**Monitoring the physical processes driving the mass loss of Tapado Glacier, Dry Andes of Chile**

**Supplementary Information**

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Figures

**A collage of a person climbing a glacier

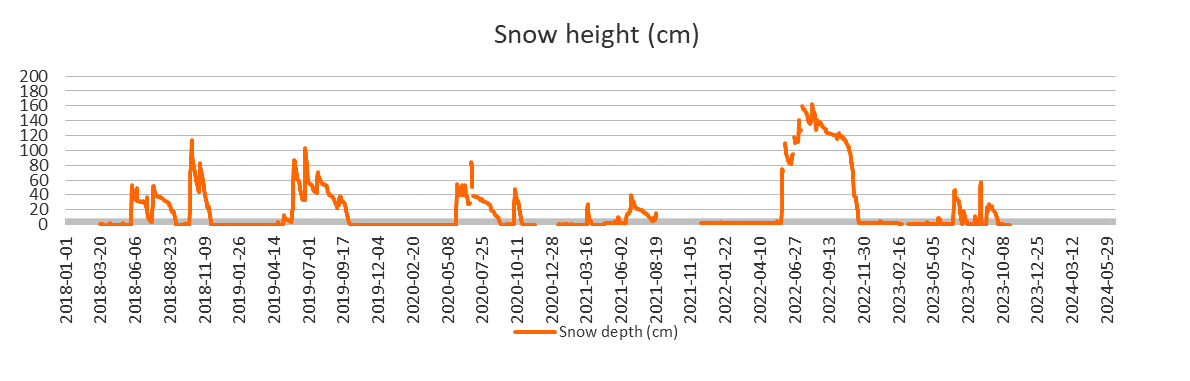
Description automatically generated**

**Figure S1:** Penitentes on Tapado Glacier

**A comparison of a mountain

Description automatically generated with medium confidence**

**Figure S2:** Upper panel: Point cloud classification using a terrain filter in Pix4DSurvey. Bottom panel: Segmented point cloud showing the tops of each penitente using a low pass filter on the classified point cloud.

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**Figure S3:** Daily snow depth at TAP AWS

A collage of snow on a mountain

Description automatically generated

**Figure S4**: Example of an ice fall from the marginal ice cliff in the debris-free section on 03/2021 captured by the automatic camera (a and b) and Sentinel images (c and d). The red frames indicate the location of the ice fall.

A close-up of a snow covered ground

Description automatically generated

**Figure S5**: Debris between the penitentes shown by images taken during the UAV flight in March 2024.

Tables

**Table S1:** Bands of the satellite products

| **Satellite** | **Bands** |
| --- | --- |
| Geo Eye | 1. Blue (0,450 - 0,510 µm) |
| 2. Green (0,510 - 0,580 µm) |
| 3. Red (0,655 - 0,690 µm) |
| 4. NIR (0,780 - 0,920 µm) |
| 5. PAN (0,450 - 0,800 µm) |
| Pléiades | 0. Blue (0.450 – 0.530 µm) |
| 1. Green (0.410 – 0.590 µm) |
| 2. Red (0.620 – 0.700 µm) |
| 3. NIR (0.775 – 0.915 µm) |
| 4. PAN (0.480 – 0.820 µm) |
| Pléiades Neo | 1.Red (0.619 – 0.690 µm) |
| 2.Green (0.5330– 0.591 µm) |
| 3.Blue (0.446 – 0.520 µm) |
| 4.NIR (0.768 – 0.888 µm) |
| 5.Red Edge (0,697 - 0,750 µm) |
| 6.PAN (0.416 – 0.457 µm) |
| Planet Scope | 1. Blue (0.455 – 0.515 µm) |
| 2. Green (0.500 – 0.590 µm) |
| 3. Red (0.590 – 0.670 µm) |
| 4. NIR (0.780 – 0.860 µm) |
| Rapid Eye | 1. Blue (0,440 - 0,510 µm) |
| 2. Green (0,520 - 0,590 µm) |
| 3. Red (0,630 - 0,685 µm) |
| 4. Red Edge (0,690 - 0,730 µm) |
| 5. NIR (0,760 - 0,850 µm) |

**Table S2:** Comparison of glacier mass balance for the debris-free and debris-covered sections according to previous studies

| **Hydrological year** | **Section** | **Reported**  **Winter MB**  **(m w.e. season−1)** | **Reported Summer MB**  **(m w.e. season−1)** | **Reported Annual MB**  **(m w.e. a−1)** | **Reported area (km2)** | **Area for normalisation (km2)** | **Normalised Annual MB**  **(m w.e. a−1)** | **Method for distribution** | **Seasons duration**  **(W: winter, S:summer)** | **Reference** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 2009-2010 | Debris-free | 0.5 | -1.4 | -0.8 | 1.09 | 1.14  (year 2000) | -0.76 | Net mass balance elevation gradient | W: 04/2009-11/2009  S: 11/2009-04/2010 | CEAZA (2010) |
| 2011-2012 | Debris-free | 0.2 | -1.1 | -1.0 | 1.05 | 1.14  (year 2000) | -0.92 | Statistical relation with topography | W: 04/2011-11/2011  S: 11/2011-04/2012 | CEAZA (2012) |
| 2013-2014 | Debris-free | 0.3 | -0.8 | -0.5 | 0.99 | 1.14  (year 2000) | -0.43 | Statistical relation with topography | W: 04/2013-11/2013  S: 11/2013-03/2014 | CEAZA (2015) |
| 2020-2021 | Debris-free | No snow measurements | -0.8 | Not reported | 0.92 | 0.94  (year 2020) | - | Net mass balance elevation gradient | S: 01/2021-04/2021 | This study using CEAZA (2021) data |
| 2021-2022 | Debris-free | 0.3 | -1.7 | -1.4 | 0.89 | 0.94  (year 2020) | -1.33 | Net mass balance elevation gradient | W:04/2021-11/2021  S: 11/2021-04/2022 | This study using CEAZA (2022) data |
| 2022-2023 | Debris-free | No snow measurements | -1.1 | Not reported | 0.87 | 0.94  (year 2020) | - | Net mass balance elevation gradient | S: 11/2022-04/2023 | CEAZA (2023) |
| 2013-2014 | Debris-covered | 0.0 | -0.6 | -0.6 | 0.50 | 0.47  (year 2000) | -0.64 | Statistical relation with topography | W: 04/2013-11/2013  S: 11/2013-03/2014 | CEAZA (2015) |
| 2022-2023 | Debris-covered | No snow measurements | -0.5 | Not reported | 0.75  (includes Tapado rock glacier) | 0.51  (year 2020) | - | Statistical relation with topography | S: 11/2022-04/2023 | CEAZA (2023) |
| 2000-2013 | Debris-free | - | - | 0.1±0.2 | 1.189 | 1.14  (year 2000) | +0.08 | Geodetic mass balance | - | Braun et al. (2019) |
| 2000-2010 | Debris-free | - | - | -0.3±0.3 | 1.189 | 1.14  (year 2000) | -0.33 | Geodetic mass balance | - | Hugonnet et al. (2022) |
| 2010-2020 | Debris-free | - | - | -0.5±0.3 | 1.189 | 1.14  (year 2000) | -0.48 | Geodetic mass balance | - | Hugonnet et al. (2022) |

**Table S3:** Area changes of Tapado Glacier debris-free section

| **Year** | **Area (km2)** | **Area change (km2)** | **Annual rate change**  **(km2 a-1)** | **Annual rate change**  **(% a-1)** | **Threshold** | **Image source** | **Image date (D/M/Y)** | **Spatial resolution (m)** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1956 | 1.32 | 0.00 |  |  | M | IGM | 4/4/1956 | 1.0 |
| 1978 | 1.25 | -0.07 | -0.003 | -0.230 | M | SAF | 5/31/1978 | 1.0 |
| 2000 | 1.14 | -0.12 | -0.005 | -0.422 | M | SAF | 1/31/2000 | 1.0 |
| 2010 | 1.09 | -0.05 | -0.005 | -0.433 | 0.01 | GeoEye | 4/12/2010 | 0.5 |
| 2011 | 1.07 | -0.02 | -0.015 | -1.415 | -0.10 | RapidEye | 3/12/2011 | 5.0 |
| 2012 | 1.05 | -0.02 | -0.022 | -2.022 | M | GeoEye | 3/23/2012 | 0.5 |
| 2013 | 1.03 | -0.02 | -0.023 | -2.157 | -0.13 | RapidEye | 4/16/2013 | 5.0 |
| 2014 | 1.02 | -0.01 | -0.012 | -1.141 | -0.10 | RapidEye | 3/14/2014 | 5.0 |
| 2015 | 1.00 | -0.02 | -0.022 | -2.129 | -0.15 | RapidEye | 3/6/2015 | 5.0 |
| 2016 | 0.99 | -0.01 | -0.009 | -0.920 | -0.10 | RapidEye | 3/28/2016 | 5.0 |
| 2017 | 0.97 | -0.01 | -0.012 | -1.227 | -0.19 | PSScene | 4/13/2017 | 3.0 |
| 2018 | 0.96 | -0.02 | -0.017 | -1.730 | -0.10 | PSScene | 4/7/2018 | 3.0 |
| 2019 | 0.95 | -0.01 | -0.007 | -0.685 | -0.05 | PSScene | 4/14/2019 | 3.0 |
| 2020 | 0.94 | -0.01 | -0.014 | -1.471 | -0.03 | Pléiades | 3/1/2020 | 0.5 |
| 2021 | 0.92 | -0.02 | -0.015 | -1.626 | -0.10 | PSScene | 3/13/2021 | 3.0 |
| 2022 | 0.91 | -0.01 | -0.015 | -1.577 | 0.35 | PSScene | 4/13/2022 | 3.0 |
| 2023 | 0.89 | -0.02 | -0.020 | -2.192 | 0.36 | PSScene | 4/20/2023 | 3.0 |
| 2024 | 0.85 | -0.03 | -0.032 | -3.627 | 0.01 | Pleiades Neo | 3/19/2024 | 0.3 |