Thermokarst processes as triggers of debris flows:
A case study at Hüttekar Rock Glacier (Austrian Alps)

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A cascading process including thermokarst lake outburst, debris flow initiation, and river blockage, hit a high mountain valley in the Austrian Alps during summer 2019. The rapid development of thermokarst features on an active rock glacier, including a lake with a water volume of approximately 166,000 m³ as well as a 350 m long drainage channel, most likely triggered the failure of ice-cemented debris within its front, with subsequent mobilization of roughly 50,000 m³ of sediment. This study explores the drivers of thermokarst evolution by tracking the lake development using satellite imagery and modeling its energy budget. We employ a simple balance model, assuming that the atmospheric energy input was efficiently transferred to the frozen rock glacier core through convection of lake water. This process provided sufficient melting energy to establish the thermokarst channel draining the lake within several hours. Our results highlight the need to account for thermokarst processes in hazard assessment studies involving permafrost-affected terrain.

Thermokarst lake outburst and debris flow

- Active rock glacier front failure and debris flow mobilization was initiated by a thermokarst lake outburst about 350 m behind the rock glacier front (Figure 1)
- Thermokarst lake development initiated on 3 June 2019, storing 166 000 m³ water before the outburst flood occurred on 13 August 2019
- Rapid evolution of a thermokarst channel network drained the lake within ~1 day (Figure 2)
- Energy provided by the upstream thermokarst lake governed expansion rates of the drainage system
- Field evidence (undercutting and vertical pipe structures) suggests thermal convection of lake water efficiently transported energy from the lake surface to the frozen rock glacier core at the lake bottom (Figure 2)
- Atmospheric energy input accelerated thermokarst evolution, inducing rapid energy turnover and melting of ice beneath the lake (Figure 3)
- Our study assesses this energy input to obtain an order of magnitude estimate of the available ice melting energy which limited the evolution rates of the observed thermokarst features

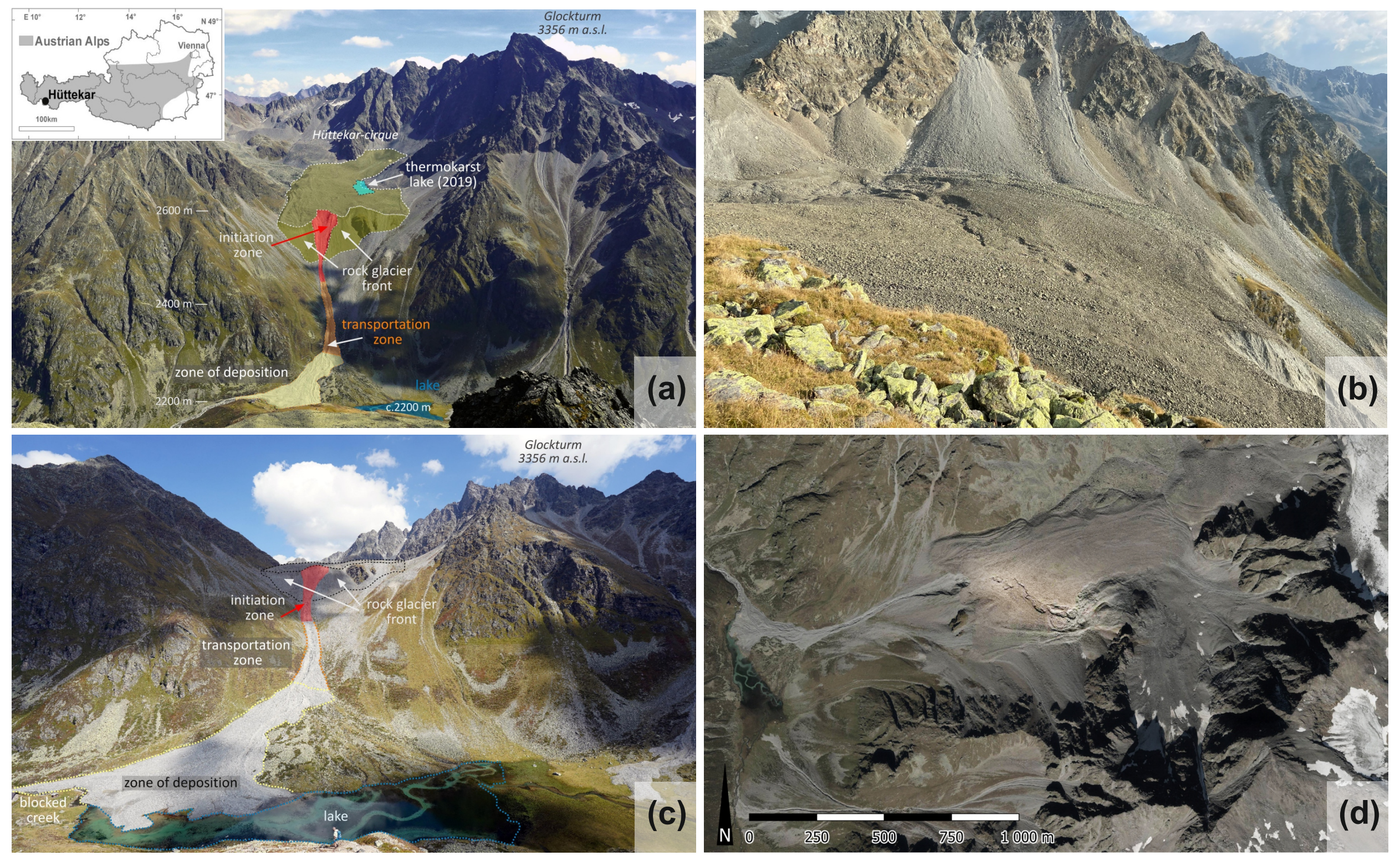


Figure 1. (a) Hüttekar-cirque, Hüttekar Rock Glacier, the debris flow and the impounded lake (view is towards the east). The debris flow was initiated at the steep front of Hüttekar Rock Glacier (highlighted), caused by rapid drainage of a thermokarst lake that existed between 01 June and 13 August 2019 (former position indicated). (b) Cluster of collapse structures connecting the former thermokarst lake to the debris flow initiation zone. (c) Debris flow morphology two years after ist initiation. The progressively enlarging initiation zone eroded already significant parts of the steep rock glacier front. The transport zone is characterized by a set of levees along a narrow channel. The former flow path of the blocked river ist still clearly visible below the lake surface. The channel draining the lake was excavated to prevent a potentially catastrophic outburst following river blockage in August 2019. (d) Collapse structures (highlighted) connecting the former position of the thermokarst lake and the debris flow initiation zone.

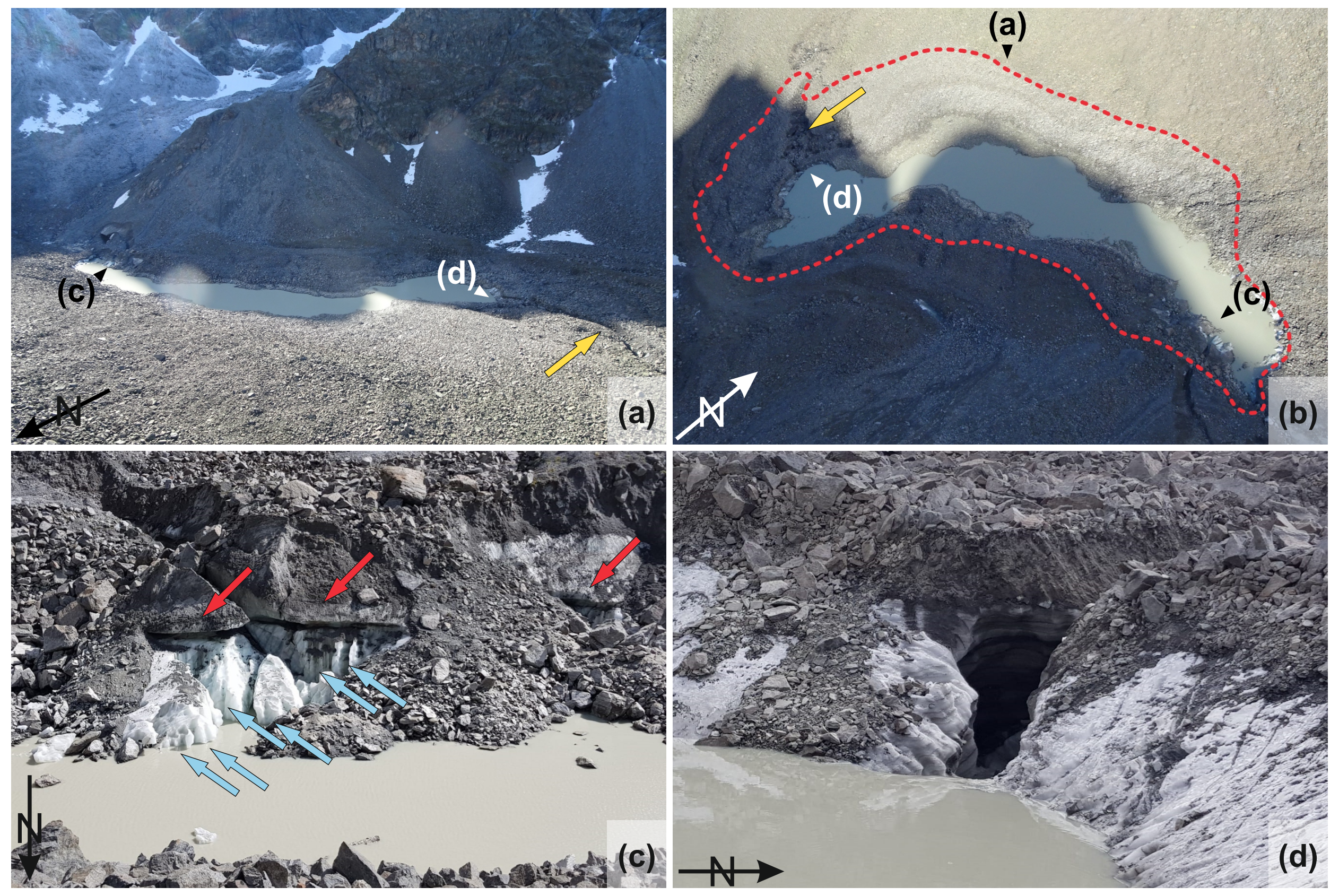


Figure 2. (a) Thermokarst lake and drainage channel (yellow arrow) on Hüttekar Rock Glacier (b) Extent of thermokarst lake on 14 August 2019 and maximum extent one day earlier (dashed line). The channel connecting the lake to the debris flow initiation zone is indicated by the yellow arrow. (c) Impermeable ice underlying the thermokarst lake. Blue arrows indiciate vertical convexities attributed to thermal convection of water during the lake development. Red arrows indicate undercutting of the ice along the lake shoreline, promoted by thermal convection. (d) Thermokarst channel eroded into the frozen rock glacier core, facilitating rapid drianage of the thermokarst lake. Photos: Roman Außerlechner, Thomas Figl, Werner Thöny, 14 August 2019 (a, b); Josef Waldner, 13 August 2019 (c, d).

Energy balance model

- Satellite imagery allows tracking the thermokarst lake surface through time (Copernicus data processed by Sentinel Hub, www.sentinel-hub.com)
- First-order lake water volume estimates obtained by combining digital elevation model of rock glacier surface to lake surface (Figure 4)
- Heating of the lake surface water increases density up to ~4°C, while energy transfer to the underlying permafrost ice decreases density, inducing thermally driven convection cells in the shallow thermokarst lake that efficiently transport energy to the frozen rock glacier core (Figure 3)
- Assuming energy transport across lake >> energy stored within lake, small changes in lake water temperature, and efficient heat transport to the underlying permafrost ice allows setting up a simple energy balance model for the thermokarst lake surface

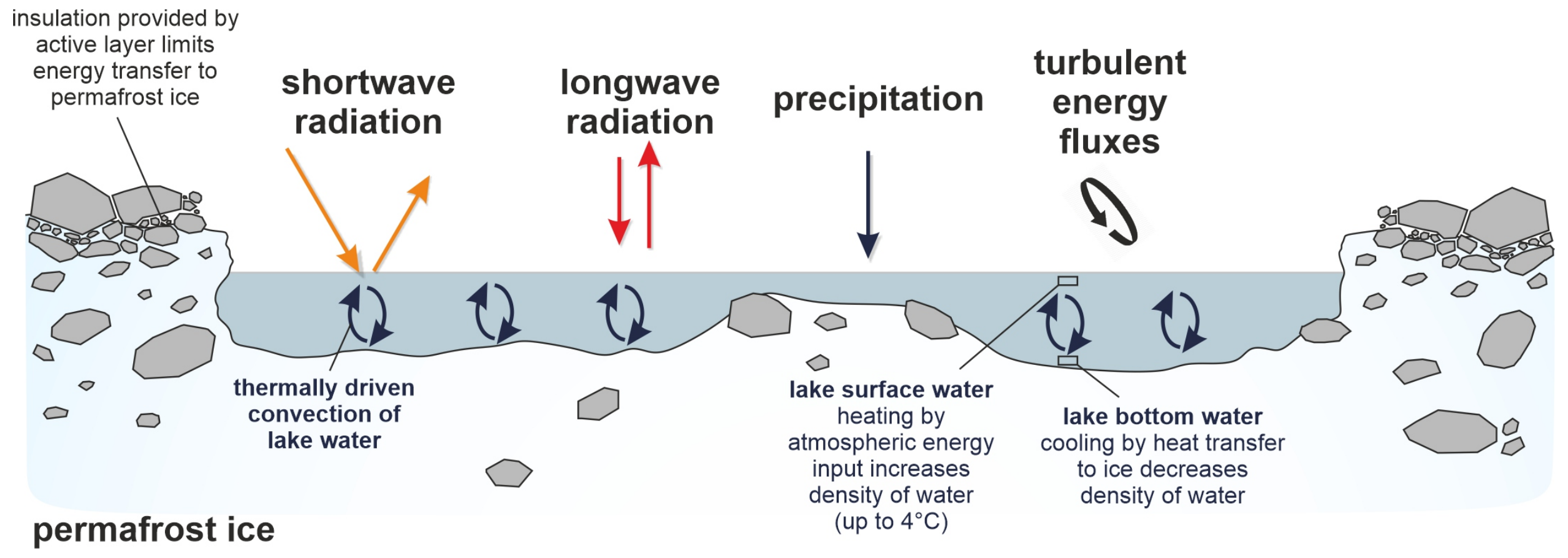
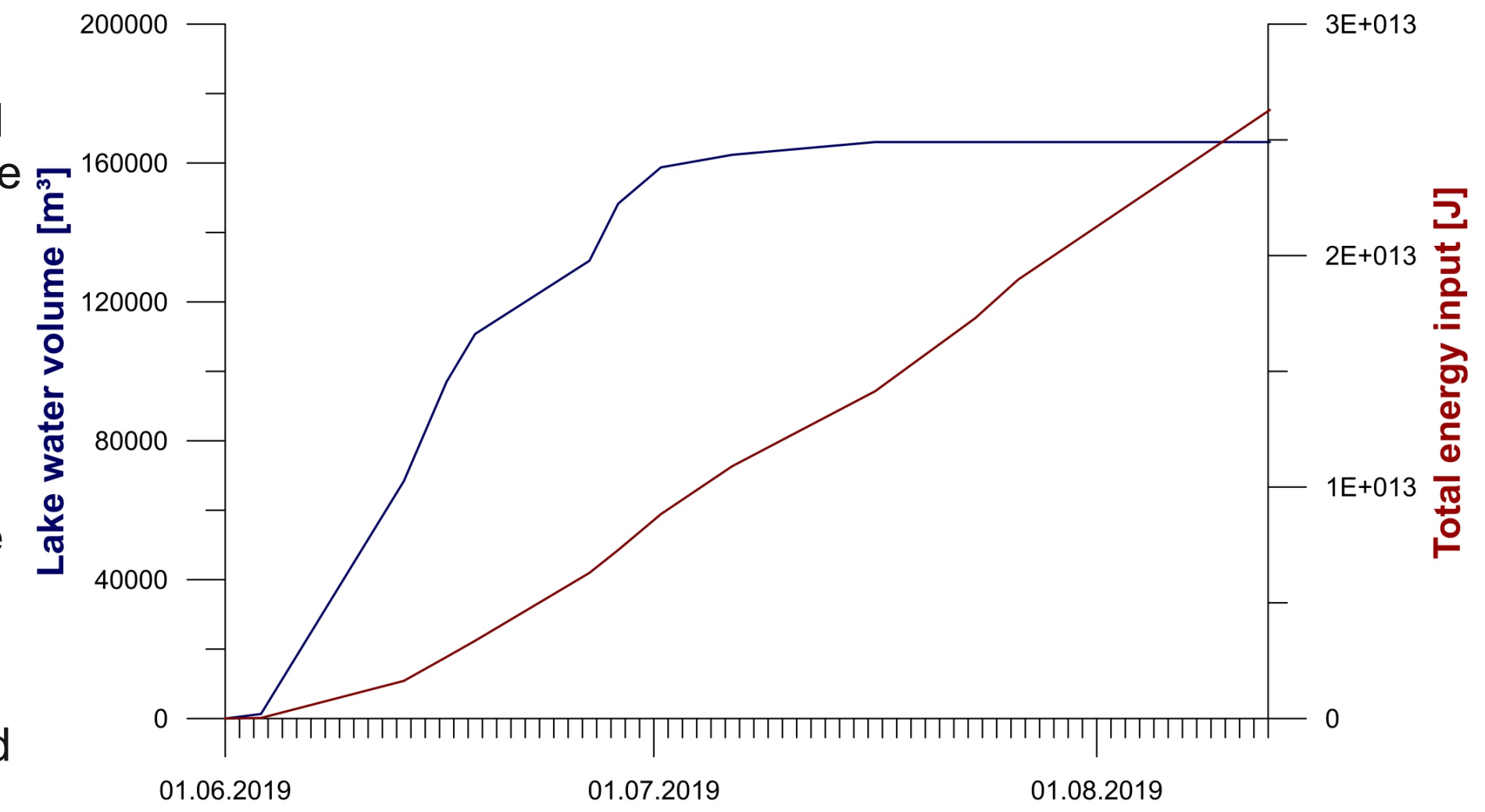


Figure 3. Energy balance model for the thermokarst lake. Indivudal energy flux density contributions are estimated at the lake surface. Thermally driven convection rapidly transfers this energy to the underlying permafrost ice of the frozen rock glacier core. Modified after Oerlemans (2010).

Calculation procedure

- Global radiation, air temperature, precipitation, specific humidity, and wind speed obtained from Integrated Nowcasting through Comprehensive Analysis (INCA) dataset (Haiden et al., 2011)
- Shadowing and reflectance by surrounding terrain obtained from high-resolution (1 × 1 km) digital elevation model (provided by the Government of the Province of Tyrol) using GRASS GIS 8.0 (Hofierka et al., 2007)
- Roughness length estimates collected during field surveys
- Lake surface area linearly interpolated between cloud-free satellite images (data provided by Copernicus and processed by Sentinel Hub, www.sentinel-hub.com)
- Individual energy flux density contributions (Figure 3) estimated according to Cuffey and Paterson (2010), accounting for shortwave radiation, longwave radiation, sensible heat flux, latent heat flux, and precipitation heat flux
- Total energy input (2.6 × 10^{13} J) obtained by multiplying energy flux density by lake surface area and integrating over time, corresponding to the energy needed to melt 87 000 m³ ice

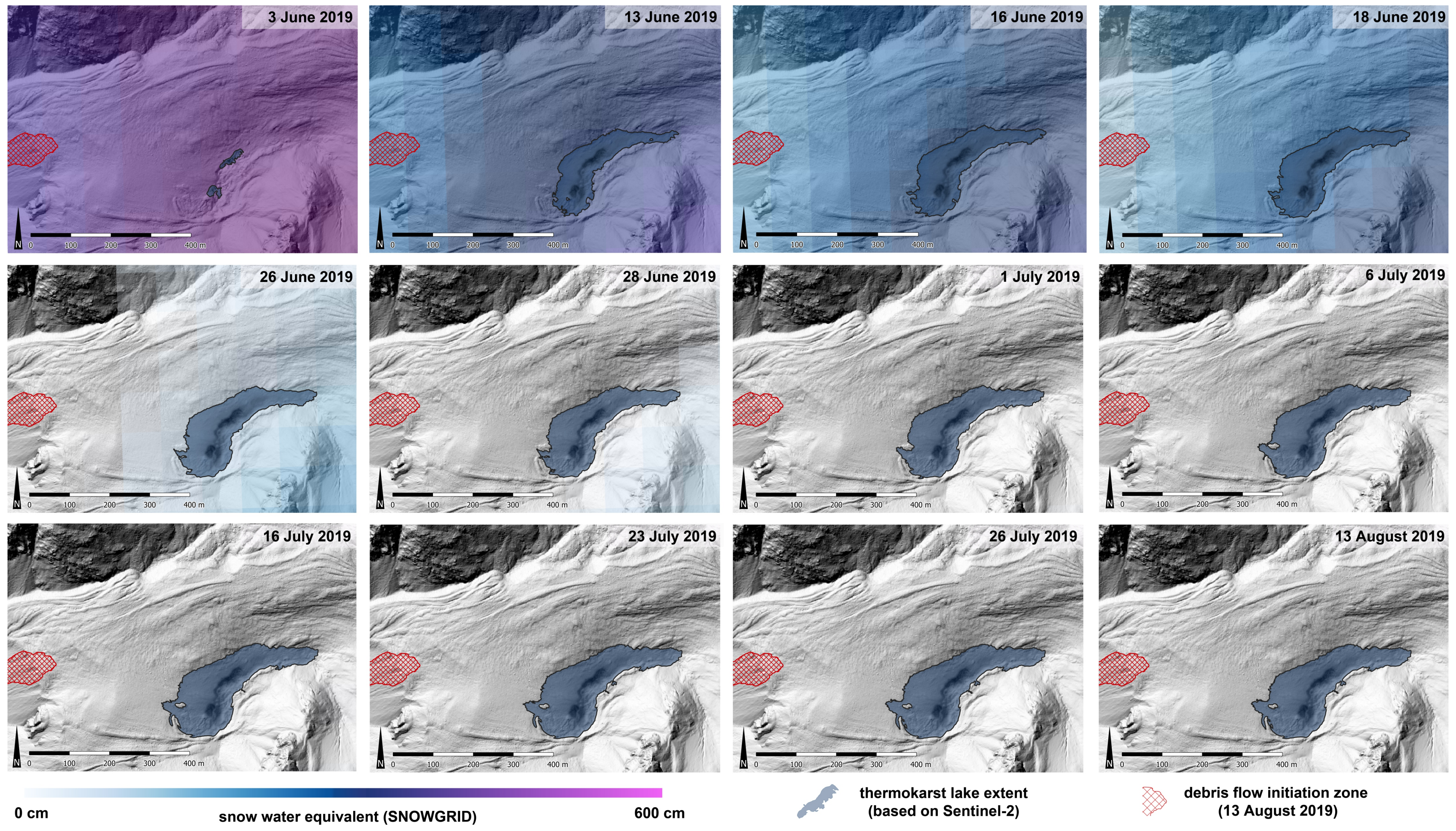
Figure 5. Thermokarst lake development in terms of lake water volume (blue) and total energy input (red). Note that the lake water volume (as inferred from the lake surface area) stayed constant after the beginning of July, while the energy input was considerable therafter, suggesting that extensive ice melt occured beneath the surface during July and early August.



Thermokarst evolution: New insights

- The energy provided by the thermokarst lake strikingly exceeded the melting energy necessary to melt the channel network connecting the lake to the rock glacier front (debris flow initiation zone)
- The establishment of the thermokarst lake and its drainage channel system was possible within 10 weeks, challenging monitoring and prediction of such potentially hazardous thermokarst developments in permafrost-affected terrain
- Once established, these channel systems are capable of transporting large amounts of water within a short time, threatening slope stability and downstream areas by lake outburst floods.

Figure 4. Thermokarst lake development between 3 June 2019 (thermokarst lake first time identifiable in satellite data) and 13 August 2019 (lake drainage and debris flow initiation at the rock glacier front). The lake started to develop during a period of intense snowmelt, visualized employing SNOWGRID (Olefs et al., 2013). The lake water volume was inferred by mapping the thermokarst lake surface on the latest available digital elevation model (provided by the Government of Tyrol, 2018), and calculating the volume between rock glacier surface and lake water surface. The thermokarst lake reached a maximum extent of 37 000 m² and a maximum water depth of 4.5 m (averaged across the lake), promoting thermally driven convection of water by its shallow bathymetry (Figure 3). Since the digital elevation model was collected prior to lake development and debris flow initiation, the drainage channel system connecting lake and debris flow initiation zone (Figure 1b, 1d) does not exist yet. Data: Government of the Province of Tyrol.



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An associated manuscript was submitted to Natural Hazards and Earth System Sciences (NHESS) and is currently under review (Kainz, S., Wagner, T., Krainer, K., Avian, M., Olefs, M., Haslinger, K., and Winkler, G.: The role of thermokarst evolution in debris flow initiation (Hüttekar Rock Glacier, Austrian Alps)). A preprint is available at EGUsphere (https://egusphere.copernicus.org/preprints/2022/egusphere-2022-567).

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