Supplementary Information

El Niño Enhances Snowline Rise and Ice Loss on the World's Largest Tropical Ice Cap

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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_19900909	11	
Landsat 5	7/26/1991	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19910726	1	
Landsat 5	9/14/1992	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19920914	4	
Landsat 5	6/29/1993	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19930901	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	8/1/1999	LANDSAT/LT05/C02/T1_TOA/LT05_003070_19990801	3	
Landsat 5	8/3/2000	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20000803	12	
Landsat 5	8/6/2001	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20010806	1	
Landsat 5	9/29/2003	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20030929	11	
Landsat 5	7/13/2004	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20040713	2	
Landsat 5	8/17/2005	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20050817	1	
Landsat 5	9/5/2006	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20060905	4	Copernicus DEM 30m
Landsat 5	8/7/2007	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20070807	1	
Landsat 5	8/25/2008	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20080825	0	
Landsat 5	8/28/2009	LANDSAT/LT05/C02/T1_TOA/LT05_003070_20090828	1	
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	8/26/2014	LANDSAT/LC08/C01/T1_SR/LC08_003070_20140826	13.0	
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	7/4/2018	LANDSAT/LC08/C01/T1_SR/LC08_003070_20180704	2.0	
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	
Landsat 8	8/13/2021	LANDSAT/LC08/C01/T1_SR/LC08_003070_20210813	3.7	
Landsat 9	9/9/2022	LANDSAT/LC09/C02/T1_TOA/LC09_003070_20220824	1.4	
Sentinel-2	10/11/2023	COPERNICUS/S2_SR_HARMONIZED/20231011T145729_20230926T150056_T19LBE	3.1	

Table S1: Imagery Collection Details and DEM usage information.

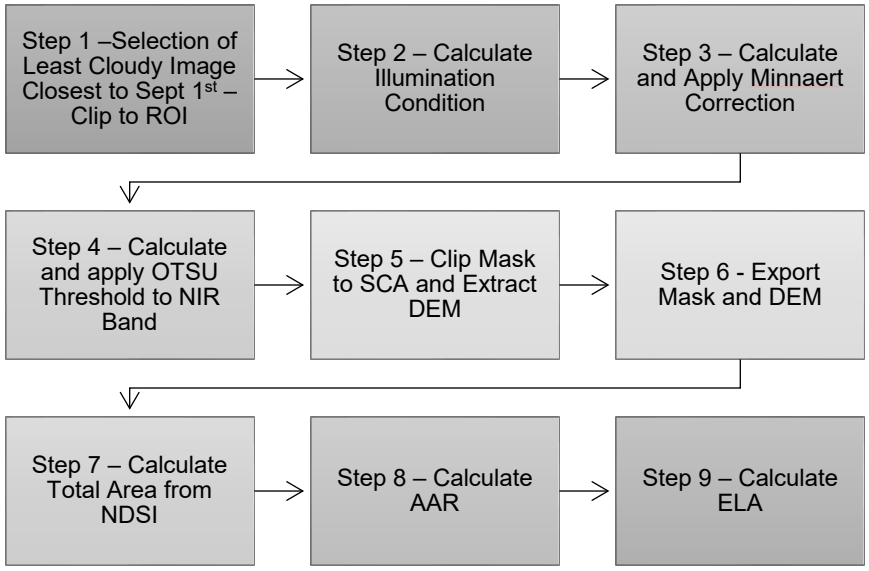


Figure S1: Flowchart depicting pre-processing and processing steps to calculate and export a full detail of variables from the end of the dry season on the QIC.

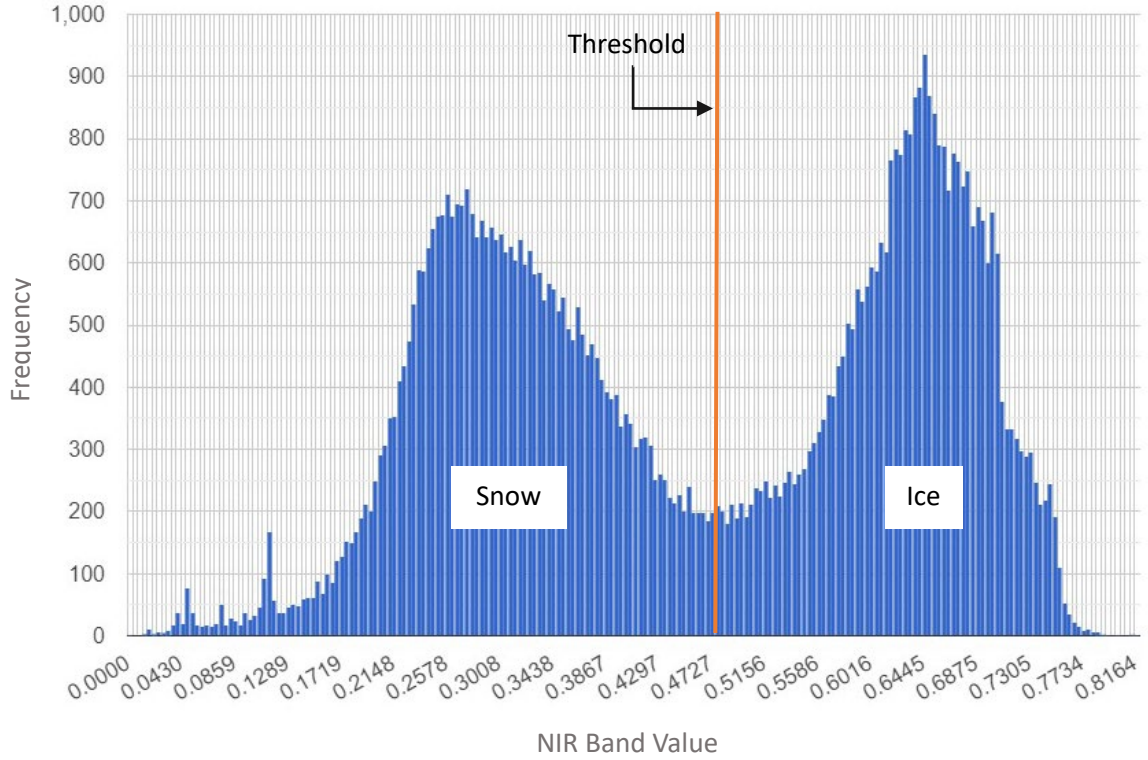


Figure S2: Sample NIR band histogram from 2015 to display the bimodal distribution of snow versus ice reflectance, used for calculating the OTSU threshold. The threshold is displayed in orange (0.478).

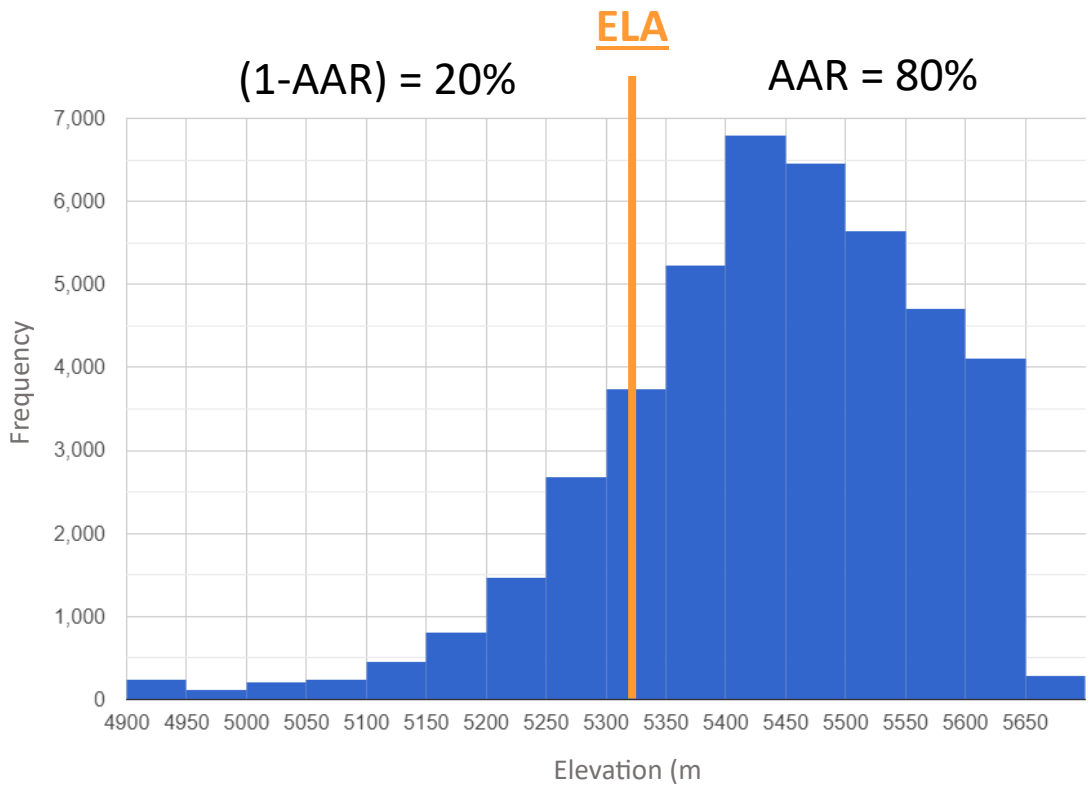


Figure S3: Sample ELA calculation using the DEM from the total area with an AAR of 0.8 (80%). The DEM is backfilled using 1-AAR to find the ELA.

Imagery Date	Total Area (km^2)	SCA (km2)	AAR	Med Elev (m)	ELA (m)
7/25/1985	59.57	46.79	0.79	5421.47	5249.45
7/12/1986	59.30	46.99	0.79	5421.47	5245.53
9/3/1988	53.07	37.41	0.70	5457.50	5317.47
9/22/1989	55.41	44.68	0.81	5433.46	5257.53
8/8/1990	54.30	38.72	0.71	5453.40	5309.50
7/26/1991	53.46	37.27	0.70	5457.50	5317.46
9/14/1992	51.73	36.39	0.70	5461.52	5325.51
6/29/1993	54.98	42.13	0.77	5437.46	5281.56
9/7/1995	51.00	32.65	0.64	5477.45	5361.45
9/9/1996	51.08	36.68	0.72	5461.54	5321.63
8/27/1997	51.04	38.26	0.75	5457.50	5309.51
9/15/1998	47.62	14.25	0.30	5541.60	5497.46
8/1/1999	52.14	40.22	0.77	5441.51	5285.48
8/3/2000	48.81	36.89	0.76	5457.49	5317.45
8/6/2001	52.34	42.70	0.82	5437.47	5273.49
9/29/2003	47.94	38.07	0.79	5457.49	5305.47
7/13/2004	53.33	41.29	0.77	5441.50	5277.60
8/17/2005	45.77	25.96	0.57	5505.64	5413.51
9/5/2006	45.03	31.87	0.71	5481.51	5365.49
8/7/2007	45.34	32.11	0.71	5481.50	5361.46
8/25/2008	45.02	31.87	0.71	5481.52	5365.48
8/28/2009	44.24	29.16	0.66	5489.53	5385.58
9/16/2010	43.08	26.51	0.62	5501.53	5405.47
9/3/2011	45.05	36.55	0.81	5461.54	5317.45
9/8/2013	44.93	38.32	0.85	5458.08	5286.10
8/26/2014	44.48	36.49	0.82	5465.98	5318.04
9/14/2015	42.85	33.36	0.78	5470.03	5346.04
9/16/2016	40.65	20.58	0.51	5522.02	5454.08
9/3/2017	39.96	29.15	0.73	5490.04	5386.07
7/4/2018	45.48	34.62	0.76	5470.05	5334.01
9/25/2019	40.12	29.50	0.74	5490.03	5381.97
8/26/2020	40.36	30.54	0.76	5490.03	5373.99
8/13/2021	41.58	32.05	0.77	5482.01	5353.85
9/9/2022	39.64	25.35	0.64	5505.98	5418.01
10/11/2023	36.44	19.04	0.52	5533.97	5449.99

Table S2: All result calculated for the end of the dry season total area, SCA, AAR, median elevation of the SCA, and the ELA.

	SCA	SCA (no El Niño)	ELA	ELA (no El Niño)
R-squared	0.35	0.50	0.31	0.42
Intercept	817.55	752.98	-592.72	-121.83
Coefficient (slope)	-0.39	-0.36	2.96	2.72
Standard deviation	0.09	0.06	0.75	0.59
p-value	<0.001	<0.001	<0.001	<0.001

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

	Med Elev	SCA	AAR	Total Area	ELA
Med Elev	1.000	-0.996	-0.809	-0.798	0.980
SCA	-0.996	1.000	0.835	0.772	-0.980
AAR	-0.809	0.835	1.000	0.302	-0.849
Total Area	-0.798	0.772	0.302	1.000	-0.747

Table S4: Pearson correlation coefficients (r) showing QIC variable relationships. All values shown are statistically significant ($p < 0.05$).

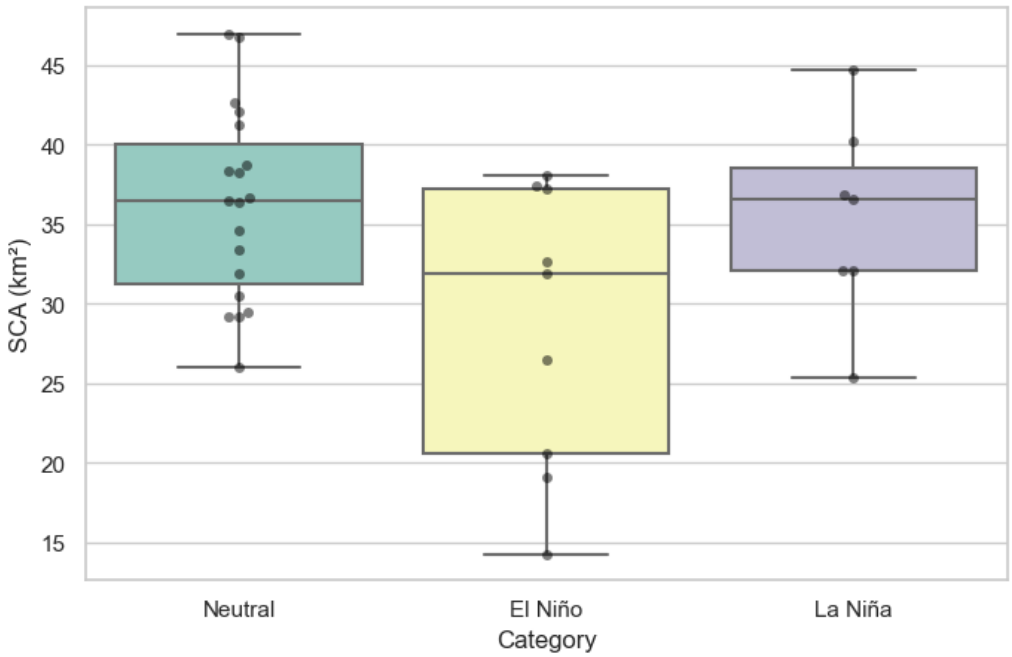
	Group 1	Group 2	Mean Difference	p-value	Reject
SCA	El Niño	La Niña	6.816	0.138	FALSE
	El Niño	Neutral	7.749	***0.024***	**TRUE**
	La Niña	Neutral	0.932	0.95	FALSE
ELA	El Niño	La Niña	-55.734	0.131	FALSE
	El Niño	Neutral	-61.404	***0.027***	**TRUE**
	La Niña	Neutral	-5.670	0.971	FALSE
AAR	El Niño	La Niña	0.143	***0.011***	**TRUE**
	El Niño	Neutral	0.137	***0.002***	**TRUE**
	La Niña	Neutral	-0.006	0.989	FALSE
Total Area	El Niño	La Niña	0.488	0.986	FALSE
	El Niño	Neutral	2.240	0.628	FALSE
	La Niña	Neutral	1.752	0.786	FALSE

Table S5: Analysis variance with post hoc testing results. Significant p-values are recorded in bold italic.

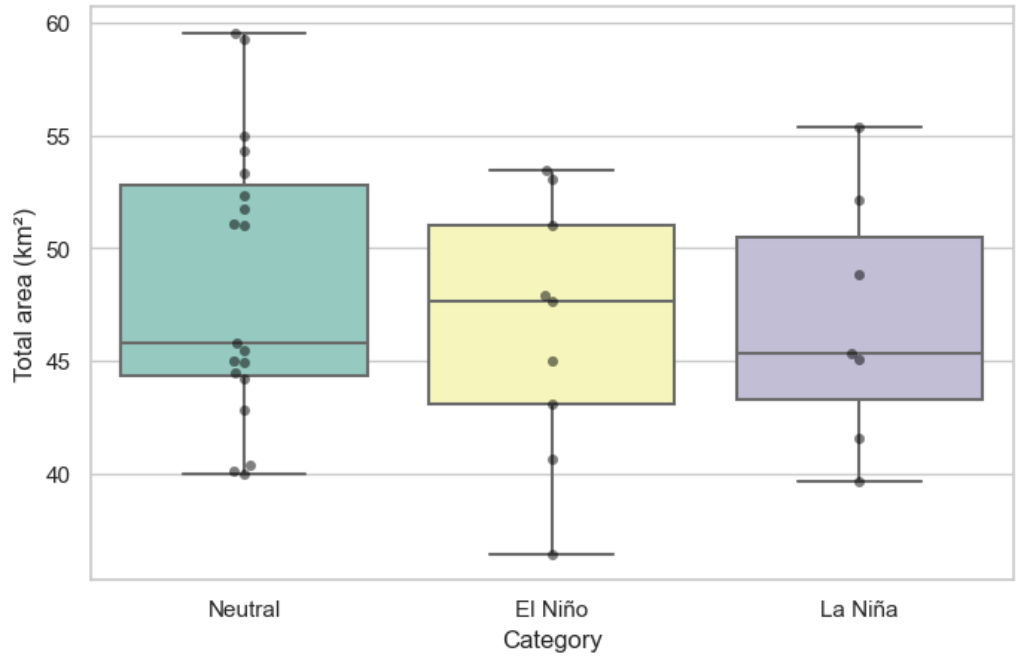
Preceding Month	MVI			SOI			ONI		
-	ELA	SCA	Med Elev	ELA	SCA	Med Elev	ELA	SCA	Med Elev
September	0.451	-0.519	0.522	-0.345	0.422	-0.425	0.608	-0.641	0.644
October	0.382	-0.437	0.440	-0.33	0.383	-0.386	0.555	-0.614	0.616
November	0.397	-0.454	0.46	-0.476	-0.513	-0.527	0.551	-0.609	0.612
December	0.443	-0.509	0.512	-0.306	0.375	-0.396	0.549	-0.607	0.611
January	0.478	-0.537	0.535	-0.462	0.482	-0.466	0.547	-0.599	0.602
February	0.545	-0.602	0.600	-0.454	0.488	-0.479	0.548	-0.593	0.596
March	0.513	-0.573	0.578	-0.381	0.426	-0.437	0.517	-0.555	0.562
April	0.509	-0.558	0.536	-0.396	0.396	-0.402	0.441	-0.475	0.489
May	0.424	-0.456	0.468	-0.084	0.093	-0.121	0.271	-0.288	0.311
June	0.067	-0.061	0.084	0.319	-0.297	0.282	0.012	-0.005	0.034
July	-0.197	0.225	-0.199	0.29	-0.308	0.294	-0.148	-0.176	-0.142
August	-0.262	0.311	-0.287	0.305	-0.338	0.311	-0.213	0.245	-0.211

Table S6: Pearson correlation coefficient (r) values for the equilibrium line altitude (ELA), snow cover area (SCA), and median elevation (med elev) in relation to ENSO indices, including: the Multivariate ENSO Index (MEI), the Ocean Niño Index (ONI), and the Southern Oscillation Index (SOI). Statistically significant p-values (<0.05) are marked in italics and underlined.

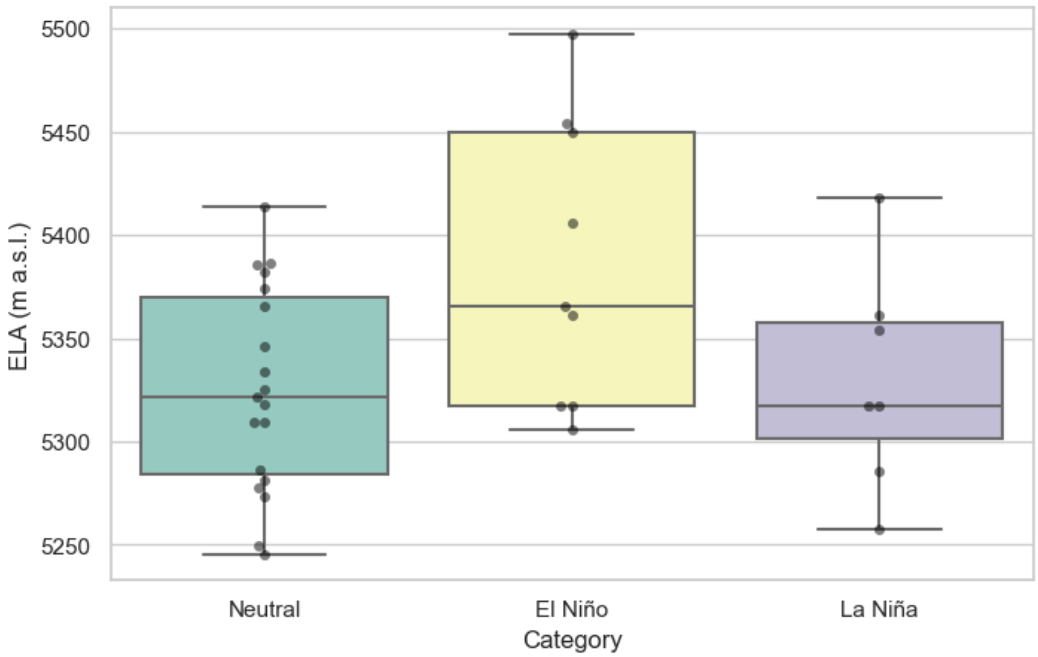
a)


45
40
35
30
25
20
15
SCA (km²)
Neutral
El Niño
La Niña
Category

b)


60
55
50
45
40
Total area (km²)
Neutral
El Niño
La Niña
Category

c)



d)

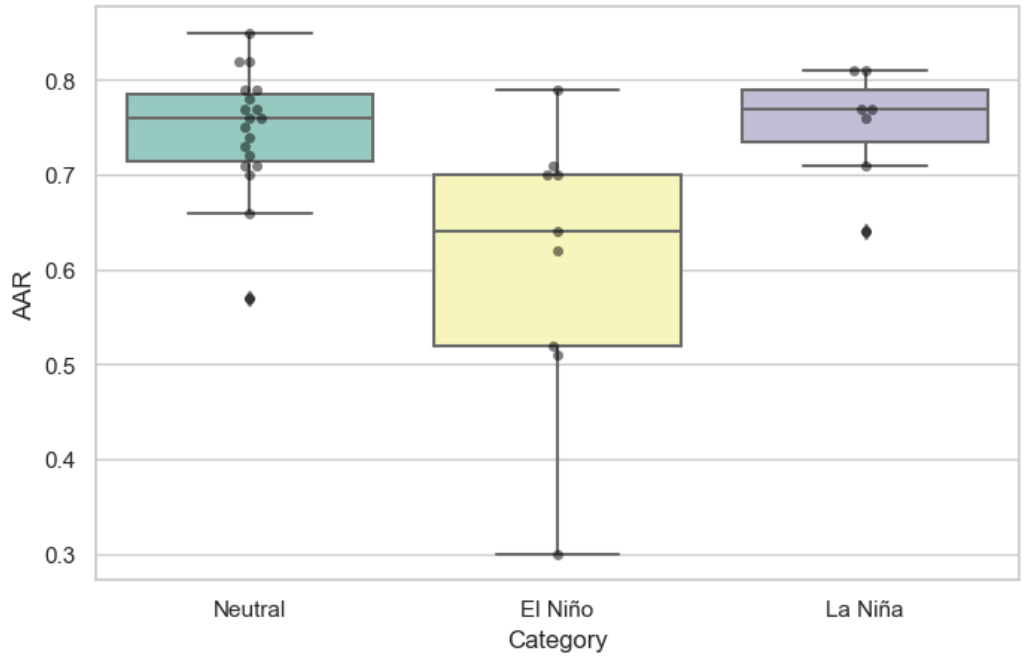


Figure S4: Box and whisker plots displaying differing means in the a) SCA, b) TA, c) ELA, and d) AAR from El Niño, La Niña, and neutral events.

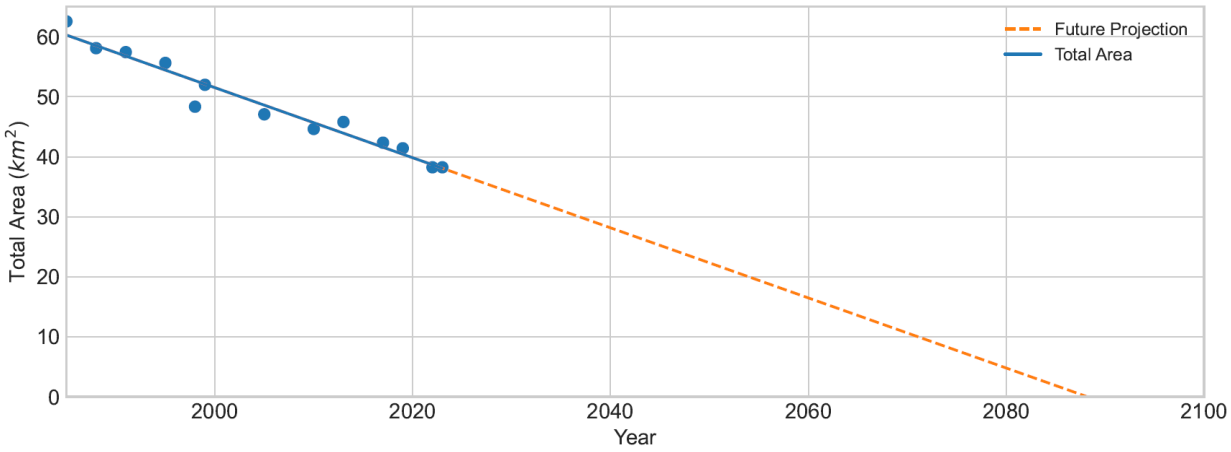


Figure S5: Projected disappearance of the entire QIC on the condition that it continues to follow the linear decline as recorded by the last 40 years.