Brief communication: Tropical glaciers on Puncak Jaya (Irian Jaya/West Papua, Indonesia) close to extinction

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Abstract. Glaciers have been retreating for many decades on a global scale due to anthropogenic climate change, including the mostly small glaciers in the Tropics. In this brief report, we document area changes of the Puncak Jaya glaciers in South-East Asia on West Papua, Indonesia, until the present. The survey was based on high resolution multispectral satellite imagery of PlanetScope and Pléiades missions from 2023 and 2024. Additionally, we digitized and georeferenced historical glacier accounts from analogue maps, resulting in a new overview map of glacier change on Puncak Jaya since 1850 (DOI requested from Pangäa). The results show a decrease of total glacier surface area by more than 99% since 1850 and by 64% since the last survey in 2018. Current glacier area (in 2024) amounts to 0.165 km^2. The development of Puncak Jaya glaciers is thus in line with the global shrinkage of (tropical) glaciers. Assuming the current area retreat rates to continue, it is very likely that Puncak Jaya glaciers will disappear around 2030.

1 Introduction

Global air temperatures have risen due to anthropogenic climate change (World Meteorological Organization, 2022). While the global annual mean near-surface air temperature of 2022 climbed 1.15°C above the 1850-1900 pre-industrial average, corresponding to a global warming rate of 0.2 ± 0.1°C per decade, surface air temperatures in mountainous areas show an enhanced increase of 0.3 ± 0.2°C per decade (Hock et al., 2022; World Meteorological Organization, 2022). This rise in air temperatures varies globally. In South-East Asia, mean annual air temperatures already started to rise between 1870 and 1940 and were 0.46°C above the 1961-1990 average in 2022 (Allison and Kruss, 1977; World Meteorological Organization, 2022). In Indonesia, where Puncak Jaya glaciers are located, mean daily maximum air temperatures increased by 0.18°C per decade between 1983 and 2012 (Supari et al., 2017). Regardless of region, glaciers around the globe have been in a mode of mass loss for many decades and tropical glaciers are no exception (Hock et al., 2022; Hinzmann et al., 2024; Fox-Kemper et al., 2021).

While the majority of glaciers on the globe are located in mid and high latitudes, glaciers also exist at low altitude and are termed "tropical" when the following criteria are fulfilled (Kaser and Osmaston, 2002). Firstly, they must be located in the astronomic tropics between the Tropic of Cancer and the Tropic of Capricorn (23°26'13.3'' N; 23°26'13.3'' S); secondly,

they must be located within the oscillation range of the Intertropical Convergence Zone (ITCZ); thirdly, the annual range of the air temperatures must be equal to, or smaller than, the daily temperature range. Currently, three areas fulfill these criteria. The Andes where the majority of tropical glaciers is located, East Africa and New Guinea (Kaser and Osmaston, 2002). On New Guinea, glacier ice only exists in the West Papua region, formerly known as Irian Jaya region. They are located in the West of the New Guinea Highlands on the rugged Sudirman range around Puncak Jaya peak (4.884 m a.s.l.) (Figure 1a) (Permana et al., 2019).
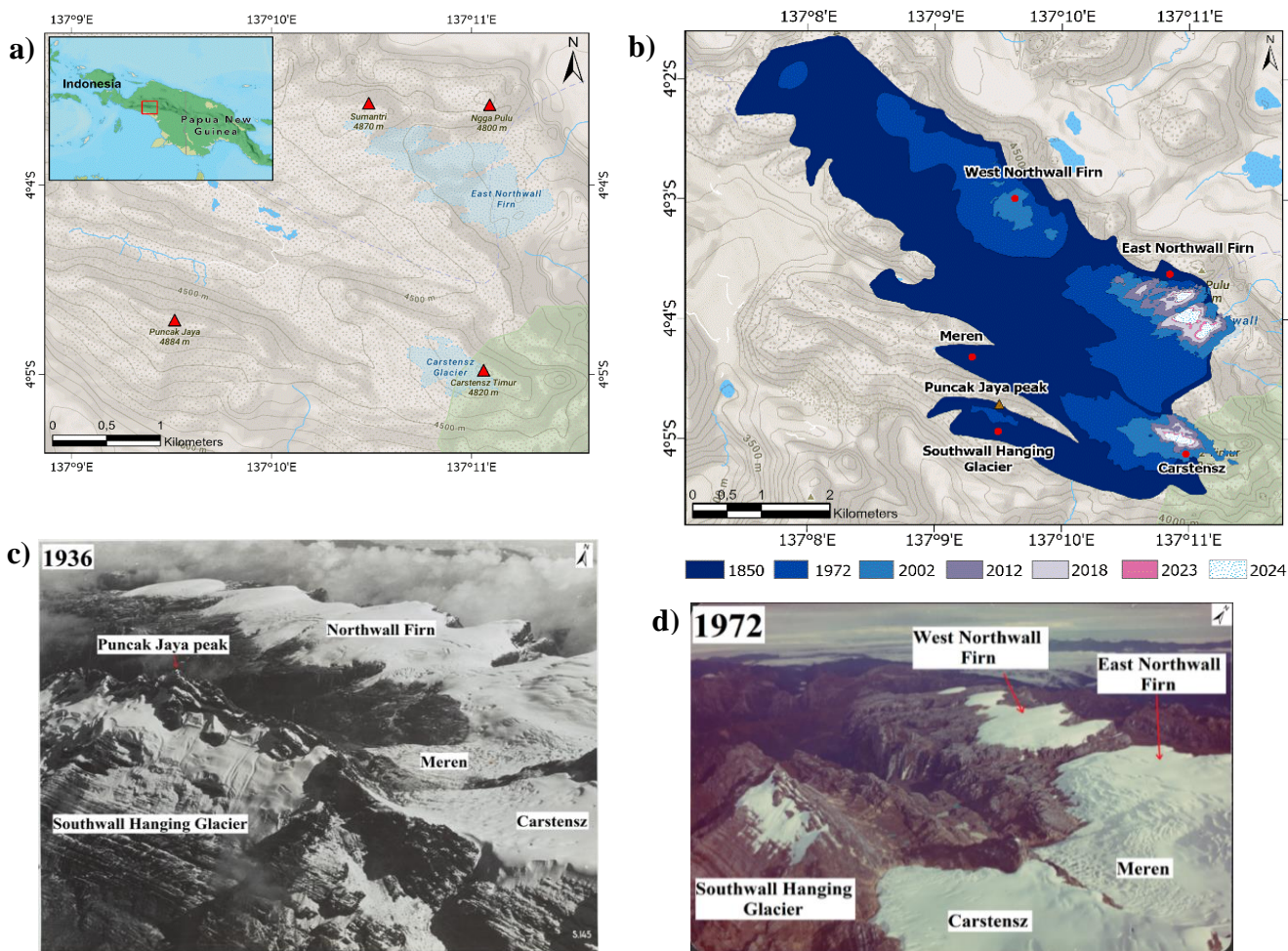
Figure 1: The geographic setting of glaciers around Puncak Jaya. a): Overview of glaciers and surrounding peaks (marked with red triangles) in the Puncak Jaya mountains. Puncak Jaya, with an altitude of 4,888 m a.s.l., represents the highest peak in the region. East Northwall Firn glacier is located close to (Gunung) Sumantri and Ngga Pulu peaks, while Carstensz glacier lies next to Carstenz Timur peak. Glacier extents in the map are from 2005 (Openstreetmap Base map with contour lines (© OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.), ESRI, NASA). **b):** Glacier changes between ~1850 to 2024,

based on data of own surveys and of authors mentioned in Table S1 (Openstreetmap Base map with contour lines (©
OpenStreetMap contributors 2024. Distributed under the Open Data Commons Open Database License (ODbL)
v1.0.), ESRI). c) and d): Oblique photographs, taken during the 1936 and 1972 expeditions, showing glacial retreat
especially of the Northwall Firn, indicated by a bifurcation in 1972, separating the Northwall Firn into an East and
West part (Dozy, J.J. (1936) and Carstensz Glacier Expedition (1972), Glacier Photograph Collection, National Snow
and Ice Data Center, edited).

Tropical glaciers are interesting from a scientific point of view in several ways, as their changes are influenced by local climatic drivers as well as by prominent modes of macro- and mesoscale climatic dynamics (e.g. Mölg et al. 2020; 2009). Moreover, their high-altitude location between the 600 and 500 hPa levels in the atmosphere makes them good indicators of global climatic changes in the mid troposphere (Allison and Kruss, 1977; Mölg et al., 2009). Therefore, glacier systems located in the tropical Andes and in East Africa have been examined extensively in the last decades, focusing on glacier area changes and the differentiation of global and local climatic factors influencing glacial retreat. Recent examples are e.g. Carrivick et al. (2024), Gorin et al. (2024), Hinzmann et al. (2024), Mölg et al. (2020), Turpo Cayo et al. (2022). However, the glaciers on Puncak Jaya have received less attention as the only modern expeditions took place in 1973 and 2011 and the latest remote surveys were carried out between 2015 and 2018, creating a data gap to the present (Permana et al., 2019; Permana, 2011; Allison and Peterson, 1976). Thus, the present study aims to (i) close the existing data gap by examining the changes of glacier extent since the last surveys in 2015 and 2018 using high resolution multispectral satellite imagery, and (ii) construct a new map of glacial development from 1850 onwards by conducting a comprehensive data acquisition of (historical) analogue and digital data, which allows us to put the results of current glacier change into historical perspective.

2 Brief history of Irian Jaya glacier studies

During the Last Glacial Maximum (LGM) large parts of the high mountain areas of New Guinea, including Puncak Jaya area, were covered by ice and snow with an area of about 2000 – 2200 km^2 (Kaser and Osmaston, 2002; Brown, 1990). After several glacier surges and retreats during the Greenlandian and Northgrippian stage of the Holocene, glaciers in the Puncak Jaya mountains began to retreat by the end of the Little Ice Age (LIA) between 1850 and 1875 (Allison and Kruss, 1977; Bowler et al., 1976; Prentice et al., 2011). Interestingly, the aforementioned glacier advances took place almost synchronously with neoglacial glacier advances on western Greenland and in the east African Rwenzori mountains (Bowler et al., 1976; Löffler, 1980; Peterson et al., 1973).

After the first description of glacier sightings in the Sudirman Range/Puncak Jaya mountains by the Dutch seafarer Jan Carstensz in 1623, the first expeditions did not take place until 1907 and 1909 (Wollaston, 1914; Temple, 1962; Hope, 1976). These expeditions were not able to reach the glaciers but documented their existence and extent through photography

and land markings. After the first expedition that successfully reached the glaciers in 1912, led by A.F.R. Wollaston and A. van de Water, the next expedition took place in 1936, led by A.H. Colijn and J.J. Dozy, followed by several reconnaissance flights conducted by the US military during World War II (Coljin, 1937; Allison, 1974; Ballard, 2001). During these surveys, terrain markings of glacial extent were erected and images were taken that were of great value for understanding glacier change on Puncak Jaya later on (Figure 1b,c,d).

The first ascent of Puncak Jaya mountain itself and the surrounding glaciers was accomplished by Heinrich Harrer in 1962 (Harrer, 1963; Hope, 1976). At this time, glacier retreat was already evident compared to the glacier extent in 1936 (Harrer, 1963). The first complete quantitative survey of all existing glacier areas on Puncak Jaya took place during two Australian Universities Carstensz Glaciers Expeditions between 1971 and 1973, finding only the Southwall Hanging, Carstensz, Meren, East Northwall Firn and West Northwall Firn glaciers (Figure 1b,c,d). The survey results of these expeditions indicated a further significant decline of glacier area from 13 km^2 in 1936 to 7.3 km^2 in 1972 and 6.4 km^2 in 1974 (Allison and Peterson, 1976). Additionally, during these expeditions several other small glaciers on Sudirman Range, namely on Mount Wilhelmina, Mount Juliana and Mount Idenburg, could be identified and surveyed from the air (Peterson et al., 1973).

From the 1970s onwards, remote sensing was increasingly used to measure glacier areas. The first survey of that kind was carried out in 1987 using SPOT satellite data, which revealed a further reduction in total glacier area on Puncak Jaya to 5.09 km^2 (Allison and Peterson, 1976; Klein and Kincaid, 2006). Between 1997 and 2000 Meren glacier disappeared (Prentice and Glidden, 2010; Klein and Kincaid, 2006). With the next surveys in 2000, 2002, 2003 and 2005, using high-resolution IKONOS satellite data, a further reduction in total glacier area to 2.15 km^2 was detected (Klein and Kincaid, 2006; Kincaid, 2007). During the following survey in 2010, when ice core drilling was conducted on the glaciers to measure isotope composition, the disappearance of the last remnants of the Southwall Hanging glacier was detected (Permana, 2011). The extents of the remaining glaciers East Northwall Firn and Carstensz were analysed again in 2018 using remote sensing imagery of PlanetScope mission, revealing a total surface area reduction from 0.653 km^2 in 2015, 0.552 km^2 in 2016 to 0.458 km^2 in 2018 (Permana et al., 2019).

Due to the remote location and difficult access of Puncak Jaya glaciers, very few mass balance surveys have been conducted, mostly covering short time periods: In 1972, negative mass balances of –57 x 10^3 m^3 w.e./year with a surface lowering of 0.064 m/year for the Carstensz glacier and –989 x 10^3 m^3 w.e./year with a surface lowering of 0.509 m/year for the Meren/East Northwall Firn glacier were observed by the Carstensz Glacier Expedition (Allison, 1974). Maximum ice depth was estimated to be > 60 m for the East Northwall Firn glacier and approx. 70 m for the Carstensz glacier (Allison, 1974). Between 1995 and 1997, East Northwall Firn glacier experienced a negative mass balance of –4430 x 10^3 m^3 w.e./year, whereas between 1997 and 2000 a slightly positive mass balance of 452 x 10^3 m^3 w.e./year was surveyed (Prentice and Glidden, 2010). During an expedition in 2010, ablation stakes were placed on East Northwall Firn glacier, reveiling an annual rate of approx. 1.05 m of ice thickness loss (Permana, 2015). Ice thickness on East Northwall Firn glacier further decreased from approx. 30 m in 2010 to approx. 20 m in 2016, while an estimated ice thickness of approx. 6 m remained in 2022 (Permana et al., 2019; World Meteorological Organization, 2022).

3 Data selection and methods

130   **3 Data selection and methods**

As the last surveys of 2015 and 2018 showed small glacier extents of <0.2 km^2 at Puncak Jaya, our study employed high resolution multi-spectral satellite imagery of PlanetScope mission (provided by Planet Labs PBC via the PlanetLabs Education and Research Programme) with a horizontal resolution of 3.125 m and a near-daily revisit capacity (Planet Labs PBC, 2023). Furthermore, very-high resolution multi-spectral satellite imagery of the Pléiades mission (provided by Airbus

135   DS through the European Space Agency) with a horizontal resolution of 0.5 m and a daily revisit capacity was used to compensate for potential uncertainties (e.g. due to shading effects) in the lower resolution PlanetScope imagery (Airbus Defence and Space Intelligence, 2021). Although no distinct accumulation and ablation seasons exist at Puncak Jaya glacier area due to the homogenous inner-tropical climate setting, imagery selection focused on the time period from May to August when rainfall and relative humidity minima can be expected (Permana, 2011). However, some images without cloud cover

140   from outside this season could also be considered (Table S2). Imagery selection focused on the absence of extensive cloud cover, shadowing, or fresh snowfall, which limited the number of available image acquisitions due to the high degree of cloud cover in the inner tropics and early morning cloud formation at Puncak Jaya (Prentice and Hope, 2007; Kaser and Osmaston, 2002). The selected images (Table S2), which were already provided orthorectified, color-corrected and -optimized, were loaded into Esri ArcGIS Pro (Version 3.1.3) software, where a visual check of the orthorectification of the

145   PlanetScope images by comparing several distinct landmarks using Sentinel 2 images (Table S3) was conducted. No relevant deviations were detected and, therefore, no additional orthorectification was applied.

Due to the size of remaining glaciers on Puncak Jaya, we delineated the glacier outlines manually based on visual inspection of all available high-resolution images using ArcGIS Pro. Manual delineation/digitization of glacier outlines, executed by an analyst using cursor tracking, is less influenced by disturbing factors such as shading or debris cover, as it relies on the

150   analyst's dynamic interpretation and visual verification. Despite the fact that this approach is typically more time-consuming than an automated survey (e.g. using band arithmetic methods), it is very effective for small glacier areas with potential interferences, e.g. shading or snow cover, since visual validation is already included in the process (Hinzmann et al., 2024). As we used high-resolution multispectral imagery and did not detect snow cover, debris cover or shading issues, the ice areas were clearly distinguishable from surrounding rocky terrain and additional manual delineation runs were not necessary.

155   However, to further increase the accuracy, we compared the results to very-high resolution Pleiades imagery and oblique photography from recent expeditions, whereby no deviations were detected.

In addition to the acquisition of present-day glacier area using satellite imagery, a new digital map with historical glacier extents dating back to 1850 was generated. This map was primarily based on the one created during the Carstensz Glacier Expedition in 1972, which compiled survey results of historic glacier extents back to the 19th century (Anderson, 1976; Hope

160   et al., 1976) . While digitizing the analogue map using ArcGIS Pro, georeferencing was done by using three landmarks ("NE", "PHOTO B", "CARSTENSZ PYRAMID") that were contained in the said analogue map (Hope et al., 1976); co-registering was performed using Sentinel 2 imagery (Table S3) to check for distortions and shifts. The glacier areas were

subsequently delineated manually and saved as polygon shapefiles. Furthermore, glacier contours were manually delineated for the years 2012, 2016 and 2018 based on RapidEye and PlanetScope data (Table S4), as the contemporaneous outlines by Permana et al. (2019) were not available. Glacier extents of 2002 were provided by the study of Klein and Kincaid (2006).

4 Results and discussion

The trend of recession of Puncak Jaya glaciers since ~1850, documented in previous publications (Allison and Peterson, 1976; Harrer, 1963; Permana et al., 2019; Klein and Kincaid, 2006; Kincaid, 2007), has continued in 2023 and 2024: The total glaciated area shrunk from 19.3 km^2 in 1850 to 6.4 km^2 in 1974 and 2.15 km^2 in 2002, and to 0.196 km^2 in 2023 and 0.165 km^2 in 2024 (Figure 2, Table S1 and S5). Between 2018 and 2024 the total glacier area shrunk by 0.313 km^2 or ~65%. The western part of the East Northwall Firn shows the smallest glaciated area with only ~0.022 km^2 in 2024 and is likely to disappear first in the years ahead (Figure 2).
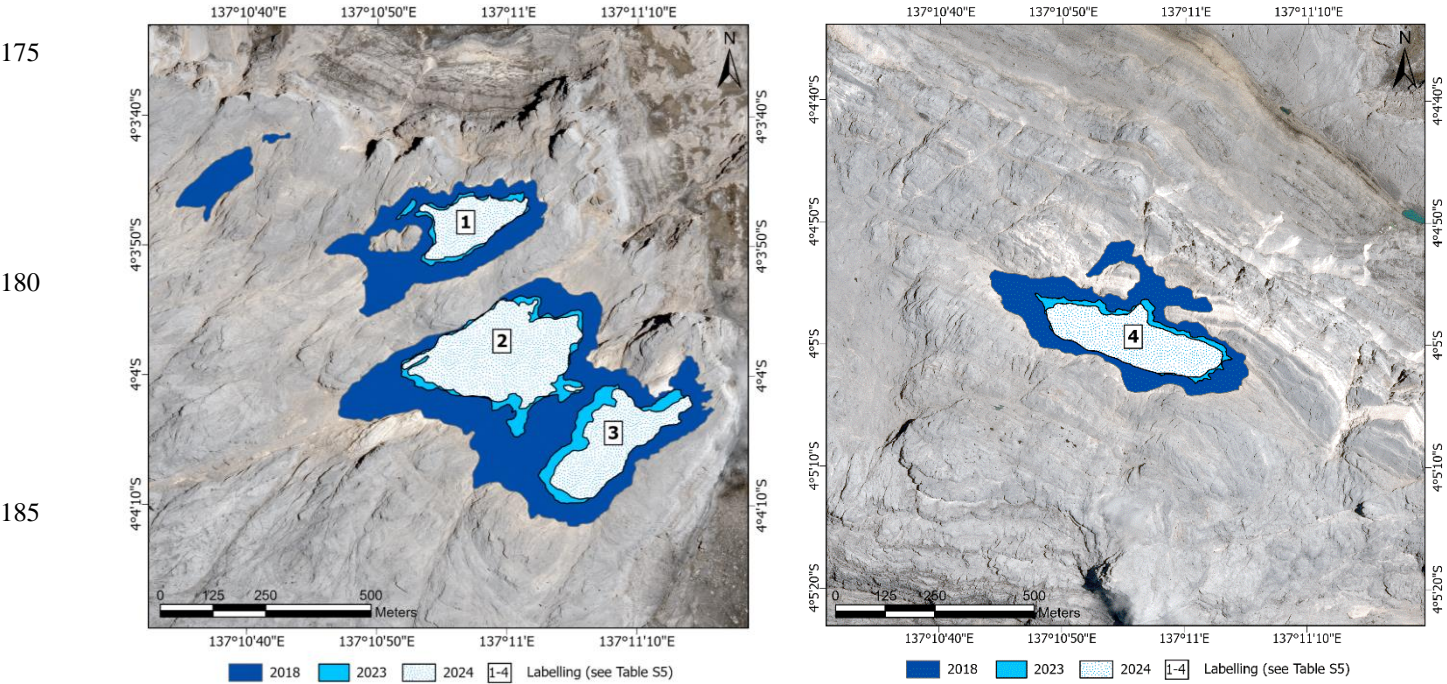
Figure 2: Glacial retreat of East Northwall Firn glaciers (left) and Carstensz glacier (right) between 2018 and 2024. Labels 1-4 on glacier areas refer to Table S5 (Based on image data by © 2023, 2024 Planet Labs PBC and © CNES (2023), distribution Airbus DS, data provided by the European Space Agency. Background imagery of Pléiades mission provided by CNES (2023))

195   Since the last survey in 2018, the westernmost part of the East Northwall Firn has disappeared and the main body of the East Northwall Firn has been separated into two parts by a bifurcation. All surveyed areas experienced area loss, while the East Northwall Firn experienced greater loss (0.239 km^2) compared to the Carstensz glacier (0.074 km^2) from 2018 to 2024 (Figure 2, Table S5), most likely due to the fact that the lost parts of the East Northwall Firn were located at a lower altitude than the Carstensz glacier area.

200   By putting the current survey's results into perspective to historical changes of Puncak Jaya glaciated areas, the drastic decline becomes evident (Figure 1b, Table S1). By 2002, the total glaciated area had declined by almost 90% since 1850 (Klein and Kincaid, 2006) and in 2024 less than 1% of the ~1850 glacier surface area remains. The former Northwall Firn Glacier split into two parts at some time between 1942 and 1962, resulting in the West Northwall Firn and East Northwall Firn part (Allison and Peterson, 1976). Meren Glacier vanished between 1997 and 2000 (Klein and Kincaid, 2006), while

205   West Northwall Firn and Southwall Hanging glaciers disappeared between 2005 and 2012 (Figure 1b; Kincaid, 2007). Within the last two decades, the glaciers consisting of the remnants of East Northwall Firn and Carstensz glacier retreated to areas of the highest altitudes possible, close to the mountain tops of Carstensz Timur and Ngga Pulu.

The area loss rate shows a steady decline since ~1850 and indicates no climatological time period of glacier growth within the last 170 years (Figure 3). It can be noted that this rate slowed down between 2016 and 2024 compared to the recession

210   between 2000 and 2015, as visible in Figure 3. However, this is typical of glaciers in a state of disappearance (Kaser et al., 2010). A comparison of the loss rate with the glacier area extent changes indicates that the observed slowdown between 2016 and 2024 happened after the complete loss of glacier parts at lower altitudes, with the remaining glacier parts at higher altitudes only, where more favourable climate conditions for glaciers exist.

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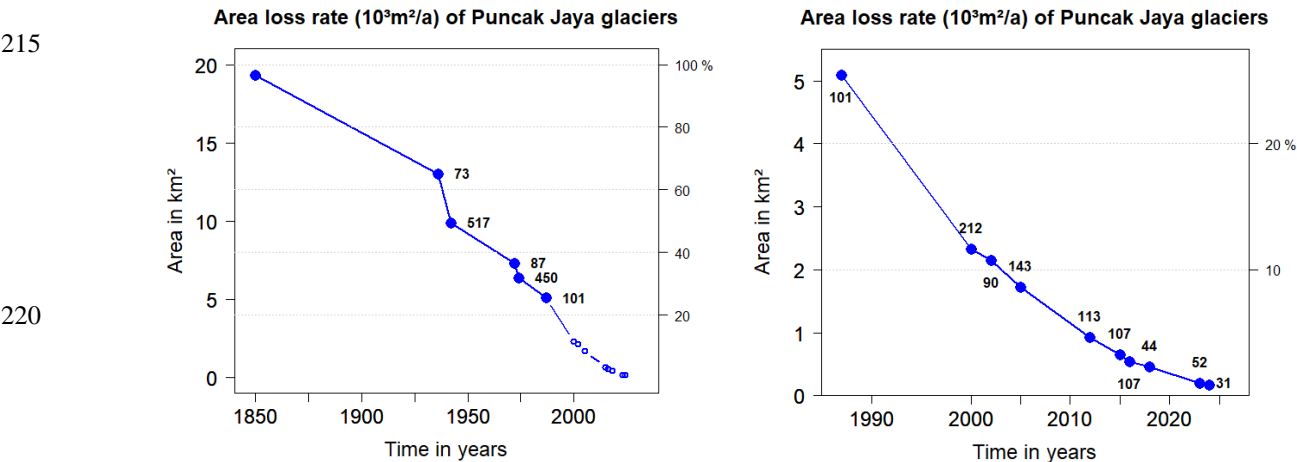
Figure 3: Annual area loss rate (10^{3}m^2/a) of all Puncak Jaya glaciers. The labels affixed to the data points correspond

225   **to the annual loss rate rate (10^3 m^2 per year) in the previous time range. The right panel zooms into the most recent decades.**

As important reason for the retreat of Puncak Jaya glaciers, the rise of mean annual air temperatures at the 550 hPa pressure
230   level has been reported, with a rise of ~1°C alone at glacier altitude between 1972 and 2000, which has resulted in a near
zero probability of average daily temperatures falling below freezing point on the glaciers after 1997 (Permana et al., 2019;
Prentice and Hope, 2007). Additional factors, such as sea surface temperature changes, changes in the phase of precipitation
due to air temperature rise, changes in radiation absorption as well as El Niño Southern Oscillation and monsoon variability,
are playing further roles (Permana, 2015; Prentice and Hope, 2007; Permana et al., 2019; Kincaid, 2007). However, due to
235   the lack of climatological datasets for the area, the direct local/regional climatic drivers are harder to identify (van Ufford
and Sedgwick, 1998; Prentice and Hope, 2007). Based on the locations of the glacier remnants, the topography appears to
have some influence, as all present ice masses are located on the western and southwestern ridges of their respective
mountains, facing away from the morning sun (when skies are most likely cloud-free). This effect was already demonstrated
by Hastenrath and Kruss (1988) to play a role for vanishing tropical glaciers.

5 Conclusion

In this brief communication, the strong recession of Puncak Jaya glaciers is documented, both for recent years and for the
historic time range since the mid 19th century. New glacier surface areas for 2023 and 2024 on Puncak Jaya were determined,
which closes an existing data gap. Besides, we transferred historic glacier extent data into a digital format combined with a
thorough analogue and digital data acquisition and collection, resulting in an up-to-date overview map of Puncak Jaya
245   glacier history, which ranges from ~1850 to 2024. Using high- and highest resolution optical imagery for surveying glacier
extent will become more important in the future since small glaciers, which will become more common due to climate
change, will be hard to survey using medium-resolution imagery (e.g. Hinzmann et al., 2024). It is expected that Puncak Jaya
glaciers will disappear around 2030, if the observed annual area retreat rate since 2018 persists.

Author contribution

DI conducted the data analysis under supervision of CS and TM. The writing was led by DI, with contributions from TM and
CS. All authors discussed the results and edited the manuscript.

Data availability statement

The data that support the findings of this study are openly available in PANGÄA (Data has been uploaded to PANGÄA and
255   DOI has been requested).

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260 Space Agency for providing access to Pléiades imagery (Proposal ID: PP0093912).

Competing interest

At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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