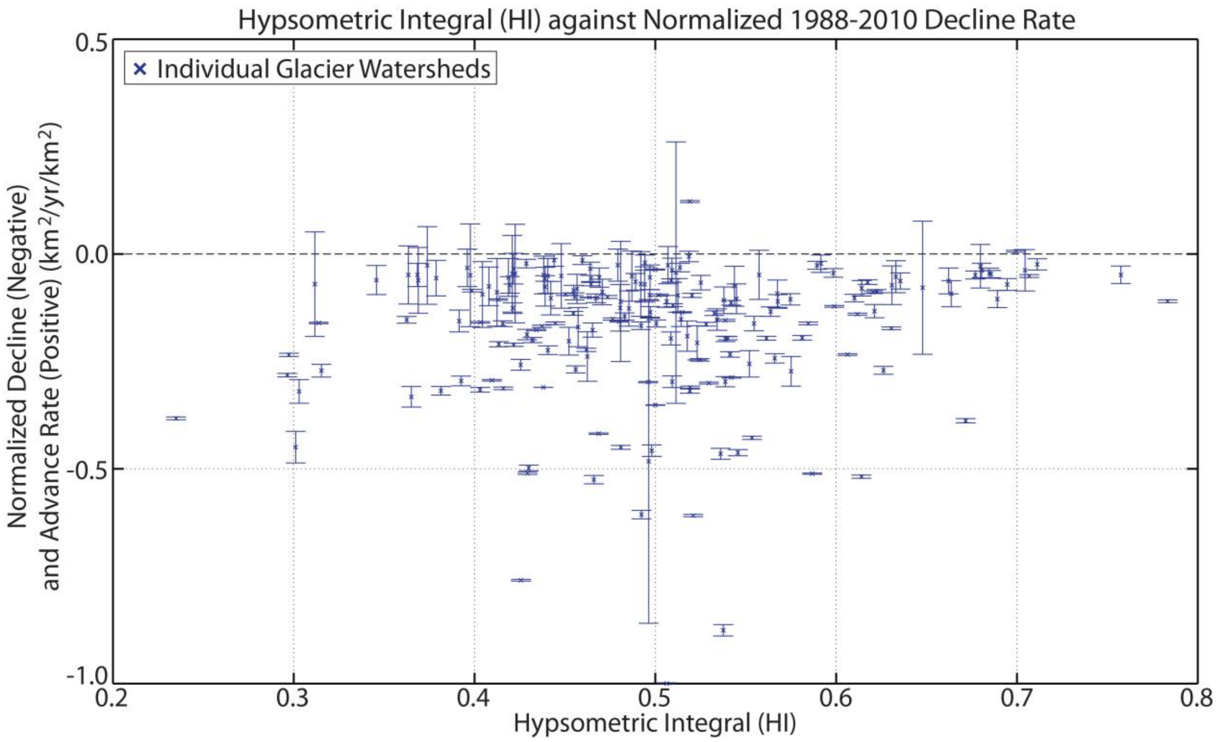

Figure S14: Normalized (against median area) decline rates against the hypsometric integral (HI) within individual glacial watersheds. Error bars indicate 95 % CI. The hypsometric integral (HI) shows the shape of the basin: HI values < 0.5 indicate more area at lower elevations, whereas a HI > 0.5 indicate more area at higher elevations.

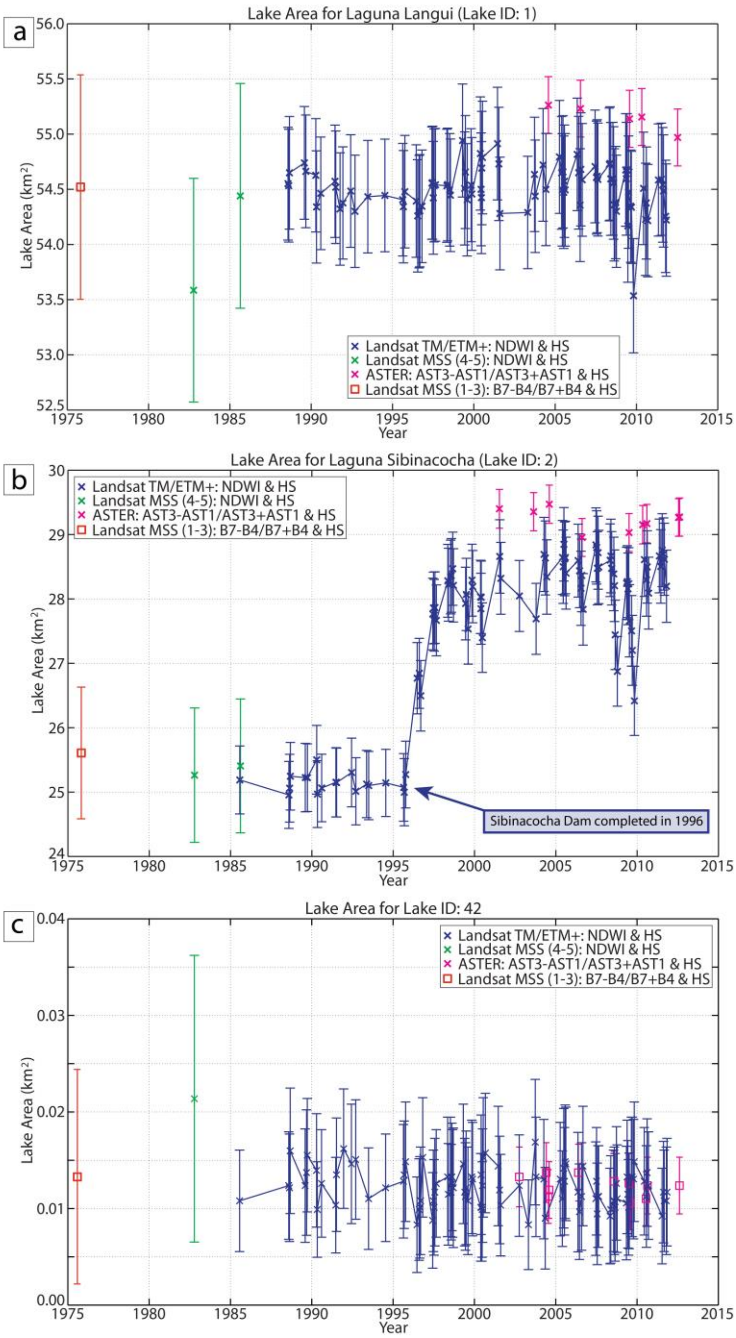

Figure S15: Graphical results for three lakes to illustrate lake area changes beyond uncertainties: a) Laguna Langui (Lake ID: 1, Figure 8) – the largest lake in this region, represents a large lake which does not change beyond its uncertainties, b) Laguna Sibinacocha (Lake ID: 2, Figure 8) is a managed lake which we have removed from our analyses, but here we use it to represent a large lake which does change beyond its uncertainties, and c) Lake ID: 42 (unnamed, Figure 8) represents a small lake which does not change beyond its uncertainties. Examples of small lakes which do change beyond their uncertainties are provided in the main manuscript.

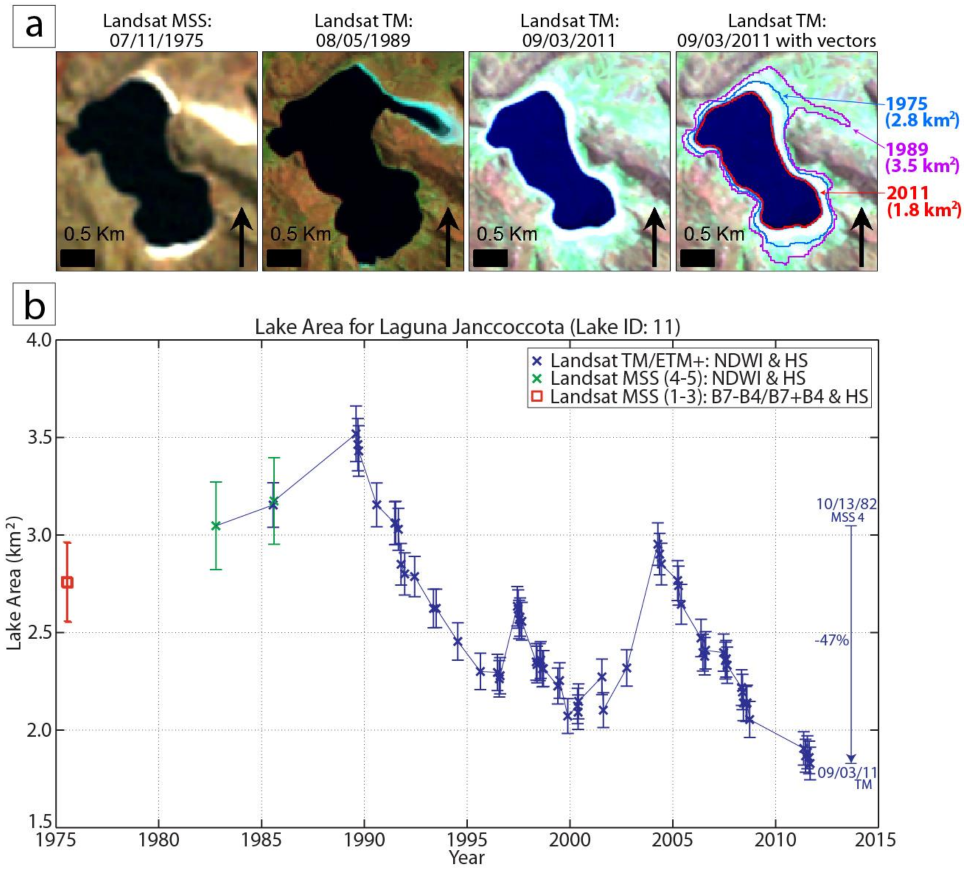

Figure S16: Visual (a) and graphical (b) results for the area of Laguna Janccoccota (Lake ID: 11, Figure 8) - a small and mostly declining lake not connected to a glacial watershed.

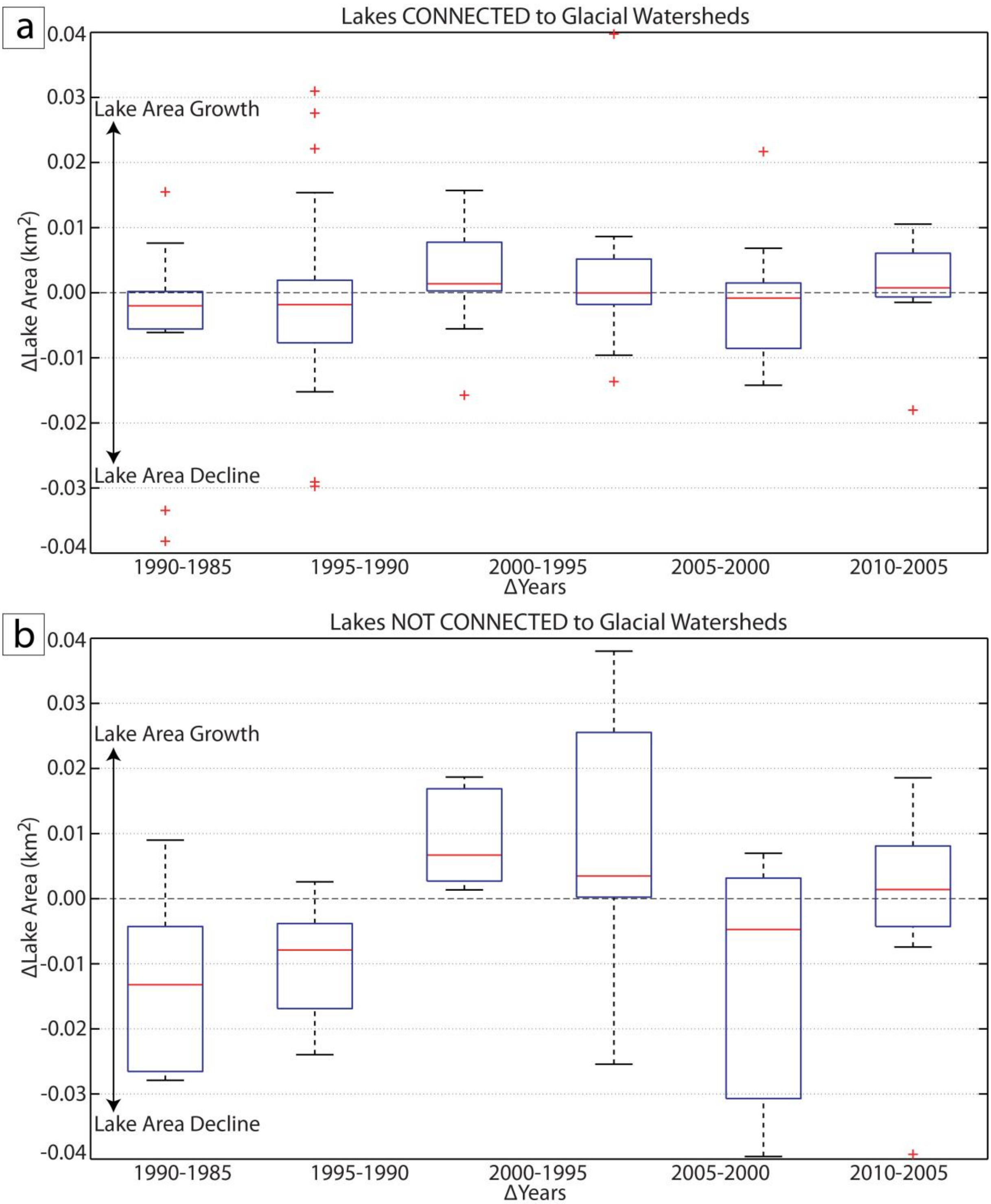

Figure S17: Lake-area changes within 5-year time intervals for a) lakes connected to glacial watersheds, and b) lakes not connected to glacial watersheds. We have calculated lake-area changes by subtracting last lake areas from first lake areas within a time interval.

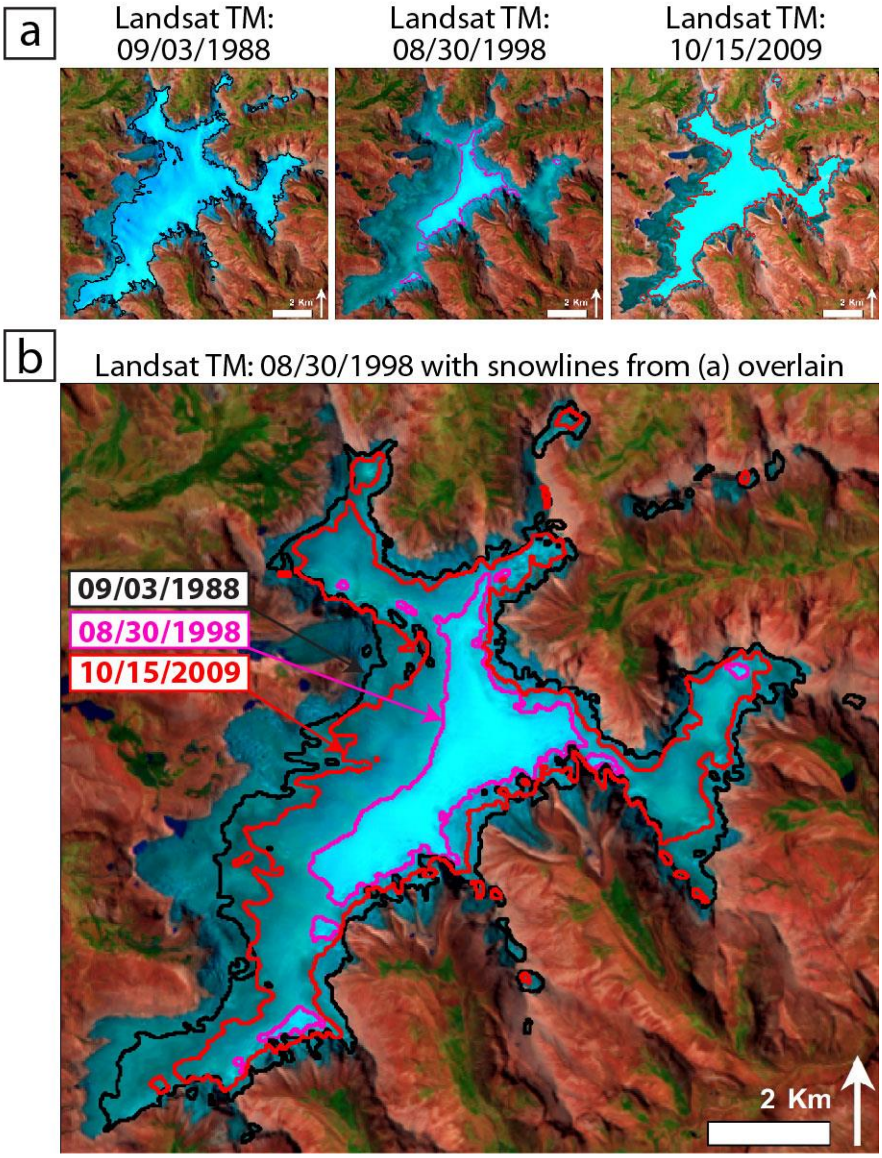

Figure S18: a) Visual snowlines for the Quelccaya Ice Cap for 1988, 1998, and 2009, and their classifications using Multiple Endmember Spectral Mixture Analysis (MESMA). In part b) we have overlain the snowlines from a) on the 08/30/1998 image to show relative changes.