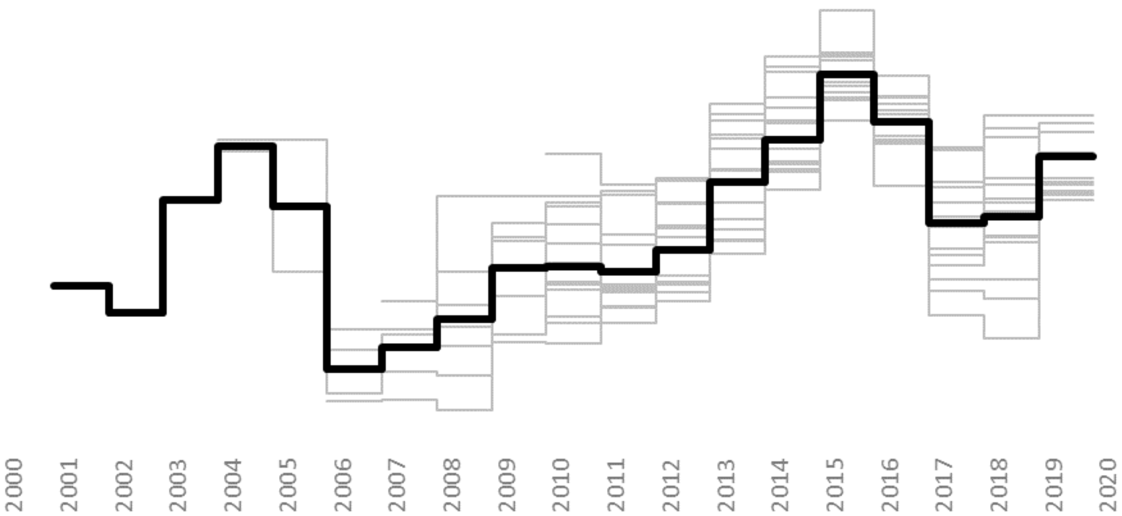
IPA Action Group Rock glacier inventories and kinematics

Rock Glacier Kinematics as an associated parameter of ECV Permafrost

(Version 2.1)



https://www3.unifr.ch/geo/geomorphology/en/research/ipa-action-group-rock-glacier (Action Group website)

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Authors and contributions

The document has been edited by the scientific committee of the Action Group Workshop II held in Fribourg (Switzerland) on 11-13 February 2020, namely and in alphabetical order Chloé Barboux (University of Fribourg, Switzerland), Aldo Bertone (University of Fribourg, Switzerland), Xavier Bodin (CNRS, France), Reynald Delaloye (University of Fribourg, Switzerland), Cécile Pellet (University of Fribourg), Line Rouyet (NORCE, Norway) and Tazio Strozzi (Gamma Remote Sensing, Switzerland).

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The purpose of this document is to serve as 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.

How to cite

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Acronym

RGK_BCv2.1

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,** meaning baseline data of long-term rock glacier velocity evolution contributing 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: a preparatory work performed by the scientific committee of the Action Group Workshop II (version 1.0); comments received on it until 2 February 2020; following discussions with the participants to the workshop held in Fribourg (Switzerland) on 11-13 February 2020; and comments from the participants to the version 2.0.

In a preliminary step in December 2019, Rock Glacier Kinematics (RGK) was proposed via GTN-P as a new associated product to the GCOS ECV Permafrost for the next GCOS Implementation Plan (IP). With the support of the participants to the 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

Feedbacks on the present document (**version 2.1**) are expected from the Action Group members until end of August 2021, using exclusively the dedicated boxes inserted at the end of each section.

A final version (3.0) is intended to be submitted for approbation by the Action Group members end of September 2021.

Practical guidelines regarding the implementation of rock glacier kinematics (RGK) as an ECV Permafrost product will be developed at a later stage.

If you have any comment about the previous section, please use this box.

Comment box 0

1. Purpose of associating Rock Glacier Kinematics to ECV Permafrost

On a global scale, the evolution of mountain permafrost is scarcely observed by temperature monitoring in boreholes, whose long-term maintenance is particularly challenging. A large majority of mountain periglacial areas is thus lacking permafrost monitoring data. Therefore, 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 permafrost creep[1] (cf. *Baseline concepts for inventorying rock glaciers*). Since early 2000s, there is a growing interest from the international community in monitoring of rock glacier velocity (hereafter referred to as kinematics). An increasing number of studies have quantified and/or monitored the kinematic behavior of rock glaciers contributing to better understand their motion mechanism and reaction to climate change. Observations show in particular that the evolution of surface displacement rates of many rock glaciers within a region is proportional to the interannual to pluridecennial changes in ground surface temperature. The long-term 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. Making available and exploiting in a consistent way the multitude of remotely sensed and in situ kinematic measurements would contribute to identify specific regional patterns or common global ones 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).

If you have any comment about the previous section, please use this box.

Comment box 1

[1] Rock glacier (or permafrost) creep has to be understood here 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 or 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**[2] 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, stability and accuracy of monitored data are proposed.

If you have any comment about the previous section, please use this box.

Comment box 2.0

2.1 Temporal variability of rock glacier kinematics

The velocity of a rock glacier depends primarily on driving factors like internal structure, landform geometry, topography and debris loading, which are often constant or almost insensitively changing over decades (glacier connected rock glaciers aside). 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 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), interacting 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:

- **Pluridecennial trend**

  The pluridecennial behavior of rock glacier velocities reflects **the impact of climate** and responds **sensitively and 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 appears to have a specific evolution.

- **Interannual variation**

[2] Rock glacier (or permafrost) creep has to be understood here 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.

Variations of rock glacier surface velocities are also observed at interannual scale. They can be large and exceed +/- 50% of the value of the previous year. However, they appear to occur simultaneously and **in a similar proportion** for many rock glaciers within a region whatever their activity rate and morphological characteristics. The interannual variations are likely **driven by annually fluctuating snow cover height and timing, precipitation rates and air temperature**.

- **Seasonal rhythm**

Rock glaciers exhibit usually a **repetitive landform-specific intra-annual behavior** (cyclic pattern). At middle and high latitudes, highest velocities are mostly reached after the warm season or in some cases already during the snow melt period, whereas a decreasing trend is occurring throughout the freezing season. The amplitude (min-to-max ratio) of the seasonal variations is extremely diverse, ranging almost from 1:1.1 to 1:10. Both landform-specific pattern and relative amplitude in comparison to the annual mean velocity have shown to remain almost constant at a decennial time scale in most documented cases.

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

- Rock glacier velocity evolutions deviating from the common pluridecennial regional trend are observed. They result 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). They suggest 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. They reflect either an actual motion related to permafrost creep (daily variation), or specific movements in the active layer (i.e. bloc sliding/tilting, etc.). They are usually consecutive to a significant input of water in the ground by snow melt or rain.

If you have any comment about the previous section, please use this box.

Comment box 2.1

2.2 Spatial variability of rock glacier kinematics

The displacements monitored at the surface of a rock glacier unit[3] generally build up a consistent flow field due to the motion mechanism of permafrost creep, which is primarily taking place at large depth. 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), lateral margins and rooting zone can be slower than the central part. However, the relative velocity changes (i.e. acceleration/deceleration rate in relation to a reference period) 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).

If you have any comment about the previous section, please use this box.

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

Comment box 2.2

2.3 Monitoring techniques for rock glacier kinematics

The term ”technique” refers here 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[4] 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 available technologies able to provide surface velocities measurements over rock glaciers are given in Tab. 1. The time resolution of each technique (not specified in Table 1) depends principally on operational specificities (e.g. cost, manpower) and data availability (e.g. satellite return frequency).

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

[4] 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
Spatial coverage	Local	Local	Local	Local	Local	Local
Spatial resolution	Single point(s) based measurement	Single point(s) based measurement	Area based, cm	Area based, cm	Area based, m @ 1km	Area based, cm
Parameter dependence to user	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 available	Not available	Referenced images, point cloud coloring	Multiband image information	Radar image	Multiband image information
Natural radiation	Independent	Independent	Independent	Dependent	Independent	Dependent
Shadow effect	-	Satellite shadowing	Data gaps due to surface shadowing	In steep terrain	Data gaps due to surface 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[5]	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

[5] *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 are resulting of an aggregation in 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
Spatial coverage	Local to regional	Local to regional	Regional to global	Regional to global	Regional to global
Spatial resolution	Area based, dm	Area based, cm	Area based, cm	Area based, m	Area based, m
Parameter dependence to user	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
Shadow effect	In steep terrain	In steep terrain	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	2D coordinate differences (slant-range and azimuth)
Accuracy **(between 2 measurements)**	dm	cm-m	dm-m	mm-cm	dm-m

If you have any comment about the previous section, please use this box.

Comment box 2.3

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

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

- **Rock glacier characteristics**

Rock glaciers characteristics must be described according to the inventorying baseline concepts[6]

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

- **Timescale**

Rock glacier kinematic time series must be recorded over long term.

Only time series recorded in a consistent way for several decades or in the perspective of being so are suited to be used as climate indicator.

Rock glacier kinematic time series should be recorded with an annual frequency.

Given the relation between the climate and the pluridecennial 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. The repetitiveness of the intra-annual behavior over time allows the exploitation of sub-annual observations. For seasonal and sub-seasonal observation frequency the considered period must remain approximately the same every year and must be long enough to prevent short term (i.e. non repetitive) variations to alter 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 boulder, ice melt induced subsidence). Areas affected by such local disturbing 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**

Rock glacier kinematic time series must be technology independent.

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

Technique characteristics determines the dimensionality (see Tab 1) of the observations and hence of the measured/computed absolute velocity values. Despite specific dimensionality, the relative changes in velocity are expected to be technology-independent.

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

Depending on the magnitude order of observed velocities, some techniques are more appropriate than others. Each technique leads to some uncertainty and eventually to bias in surface velocity measurements on the long term, which must be considered carefully (see part 3.5).

If you have any comment about the previous section, please use this box.

Comment box 2.4

3. Rock Glacier Kinematics (RGK)

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

3.1 Technical definition of RGK

Rock glacier kinematics (RGK) is defined as a **time series of kinematic data measured/computed**[7] **on a representative part of a single rock glacier unit, with an annual or pluriannual 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**.

If you have any comment about the previous section, please use this box.

Comment box 3.1

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 3.4)

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**.

If you have any comment about the previous section, please use this box.

Comment box 3.2

3.3 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. they 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, even in a unique rock glacier system.

If you have any comment about the previous section, please use this box.

Comment box 3.3

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

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

3.4 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 is optimally **annual or** eventually **pluriannual**.
- 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 be performed always 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 with observation time window longer or shorter than a year, which also impacts the frequency:

- *Observation time window > 1 year*. In that case, the frequency is limited by a large observation time window and *frequency = observation time window*. The largest recommended frequency is 2-5 years (common periodicity for aerial image coverages that can be adapted according to regional/national specificities), but longer intervals are admissible for optical images, as well as for reconstructions from archives.
- *Observation time window < 1 year*. In that case, the frequency is set to one 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 pluriannual, but seasonal or sub-seasonal. The observation is however repeated (frequency) annually at the same time of the year. Continuous measurements over a season or year must be averaged to provide an annual frequency.

If you have any comment about the previous section, please use this box.

Comment box 3.4

3.5 RGK uncertainties

RGK is characterized by two types of uncertainties: the **relative measurement uncertainty of the kinematic data** and the **instability of the time series**.

a) Relative measurement uncertainty

The **relative measurement uncertainty of the kinematic data** is defined as the uncertainty of the measurement expressed relatively to the magnitude of a particular kinematic data. It is the **ratio** between:

- the **measurement uncertainty expressed in m/y** calculated for the effective observation time window and depending on the specificities of the sensor/platform and the algorithm used in data processing,
- and the **velocity value expressed in m/y** measured/computed over the same observation time window.

The relative measurement uncertainty is expressed **in %** and must be **specified for each kinematic data** of the RGK.

A maximal relative measurement uncertainty of **20%** should allow for a reliable analysis of the long-term temporal changes in rock glacier behavior. If larger, more reliable values can be obtained by increasing the observation time window or by using a more appropriate and higher precision measurement technique.

b) Instability

The **instability of rock glacier kinematic time series** is defined as the deviation of measured/computed values (bias) on the long term.

The instability of RGK is principally caused by:

- ***secondary movement:*** Secondary movements are displacements of a permanent sensor platform (e.g. GNSS) which do not represent the large scale rock glacier creep (e.g. rotation of the boulder, measurement artifacts). Secondary movements cannot be estimated precisely since the causes are diverse and difficult to identify.
- ***change of the observed surface***: on the long term, any observed rock glacier surface is gradually changing and an instability of the time series can occur whatever the methodology used. In the case of Eulerian specification of the flow field, the location of the measurement area is constant over time whereas the creeping mass is moving (the observed surface of the rock glacier is changing). In the case of Lagrangian specification of the flow field, the location of the surveyed points is moving over time (the topographical context of the observed point is changing). Areas close to the margins of the moving mass can be critical and external events (e.g. rock fall, collapses, large avalanches) may also compromise the stability of the time series. The instability related to the change of the observed surface can be identified by observing morphological changes of the surface.
- ***methodological change***: technique and procedure used to measure/compute the kinematic data and compile RGK **must be as constant as possible over time**. The instability related to methodological changes can be estimated if time series acquired with the differing techniques overlap.

Whatever the cause, if an instability occurs and/or if any major changes are detected, the time series must be stopped or adjusted accordingly.

If you have any comment about the previous section, please use this box.

Comment box 3.5