



*Supplement of*

## **El Niño enhances snow-line rise and ice loss on the Quelccaya Ice Cap, Peru**

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Satellite	Date	Image Information	Cloud Cover %	DEM Used
Landsat 5	7/25/1985	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19850725	2	NASA SRTM DEM
Landsat 5	7/12/1986	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19860712	0	
Landsat 5	9/3/1988	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19880903	13	
Landsat 5	9/22/1989	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19890922	5	
Landsat 5	8/8/1990	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19900808	7	
Landsat 5	8/27/1991	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19910827	1	
Landsat 5	9/14/1992	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19920914	4	
Landsat 5	8/19/1994	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19940819	11	
Landsat 5	9/7/1995	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19950907	1	
Landsat 5	9/9/1996	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19960909	6	
Landsat 5	8/27/1997	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19970827	9	
Landsat 5	9/15/1998	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19980915	8	
Landsat 5	11/21/1999	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19991121	3	
Landsat 5	8/3/2000	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20000803	12	
Landsat 7	8/14/2001	LANDSAT/LE07/C02/T1_TOA/LE07_003070_20010814	1	
Landsat 7	10/20/2002	LANDSAT/LE07/C02/T1_TOA/LE07_003070_20021020	3	
Landsat 5	9/29/2003	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20030929	11	
Landsat 5	11/5/2005	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20051105	1	
Landsat 5	9/5/2006	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20060905	4	Copernicus DEM 30m
Landsat 5	8/23/2007	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20070823	1	
Landsat 5	8/25/2008	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20080825	0	
Landsat 5	10/31/2009	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20091031	2	
Landsat 5	9/16/2010	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20100916	0	
Landsat 5	9/3/2011	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20110903	1	
Landsat 8	9/8/2013	LANDSAT/LC08/C01/T1_SR/LC08_003070_20130908	6.5	
Landsat 8	10/13/2014	LANDSAT/LC08/C01/T1_SR/LC08_003070_20141013	11.0	
Landsat 8	9/14/2015	LANDSAT/LC08/C01/T1_SR/LC08_003070_20150914	9.1	
Landsat 8	9/16/2016	LANDSAT/LC08/C01/T1_SR/LC08_003070_20160916	23.0	
Landsat 8	10/5/2017	LANDSAT/LC08/C01/T1_SR/LC08_003070_20171005	2.2	
Landsat 8	9/25/2019	LANDSAT/LC08/C01/T1_SR/LC08_003070_20190925	7.6	
Landsat 8	8/26/2020	LANDSAT/LC08/C01/T1_SR/LC08_003070_20200826	3.7	
Sentinel-2	10/21/2021	COPERNICUS/S2_SR_HARMONIZED/20211021T145731_20211021T150154_T19LBE	6.0	
Landsat 9	10/11/2022	LANDSAT/LC09/C02/T1_TOA/LC09_003070_20221011	1.4	
Sentinel-2	10/11/2023	COPERNICUS/S2_SR_HARMONIZED/20231011T145729_20231011T150056_T19LBE	3.1	

Table S1: Imagery Collection Details and DEM usage information.

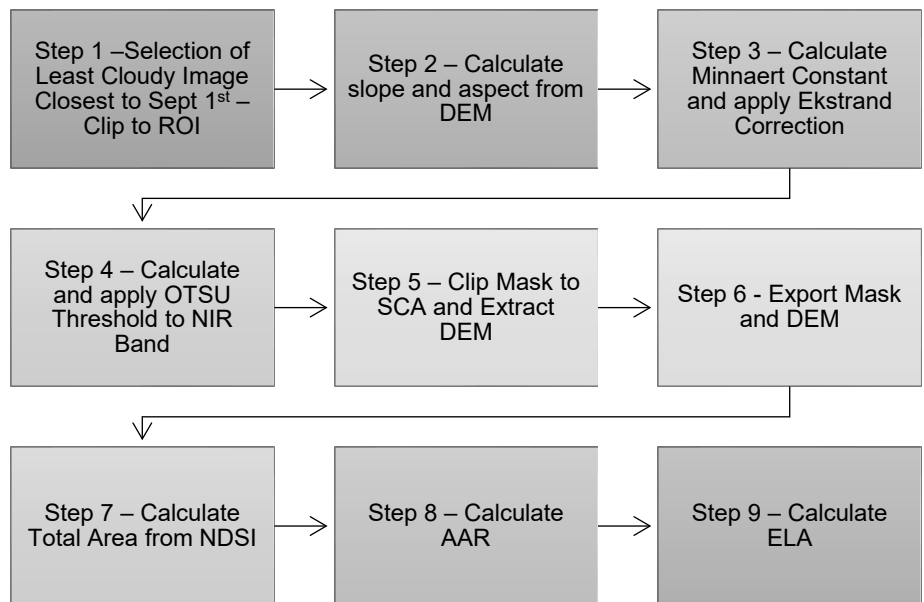


Figure S1: Flowchart depicting pre-processing and processing steps to calculate and export select variables from the end of the dry season on the QIC.

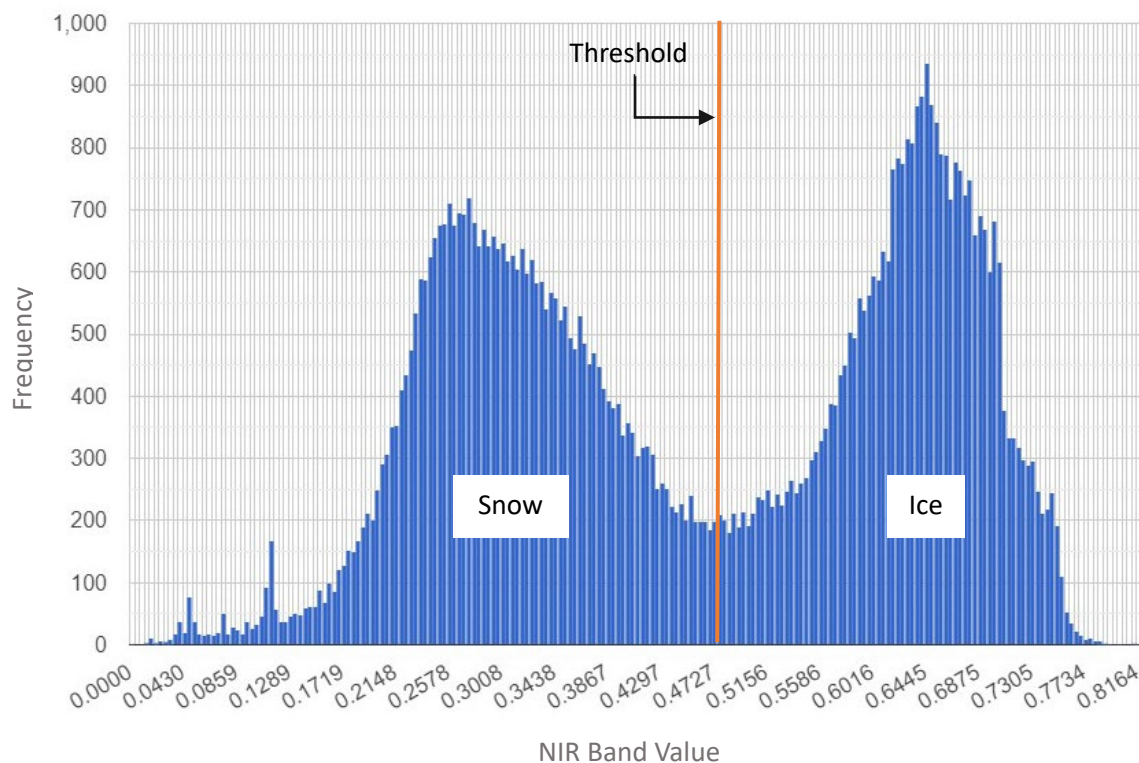


Figure S2: Example of a NIR band histogram from 2015. The bimodal distribution of snow and ice reflectance is shown. The Otsu method is applied to calculate the threshold (orange line; 0.478).

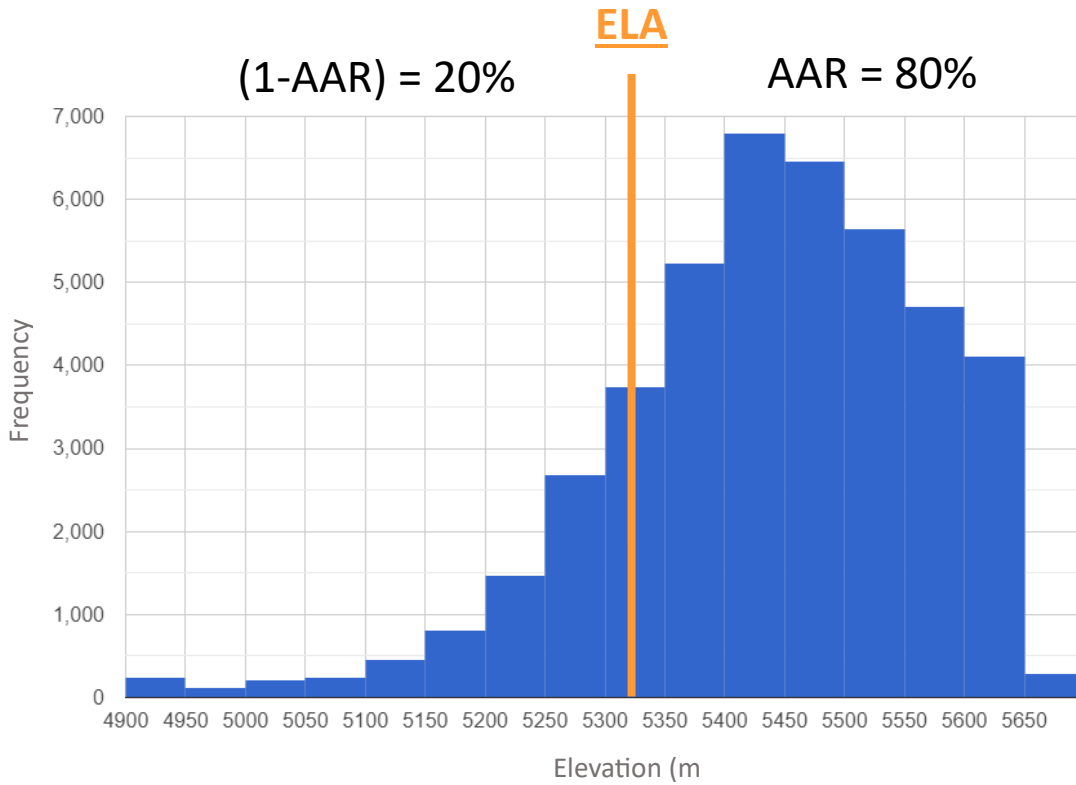


Figure S3: Example ELA calculation (with an AAR of 0.80 or 80%) using the elevation distribution of the total area. The 1-AAR value is used to find the ELA (i.e., in this case the ELA is assumed to be located at the 20<sup>th</sup> percentile of elevations in the total area).

Imagery Date	TA (km <sup>2</sup> )	SCA (km <sup>2</sup> )	AAR	Med Elev (m a.s.l.)	ELA (m a.s.l.)
7/25/1985	58.67	46.35	0.79	5421	5249
7/12/1986	58.06	45.93	0.79	5426	5249
9/3/1988	55.96	37.25	0.67	5457	5341
9/22/1989	55.34	43.66	0.79	5437	5266
8/8/1990	53.52	37.53	0.70	5457	5317
8/27/1991	51.22	34.49	0.67	5470	5341
9/14/1992	51.65	35.09	0.68	5465	5337
8/19/1994	52.24	39.68	0.76	5450	5298
9/7/1995	50.65	31.94	0.63	5481	5365
9/9/1996	50.89	35.73	0.70	5465	5333
8/27/1997	50.89	36.70	0.72	5462	5322
9/15/1998	47.65	15.11	0.32	5546	5493
11/21/1999	47.46	39.30	0.83	5453	5285
8/3/2000	48.31	36.40	0.75	5462	5322
8/14/2001	48.76	39.51	0.81	5450	5293
10/20/2002	47.00	42.22	0.90	5441	5241
9/29/2003	47.97	36.45	0.76	5462	5322
11/5/2005	45.60	36.59	0.80	5462	5310
9/5/2006	45.55	30.86	0.68	5486	5370
8/23/2007	44.94	31.15	0.69	5482	5370
8/25/2008	45.02	31.82	0.71	5458	5362
10/31/2009	43.50	29.03	0.67	5494	5386
9/16/2010	44.39	24.50	0.55	5514	5422
9/3/2011	44.93	37.01	0.82	5458	5306
9/8/2013	44.93	35.78	0.80	5466	5318
10/13/2014	44.86	35.07	0.78	5470	5346
9/14/2015	43.93	32.38	0.74	5478	5358
9/16/2016	41.26	16.41	0.40	5550	5486
10/5/2017	41.54	24.90	0.60	5510	5422
9/25/2019	42.92	31.51	0.73	5474	5366
8/26/2020	39.79	29.10	0.73	5494	5386
10/21/2021	37.85	26.00	0.69	5502	5410
10/31/2022	36.71	19.66	0.54	5534	5458
10/11/2023	34.09	17.97	0.53	5542	5474

Table S2: Annual QIC variables calculated for the end of the dry season: total area (TA), snow-covered area (SCA), accumulation-area ratio (AAR), median elevation of the SCA (Med Elev), and the equilibrium-line altitude (ELA).

	SCA	SCA (no El Niño)	ELA	ELA (no El Niño)	TA	TA (no El Niño)
<b>R-squared</b>	0.44	0.58	0.40	0.47	0.93	0.93
<b>Intercept</b>	950.93	868.19	-21890.06	-1167.41	1030.38	999.12
<b>Coefficient (slope)</b>	-0.47	-0.42	3.61	3.25	-0.49	-0.47
<b>Standard Error</b>	0.09	0.07	0.79	0.64	0.02	0.02
<b>p-value</b>	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table S3: Results of linear regression analysis for SCA, ELA and TA, with and without El Niño years (1998 & 2016).

	Group 1	Group 2	Mean Difference	p-value	Reject
<b>SCA</b>	El Niño	La Niña	6.850	0.154	FALSE
	El Niño	Neutral	8.793	<b><i>0.019</i></b>	<b>TRUE</b>
	La Niña	Neutral	1.943	0.801	FALSE
<b>ELA</b>	El Niño	La Niña	-61.901	0.110	FALSE
	El Niño	Neutral	-76.112	<b><i>0.013</i></b>	<b>TRUE</b>
	La Niña	Neutral	-14.215	0.841	FALSE
<b>AAR</b>	El Niño	La Niña	0.161	<b><i>0.007</i></b>	<b>TRUE</b>
	El Niño	Neutral	0.178	<b><i>0.001</i></b>	<b>TRUE</b>
	La Niña	Neutral	0.017	0.912	FALSE
<b>Total Area</b>	El Niño	La Niña	-0.845	0.956	FALSE
	El Niño	Neutral	1.041	0.910	FALSE
	La Niña	Neutral	1.886	0.736	FALSE

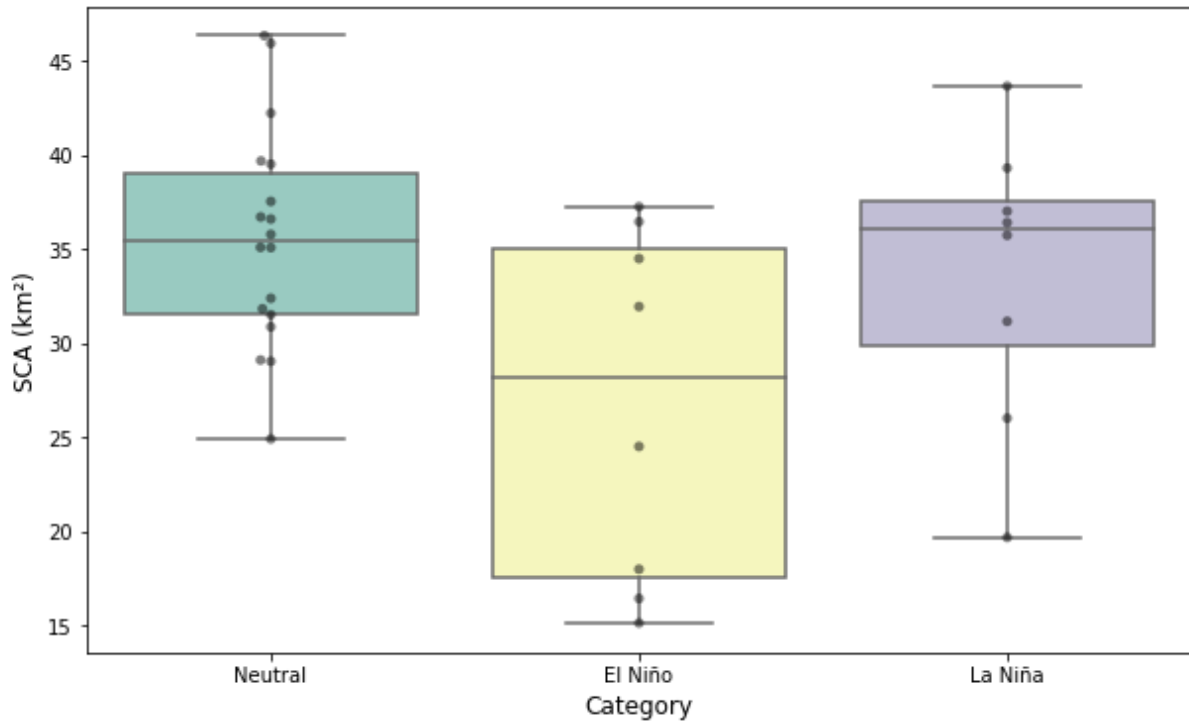
Table S4: Analysis of variance (ANOVA) with post hoc testing between El Niño, La Niña, and neutral events. Results with significant p-values ( $p < 0.05$ ) are shown in bold italics.

<u>Preceding Month</u>	<u>MEI</u>			<u>SOI</u>			<u>ONI</u>		
	<i>ELA</i>	<i>SCA</i>	<i>Med Elev</i>	<i>ELA</i>	<i>SCA</i>	<i>Med Elev</i>	<i>ELA</i>	<i>SCA</i>	<i>Med Elev</i>
-									
<b>September</b>	<i>0.484</i>	<i>-0.501</i>	<i>-0.500</i>	<i>-0.426</i>	<i>0.418</i>	<i>-0.388</i>	<i>0.577</i>	<i>-0.598</i>	<i>0.608</i>
<b>October</b>	<i>0.443</i>	<i>-0.451</i>	<i>0.455</i>	-0.420	<i>0.416</i>	<i>-0.410</i>	<i>0.543</i>	<i>-0.564</i>	<i>0.571</i>
<b>November</b>	<i>0.456</i>	<i>-0.463</i>	<i>0.467</i>	<i>-0.502</i>	<i>0.487</i>	<i>-0.485</i>	<i>0.541</i>	<i>-0.561</i>	<i>0.571</i>
<b>December</b>	<i>0.470</i>	<i>-0.495</i>	<i>0.503</i>	<i>-0.276</i>	<i>0.289</i>	<i>-0.306</i>	<i>0.550</i>	<i>-0.570</i>	<i>0.581</i>
<b>January</b>	<i>0.528</i>	<i>-0.557</i>	<i>0.560</i>	<i>-0.572</i>	<i>0.588</i>	<i>-0.591</i>	<i>0.550</i>	<i>-0.572</i>	<i>0.586</i>
<b>February</b>	<i>0.583</i>	<i>-0.611</i>	<i>0.619</i>	<i>-0.388</i>	<i>0.397</i>	<i>-0.438</i>	<i>0.541</i>	<i>-0.566</i>	<i>0.585</i>
<b>March</b>	<i>0.524</i>	<i>-0.550</i>	<i>0.570</i>	<i>-0.382</i>	<i>0.404</i>	<i>-0.413</i>	<i>0.501</i>	<i>-0.525</i>	<i>0.550</i>
<b>April</b>	<i>0.558</i>	<i>-0.577</i>	<i>0.583</i>	<i>-0.418</i>	<i>0.432</i>	<i>-0.419</i>	<i>0.411</i>	<i>-0.435</i>	<i>0.460</i>
<b>May</b>	<i>0.446</i>	<i>-0.462</i>	<i>0.462</i>	0.162	-0.147	0.156	0.233	-0.251	0.279
<b>June</b>	0.030	-0.023	0.030	0.296	-0.314	0.308	-0.039	0.028	-0.002
<b>July</b>	-0.251	0.267	-0.251	0.332	-0.332	-0.332	-0.186	0.190	-0.168
<b>August</b>	<i>-0.341</i>	<i>0.348</i>	-0.319	<i>0.404</i>	<i>-0.387</i>	<i>0.336</i>	-0.262	0.266	-0.250

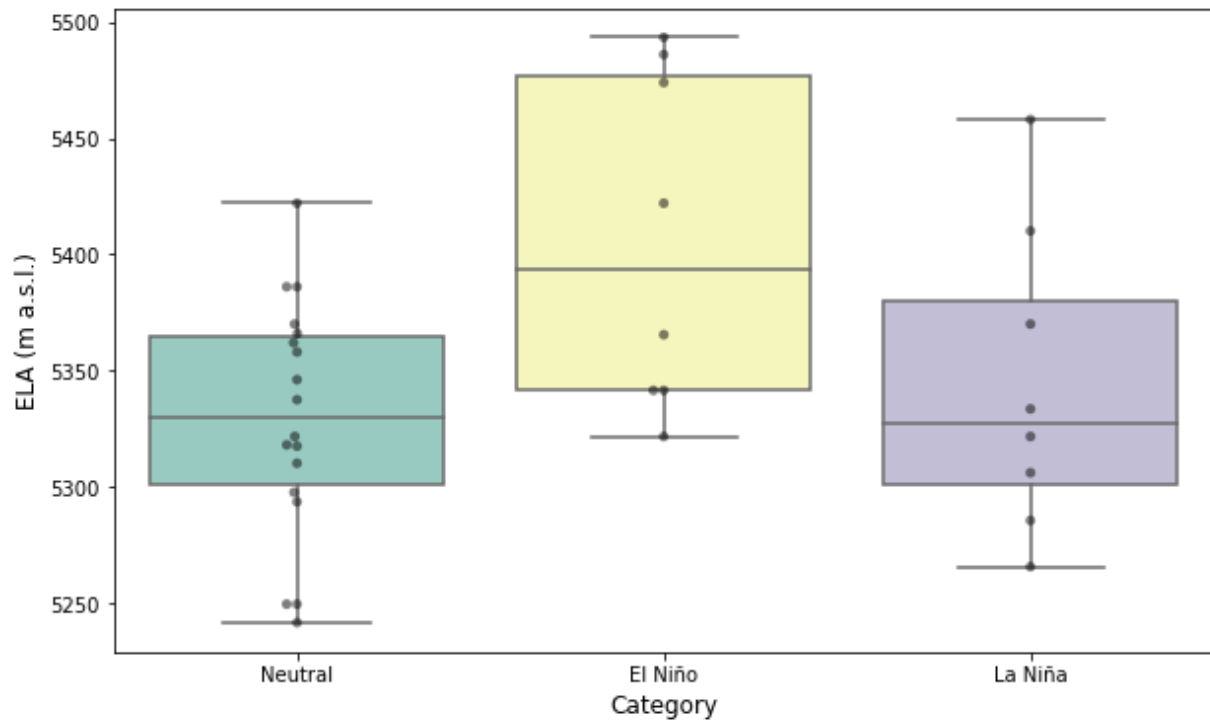
Table S5: Zero-order correlations ( $r$ ) between QIC variables (including the equilibrium-line altitude (ELA), snow cover area (SCA), and median elevation of the SCA (Med Elev)) and ENSO indices (including the Multivariate ENSO Index (MEI), the Ocean Niño Index (ONI), and the Southern Oscillation Index (SOI)). Statistically significant values ( $p < 0.05$ ) are marked in italics and underlined.



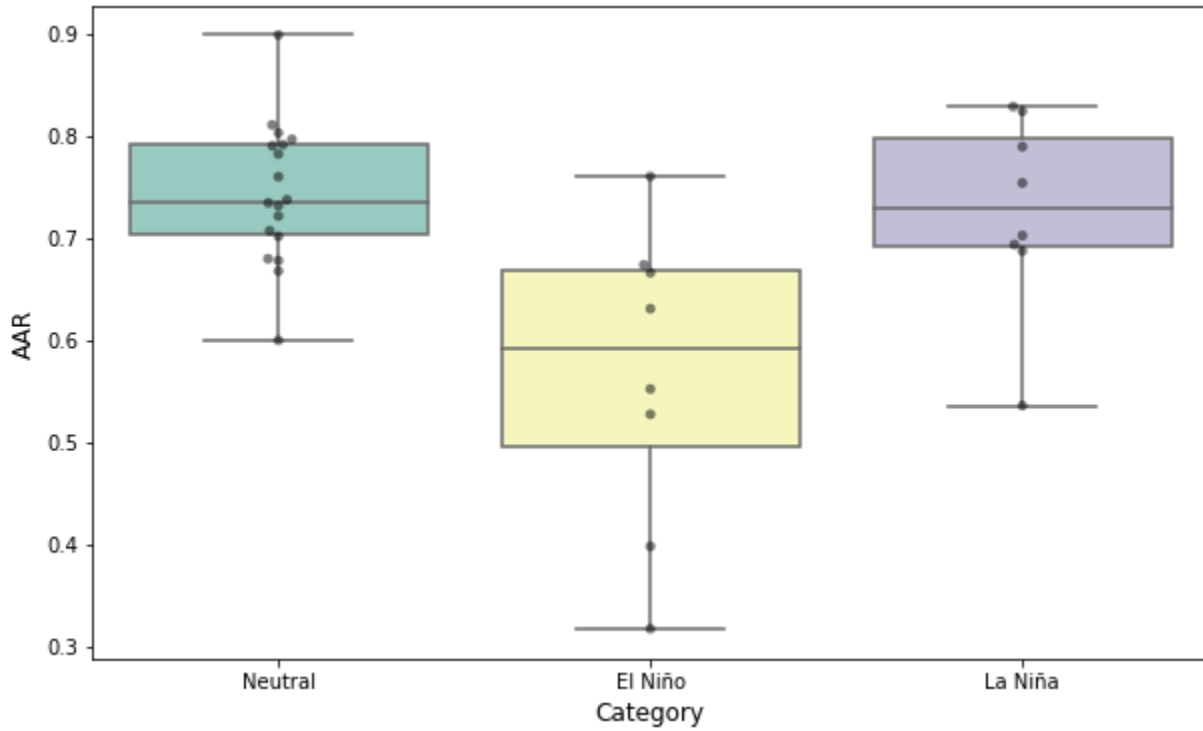
a)



b)



c)



d)

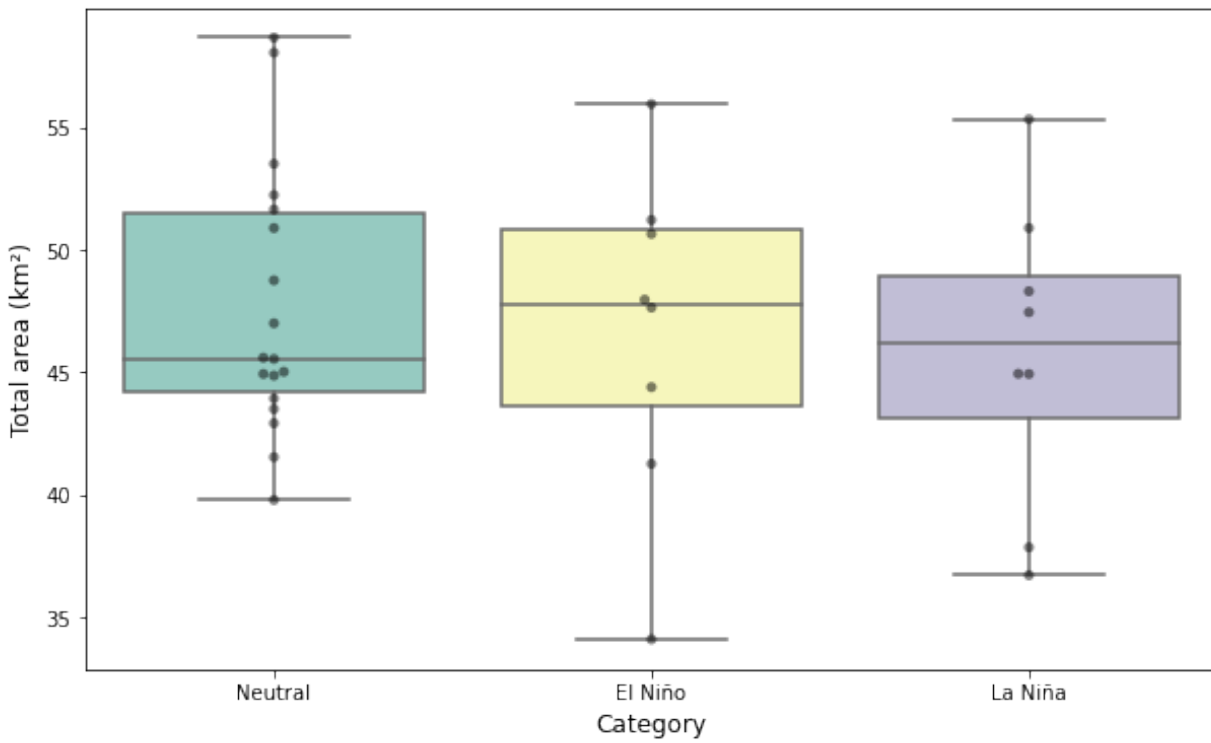


Figure S4: Box-and-whisker plots summarizing distributions in a) SCA, b) ELA, c) AAR, and d) TA during El Niño (yellow), La Niña (purple), and neutral (green) years.

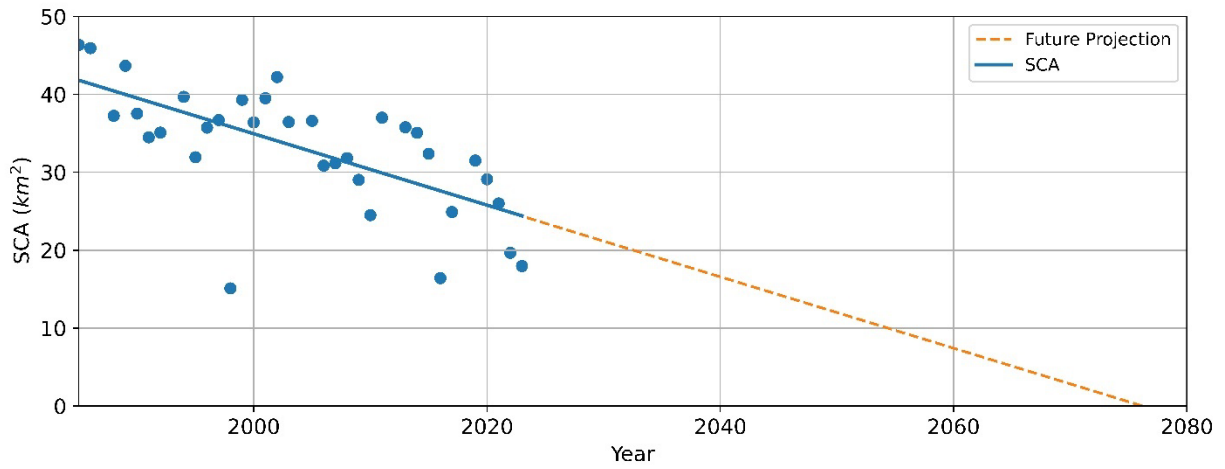
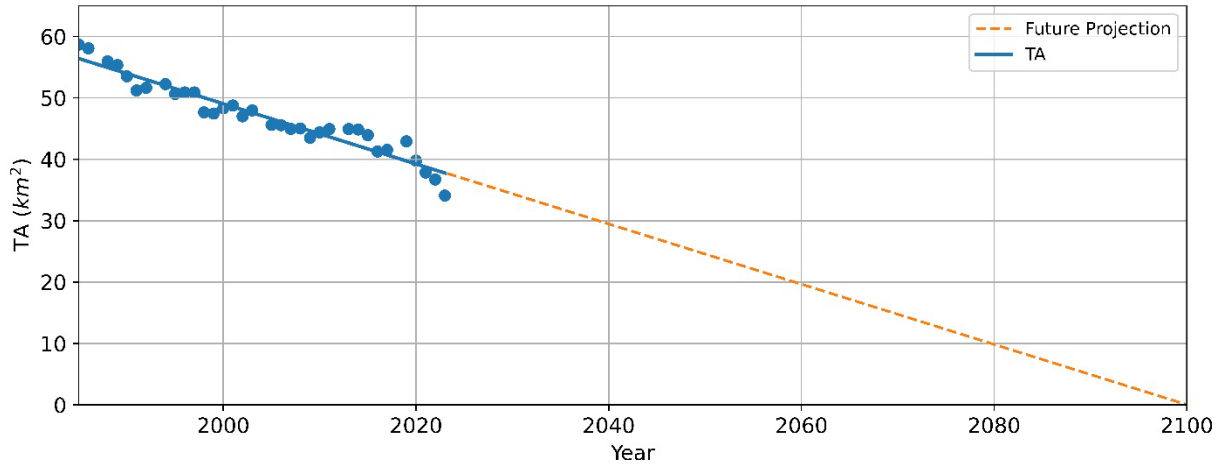


Figure S5: Projected decline in the TA (top) and SCA (bottom) of the QIC, assuming a linear decline based on the last 40 years of data.