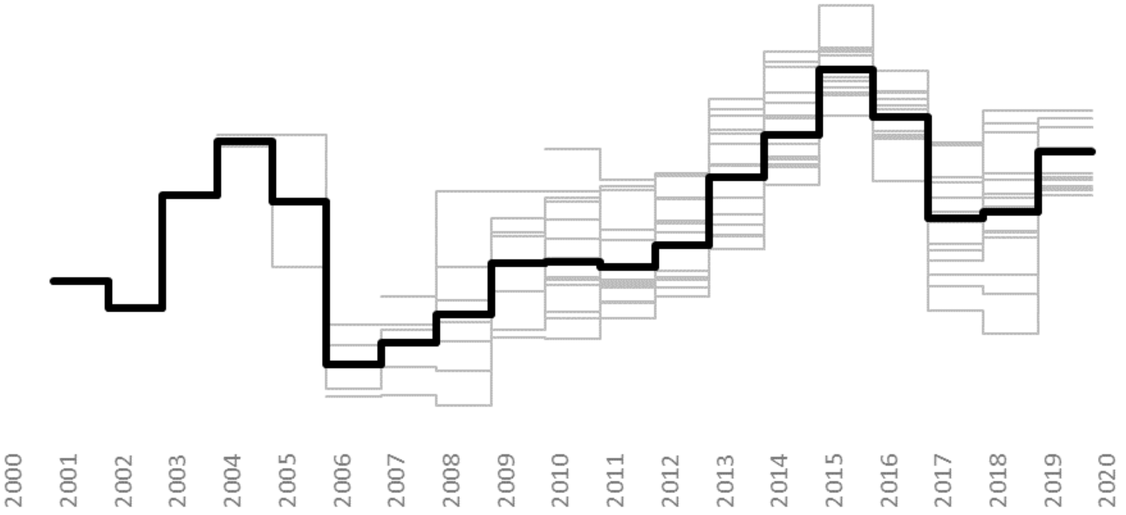
IPA Action Group Rock glacier inventories and kinematics

Rock Glacier Kinematics as an associated parameter of ECV Permafrost

Baseline concepts

(Version 3.0)



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Authors and contributions

The document has been edited by Chloé Barboux, Reynald Delaloye and Cécile Pellet (University of Fribourg, Switzerland) with the contribution of the participants at the workshop held in Fribourg (Switzerland) on 11-13 February 2020 as well as further members of the Action Group.

The purpose of this document is to serve as a baseline for the establishment of practical guidelines permitting the standardized generation of rock glacier kinematic time series in a climate-oriented context as a product of the GCOS Essential Climate Variable Permafrost.

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Updated versions including the renewed approval list and possibly very small changes and edits could be released at any time during the lifetime of the Action Group and renamed by adding a third digit in the versioning (e.g. 3.0.x). The last version will always be the one hosted on the Action Group website. There will be no specific information sent to the Action Group subscribers.

If minor content changes appear to be necessary, they will be adopted by the dedicated committee named in Evolène in September 2019, including Leif Anderson (Germany), Xavier Bodin (France), Reynald Delaloye (Switzerland), Isabelle Gärtner-Roer (Switzerland), Cécile Pellet (Switzerland), Line Rouyet (Norway) and Philippe Schoeneich (France). The second digit of the versioning will be changed (3.x) and an information will be sent to the Action Group subscribers.

If major changes are required, a thorough revision of the document must be undertaken, and the community will be questioned.

How to cite

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Acronym

RGK_BCv3

Contents

Preamble

Task 2 of the IPA (International Permafrost Association) Action Group *Rock glacier inventories and kinematics* (2018-2023) aims at **generating rock glacier kinematic time series in a climate-oriented perspective.** Specifically, this refers to the contribution of baseline data of long-term rock glacier velocity evolution to a potential new product of the GCOS Essential Climate Variable (ECV) Permafrost. The present document intends to set the **necessary concepts** for standardizing the production of homogeneous rock glacier kinematic time series in this context. It does not constitute a literature review of rock glacier kinematics at any particular time.

The document content results from the preparatory work performed by the scientific committee of the Action Group Workshop II (version 1.0), comments received on this work until 2 February 2020, following discussions with the participants to the workshop held in Fribourg (Switzerland) on 11-13 February 2020, comments from the participants to the version 2.0 and comments from the IPA AG members to the version 2.1.

In a preliminary step in December 2019, Rock Glacier Kinematics (RGK) was proposed via GTN-P as a new product associated to the GCOS ECV Permafrost for the next GCOS Implementation Plan (IP). With the support of the participants to Workshop II, a revised RGK proposition has been submitted to GCOS by the IPA Action Group in March 2020 in the framework of the GCOS IP public consultation. The proposition specifies that the present document must be considered as the reference for the development of RGK as an ECV Permafrost product.

Provisional timeline

The current document is the final version and is submitted for approbation until 31 December 2021.

Practical guidelines regarding the implementation of rock glacier kinematics (RGK) as an ECV Permafrost product based on the present version of the baseline concepts will be developed at a later stage. A number of technical aspects will be integrated and further detailed in these practical guidelines.

1. Purpose of associating Rock Glacier Kinematics to ECV Permafrost

On the global scale, the evolution of mountain permafrost is mainly observed by temperature monitoring in boreholes, which is the only direct observation method. However, long-term maintenance is particularly challenging, and the observations are limited to single locations that are scarcely distributed around the world. Thus, a large majority of mountain periglacial areas is lacking permafrost monitoring data, and the response of mountain permafrost to ongoing climate change is hardly known in most regions on Earth.

Rock glaciers are characteristic debris landforms associated with mountain periglacial landscapes and results from the former or current creep of perennially frozen ground (permafrost) [1] (cf. *Baseline concepts for inventorying rock glaciers*). Due to ice segregation and the formation of ice in excess of the pore volume through freezing processes, which induces cohesion and reduces internal friction, the material contained in a rock glacier is flowing and shows coherent flow fields. Rock glacier landforms are the result of this cumulative deformation over long term. Monitoring rock glacier kinematics concerns the observation of the surface expression of viscous flow of ice-rich perennially frozen ground and its variability with time.

Since early 2000s, there is a growing interest from the international community in the monitoring of rock glacier kinematics. An increasing number of studies are quantifying and/or monitoring the kinematic behavior of rock glaciers, contributing to a better understanding of their motion mechanisms and reaction to climate change. In particular, observations show that many rock glaciers within a specific region have a similar interannual to longer term evolution of surface displacement rates, which strongly depends on ground temperature changes. The monitoring of changes in rock glacier kinematics thus provides information about the impact of climate change on creeping mountain permafrost and, indirectly, on its thermal state.

Developments in remote sensing technologies and the increasing emergence of open-access and high-resolution satellite data facilitate the set-up of large-scale rock glacier surveys and enable the computation of kinematic time series worldwide. The consistent availability and exploitation of the multitude of remotely sensed and in situ kinematic measurements would contribute to the identification of specific regional or common global patterns related to the evolution of mountain permafrost all over the world.

The present document is paving the way for the standardized production of time series, which will constitute the new **Rock Glacier Kinematics (RGK)** product associated to the GCOS ECV Permafrost in addition to the Thermal State of Permafrost and the Active Layer Thickness already monitored within the Global Terrestrial Network on Permafrost (GTN-P).

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[1] Rock glacier (or permafrost) creep has to be understood in this document as a generic term referring to the variable combination of both internal deformation within the crystalline structure of the frozen ground (creep stricto sensu) and shearing in one or several discrete layers at depth.

2. Monitoring rock glacier kinematics

Scientific motivations for monitoring rock glacier kinematics are diverse, ranging from process understanding to climate impact assessment, sediment transfer budgeting, geohazard management and mass balance studies (ice storage evolution). The RGK product specifically focuses on the generation of **rock glacier kinematic time series in a climate-oriented perspective**. Rock glacier **kinematics** is defined here as the quantification of the surface movement of a landform recognized as a rock glacier (cf. *Baseline concepts for inventorying rock glaciers*). In the RGK context, only rock glaciers **whose motion mechanism is dominantly related to permafrost creep**[1] are considered.

The following sections present important aspects related to rock glacier monitoring. Insights into temporal and spatial variabilities of rock glacier kinematic behavior and monitoring techniques are provided. In conclusion, general considerations to ensure the homogeneity, consistency and accuracy of monitored data are proposed.

2.1 Temporal variability of rock glacier kinematics

The velocity of a rock glacier primarily depends on driving factors like internal structure, landform geometry, topography, geology, lithology and debris loading, which are often constant or changing very slowly (excluding glacier connected rock glaciers). The temporal evolution of the velocity depends in particular on shifts in ground temperature between the permafrost table and the main shearing horizon, which are constrained by the evolution of the ground surface temperature and impact the rheological and hydrological properties of the frozen ground. The closer to 0°C that the permafrost temperature is rising, the faster the rock glacier is moving. Hydrological processes related to water infiltration (e.g. changing water content and pore pressure during snow melt or rain periods), which interact with the internal structure of the rock glacier, can also play a significant role in rock glacier kinematic behavior.

Three superimposed types of temporal variability in rock glacier kinematics must be considered:

- **Multi-decennial trend**

  The multi-decennial behavior (change over several decades) of rock glacier velocities reflects **the impact of climate change** and responds **regionally almost synchronously** to changes in permafrost temperatures. A velocity increase by a factor 2 to 10 has been reported for the last decades from various rock glaciers in different regions on Earth. Rock glaciers connected to glaciers appear to have a specific evolution that differ from rock glaciers connected to other types of upslope unit[2].

- **Interannual variation**

  Variations of rock glacier surface velocities are also observed at an interannual scale. Such variations can be large and exceed +/- 50% of the value of the previous year. However, they appear to occur simultaneously and **proportionally** for many rock glaciers within a region, independent of the activity rate and morphological characteristics. The interannual variations are likely **controlled by changes in ground temperature, which are mainly driven by annually fluctuating snow cover insulation as well as air temperature**.

- **Seasonal rhythm**

  Rock glaciers usually exhibit a **repetitive landform-specific intra-annual behavior** (annual cyclic pattern). Highest velocities are mostly reached after the warm season or in some cases already

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[2] cf. part 3.c *Baseline concepts for inventorying rock glaciers*

during the snow melt period, whereas a decreasing trend occurs throughout the freezing season[3]. The amplitude (min-to-max ratio) of the seasonal variations is extremely diverse, ranging almost from 1:1.1 to 1:10. In comparison to the annual mean velocity, both the landform-specific pattern and relative amplitude have shown to remain almost constant at a decennial time scale in most documented cases.

Behaviors diverging from the three variabilities mentioned above also occur and are not necessarily associated with a direct climate impact on the rock glacier permafrost creep:

- Rock glacier velocity evolutions deviating from the common multi-decennial regional trend are observed. This results in particular from significant changes in the rheology and internal structure of the rock glacier (including ice and water content), in its geometry and interaction with subjacent topography, or in debris loading (including interaction/connection to an eventual glacier). This suggests that the rock glacier is typically degrading (i.e. continuously decelerating) or destabilizing (i.e. excessively accelerating).
- Short term acceleration (of some hours to some weeks) can be observed at the surface of a rock glacier. This reflects either an actual motion related to permafrost creep (daily variation), or specific movements in the active layer (i.e. block sliding/tilting, etc.). This behavior is usually consecutive to a significant input of water in the ground by snow melt or rain.

2.2 Spatial variability of rock glacier kinematics

The displacements monitored at the surface of a rock glacier unit[4] build up a coherent flow field due to the motion mechanism of permafrost creep, which is primarily taking place at large depths. This flow field often displays a certain degree of spatial heterogeneity, depending on landform-related (e.g. internal structure) and topographical settings. For instance, the terminal part (front), the lateral margins and the rooting zone can be slower than the central part of the rock glacier. The relative velocity changes (i.e. acceleration/deceleration rate in relation to a reference period), however, are usually much more spatially homogeneous.

Various processes, which are not clearly related to permafrost creep, can alter the spatial homogeneity of the flow field (e.g. ice melt induced subsidence, movement of isolated boulders).

2.3 Monitoring techniques for rock glacier kinematics

The term "technique" here refers to available technologies able to provide kinematic measurements over rock glaciers including the specificities of the sensor, platform and algorithm used for data processing.

Surface velocities are measured/computed[5] either from in-situ surveys (e.g. repeated GNSS field campaigns, permanent GNSS stations) or remote sensing-based approaches (e.g. InSAR, satellite-/air-/UAV-borne photogrammetry). The characteristics of selected available technologies able to provide surface velocity measurements over rock glaciers are listed in the following non-exhaustive table (Tab 1). The time resolution of each technique (not specified in Table 1) depends principally on operational specificities (e.g. cost, workforce) and data availability (e.g. satellite return frequency).

Depending on the site-specific constraints (e.g. topography, location, vegetation, velocity range, geology, lithology) not all techniques are suitable.

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[3] Exceptions may arise where thermally contrasted seasons do not occur (i.e. tropical regions)

[4] cf. part 3.b *Baseline concepts for inventorying rock glaciers*

[5] "Measured" refers to data collected using a dedicated technique whereas "computed" refers to data obtained by a spatial and/or temporal aggregation of measurements.

Table 1: Characteristics of available technologies able to provide kinematic time series over rock glaciers.

	In situ		**Close-range remote sensing**			
	Total station	**GNSS**	**Terrestrial laser scanning**	**Terrestrial photogrammetry**	**Terrestrial radar interferometry**	**UAV-borne photogrammetry**
Platform, tool, method	Terrestrial: on site	Terrestrial: on site	Terrestrial: ground base close to site	Terrestrial: ground base close to site	Terrestrial: ground base close to site	Remote: drone
Measurement footprint	Local	Local	Local	Local	Local	Local
Measurement resolution	Single point(s) based measurement	Single point(s) based measurement	Area based, cm	Area based, cm	Area based, m @ 1km	Area based, cm
User dependent parameter	Positioning	Positioning	Positioning and distance from the object	Positioning and distance from the object	Positioning and distance from the object	Distance from the object
Image information	Not applicable	Not applicable	Referenced images, point cloud coloring	Multiband image information	Radar image	Multiband image information
Natural radiation	Independent	Independent	Independent	Dependent	Independent	Dependent
Measurement constraints (non-exhaustive)	Clear line of sight	Satellite shadowing	Data gaps due to surface shadowing	Shadowing in steep terrain	Data gaps due to surface shadowing	Shadowing in steep terrain
Data value and dimension	Direct 3D point coordinates of a single point	Direct 3D point coordinates of a single point	Direct 3D coordinate of random surface points	Indirect 3D coordinate of random surface points	Direct 1D distance in the LOS	Indirect 3D coordinate of random surface points
Geometric reference[6]	Lagrangian	Lagrangian	Lagrangian or Eulerian	Lagrangian or Eulerian	Eulerian	Lagrangian or Eulerian
Dimensionality (value provided by motion analysis)	3D coordinate differences (Displacement of an object)	3D coordinate differences (Displacement of an object)	2.5D-3D coordinate differences (horizontal shift of a surface patch & Dz at defined location in CS)	2.5D-3D coordinate differences (horizontal shift of a surface patch & Dz at defined location in CS)	Direct 1D coordinate differences in line of sight	2.5D-3D coordinate differences (horizontal shift of a surface patch & Dz at defined location in CS)
Accuracy (between 2 measurements)	cm	cm	cm	cm	mm	cm-dm

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[6] *The observation of the surface velocity can be performed according to two geometric reference frames:*

- *In the Lagrangian specification of the flow field, the trajectory of one or more specific points is recorded by following their positions moving with the flow (e.g GNSS). The velocity is calculated from the changing position of a point over time. Velocity values attributed to a rock glacier unit or defined area result from an aggregation in the case of several points. The number of specific points used for the aggregation refers to the spatial resolution (see section 3.3).*
- *In the Eulerian specification of the flow field, the surface velocity values are computed for locations or areas, whose coordinates are fixed in space (e.g. InSAR). The mesh (number of aggregated points) to derive a velocity value attributed to a rock glacier unit or defined area refers to the spatial resolution (see section 3.3).*

	Remote sensing				
	Airborne laser scanning	**Airborne photogrammetry**	**Spaceborne photogrammetry**	**Spaceborne SAR interferometry**	**Spaceborne SAR offset tracking**
Platform, tool, method	Remote: plane/helicopter	Remote: plane	Remote: satellite	Remote: satellite	Remote: satellite
Measurement footprint	Local to regional	Local to regional	Regional to global	Regional to global	Regional to global
Measurement resolution	Area based, dm	Area based, cm	Area based, cm	Area based, m	Area based, m
User dependent parameter	no	no	no	no	no
Image information	Referenced image, point cloud coloring	Multiband image information	Multiband image information	Radar image	Radar image
Natural radiation	Independent	Dependent	Dependent	Independent	Independent
Measurement constraints (non-exhaustive)	Shadowing in steep terrain	Shadowing in steep terrain	Shadowing in steep terrain	Layover & shadow	Layover & shadow effect
Measurement value and dimension	Direct 3D coordinate of random surface points	Indirect 3D coordinate of random surface points	Indirect 3D coordinate of random surface points	Direct 1D change of distance in the LOS	Indirect 2D coordinate of random surface points
Geometric reference	Lagrangian or Eulerian	Lagrangian or Eulerian	Lagrangian or Eulerian	Eulerian	Eulerian
Dimensionality (value provided by motion analysis)	2.5D-3D coordinate differences (horizontal shift of a surface patch & Dz at defined location in CS)	2.5D-3D coordinate differences (horizontal shift of a surface patch & Dz at defined location in CS)	2.5D-3D coordinate differences (horizontal shift of a surface patch & Dz at defined location in CS)	Direct 1D coordinate differences in line of sight, potentially 3D by combining both ascending and descending modes	2D coordinate differences (slant-range and azimuth)
Accuracy (between 2 measurements)	dm	cm-m	dm-m	mm-cm	dm-m

2.4 General considerations for monitoring rock glacier kinematics in a climate-oriented perspective

To collect climate-oriented long-term time series with sufficient homogeneity, consistency and accuracy, the following principles must be considered:

- **Rock glacier characteristics**

Rock glacier characteristics must be described according to the inventorying baseline concepts[7]

In particular, the spatial connection to the upslope unit (e.g. connected to a glacier or not) leads to a specific evolution of rock glacier velocities and has to be documented.

- **Timescale**

Rock glacier kinematic time series must be measured/computed over a long-term period.

To ensure the relevance of rock glacier kinematics as climate indicator, time series must be recorded in a consistent way over a long-term period.

Rock glacier kinematic time series should be measured/computed annually.

Given the relation between changes in climate and the multi-decennial and interannual variations in rock glacier kinematics, the optimal frequency of observation for climate-oriented time-series is one year.

Computing annual kinematic time series minimizes the contribution of seasonally dependent processes and short-term variations on the velocity changes, while the repetitiveness of the intra-annual behavior over time allows the exploitation of sub-annual observations. For intra-annual observations, the considered period must remain approximately the same every year and must be long enough to prevent short term (i.e. non-repetitive) variations from influencing the velocity changes (see part 3.4).

- **Spatiality**

Rock glacier kinematic time series must refer to a consistent flow field representing the downslope movement of a rock glacier unit or a representative part of it.

Considered surface displacements should represent the downslope movement of the rock glacier related to permafrost creep and should not be significantly altered by local disturbing processes (e.g. movement of isolated boulders, ice melt induced subsidence). Areas affected by such local processes should be avoided for the measurement/computation of the time series. Moreover, rock glacier monitoring strategies must account for the spatially heterogeneous kinematic behavior within a unit and be adapted accordingly.

- **Technique**

The chosen technique must be suitable to reflect changes in rock glacier velocity.

Depending on the order of magnitude of observed velocities, some techniques are more appropriate than others. Each technique yields specific uncertainties and can potentially lead to bias in surface velocity measurements in the long term, which must be carefully considered.

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[7] cf. part 3 *Baseline concepts for inventorying rock glaciers*

Relative changes in rock glacier velocity are expected to be technology-independent.

Technique characteristics determine the dimensionality (see Table 1) of the observations and hence of the measured/computed absolute velocity values. Despite specific dimensionality, the relative changes computed from rock glacier kinematic time series are expected to be technology-independent.

3. Rock Glacier Kinematics (RGK)

The following section defines the baseline concepts of RGK and their related characteristics.

3.1 Technical definition of RGK

Rock glacier kinematics (RGK) are defined as a **time series of kinematic data measured/computed**[4] **on a rock glacier unit or a representative part of it**[3]**, with an annual or interannual frequency**. It refers to observed surface velocities related to permafrost creep. The annual values of surface velocity, which build up a times series, constitute the **kinematic data**.

3.2 Kinematic data

The **kinematic data** is defined as an **annualized surface velocity**. It refers to the effective displacement rate over a year or during a shorter period (see 3.3).

The kinematic data is measured/computed as far as possible **each year**, following a **methodology** that **must be precisely documented and remain consistent over time**.

3.3 Temporal resolution

The kinematic data is strictly stamped with a frequency and an observation time window:

- The ***frequency*** defines the periodicity of the kinematic data, which ideally is **annual or** else **interannual**.
- The ***observation time window*** defines the measurement time span that is the period during which the velocity value is measured/computed. It should be **as constant as possible in time** (the data acquisition must always be performed at almost the same date/period of the year) and **long enough to avoid being altered by short-term variations** (see section 2.1).

An optimal observation time window is 1 year. However, depending on the methodology used, the kinematic data might only be obtained within an observation time window longer or shorter than a year, which also impacts the frequency:

- *Observation time window > 1 year*. In this case, the frequency is limited by a large observation time window and thus *frequency = observation time window*. The largest recommended frequency is 2-5 years (common periodicity for aerial image coverage that can be adapted according to regional/national specificities), but longer intervals are accepted for optical images, as well as for reconstructions from archives.
- *Observation time window < 1 year* (e.g. InSAR data: computing an annual displacement from summer interferograms). In this case, the frequency is set to 1 year. In order to avoid reporting short-term variations (see section 2.1), the observation time window covered by the measurements should not be shorter than 1 month (it can be obtained by an aggregation of several shorter time observation windows). The observed velocity is not annual or interannual, but seasonal or sub-seasonal. The observation is, however, repeated annually (frequency) at the same time of the year. Continuous measurements over a season or year must be averaged to provide an annual frequency.

3.4 Spatial resolution

The **spatial resolution** is defined as **the (set of) measurement point(s) or the measurement area(s)** used to measure/compute each kinematic data of the RGK.

The spatial resolution has to be chosen in order to characterize a consistent flow field **related to the surface velocity of the rock glacier unit or a part of it** (i.e. must be located within a recognized moving area[8]). It must be **consistent over time**.

In case of a high degree of spatial heterogeneity of surface displacement over a rock glacier unit (i.e. several recognized moving areas for the same unit), several RGK can be measured/computed separately for the same rock glacier unit.

RGK must be measured/computed separately for different rock glacier units.

3.5 RGK quality

The quality of the RGK can be described by the **relative error of the kinematic data** and the **consistency of the kinematic time series**.

a) Relative error

The **relative error of the kinematic data** is defined as the ratio:

- of the absolute error of a measurement, which depends on the technique and the effective observation time window,
- to the absolute value measured/computed over the same observation time window.

The relative error is expressed as a percentage and has no units. It must be **specified for each kinematic data** of the RGK.

A relative error of maximum **20%** is allowed. However, to produce a reliable analysis of long-term temporal changes in rock glacier kinematics, the smallest possible relative error should be obtained. Thus, the technique must be chosen in accordance with the absolute value measured/computed on the observed rock glacier.

b) Consistency

The **consistency of the kinematic time series** is defined as the coherence of the time series over time. It depends on the coherence over time of the monitoring technique and the monitored surface:

- The *monitoring technique* can be affected by e.g. changes in the measurement technique, sensor drift and weaknesses of the aggregation method.
- The *monitored surface* can be affected by e.g. changes of the observed rock glacier surface geometry, deviation from the expected rock glacier flow/creep model and false measurements caused for instance by landslides, rock fall or local rotations.

The consistency of the kinematic time series must be **evaluated for each addition of new kinematic data** and must be **ensured over time.**

The **technique** used to measure/compute the kinematic data and compile RGK **must be as constant as possible over time**. A change in the measurement technique is only allowed when overlapping data still ensures the consistency of the datasets. However, this remains a last resort and merging heterogeneous multi-sensor datasets is not advised.

If any major changes of the observed surface are detected, the time series must be stopped or adjusted accordingly.

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[8] see definition 2.3.1 in *Kinematics as an optional attribute of standardized rock glacier inventories*