Reply to referee 1

Review of “Time forecast of a break-off event from a hanging glacier”

by J. Faillettaz, M. Funk and M. Vagliasindi

This paper present a successful prediction 10 days in advance of a cold hanging glacier break-off that occurred in the south face of the Grande Jorasse (Mt Blanc area, Italy) on September 2014. The prediction is based on the high precision monitoring of glacier surface displacement on four different stakes over almost 3 years and until up to few hours prior to the break-off. The paper use the fact that the critical behaviours of the rupture processes can generally be described by a power law function of the time of failure for which an additional log-periodic signal is superimposed [Sornette and Sammis, 1995]. This behaviour have been observed in various domains [Sornette, 2002] and was first used in glaciology as way to describe hanging glacier rupture by Rothlisberger [1977] (power law) and by Luthi [2003] (log-periodic). Surface displacement measurement prior to rupture has been successfully reproduced using these relations in Pralong et al. [2005] and Failletaz et al. [2008]. The determination of the best fit parameters calibrated on surface velocities prior to rupture offer a way to predict the break off [Pralong et al. 2005; Failletaz et al., 2008]. This paper is another application of the same method to new data on another glacier.

Although the paper does not bring new insight about hanging glacier rupture, it shows the robustness of the failure prediction using surface displacement monitoring method [Failletaz et al., 2008] and confirms nicely the existence of the log-periodic oscillations before rupture. It also shows that using a threshold surface velocity for which the failure occur rather than using the critical time parameter lead to more precise prediction. The extrapolation of the surface velocity based on the best log periodic fit to the threshold velocity seems to give a very precise time estimation of the glacier rupture. The authors propose a value of this threshold velocity to define a highly probable time zone of break-off occurrence that can be determined about 10 days in advance.

I think the paper provide nice results and successful natural hazard prediction in Geo-science is something uncommon. The paper deserve therefore publication in The Cryosphere after substantial revision following the points addressed in general comments.

General Comments

• It remains unclear in the current paper how uncertainty on the data affect the inferred rupture time. I think the final result, which is the date of rupture, could be better defined by using a probabilistic approach. Here is what I suggest:

1. Define a probability density function for the threshold velocity, could be Gaussian, for example:

$P(V_T) \propto \exp(-0.5(V_T - V_{ref})^2/\sigma_{VT}^2)$

where V_T is the threshold velocity, V_{ref} is the most likely threshold velocity and σ_{VT} the confidence interval (or standard deviation). $P(V_T)$ could be also set to 1 if there is no preferential threshold velocity.

2. For a range of possible fixed threshold velocity (VT), calculate a density function of the rupture time for each VT from the misfit between measurement and model: each parameter set M=(tc, θ, s0, us a, C, D) is associated to one rupture time (TR) for a given VT and each parameter set (M) can be associated to one probability:

$$P(TR(M),VT\ ) \propto \exp(-0.5\ (sdata-smodel)Cm-1(sdata-smodel))$$

where sdata and smodel are respectively the measured and modelled surface displacement, Cm is the covariance matrix that describe data uncertainty.

3. A final probability density function for the rupture time can be estimated by:

$$P(TR) \propto \int V\ Tmin\ V\ Tmax\ P(TR(M),VT\ )\text{Ã—}P(VT\ )dV\ T$$

The calculation in real time of this probability density function could be a more nicer and rigorous way to estimate the rupture time by taking into account uncertainty on the data. This paper could be the opportunity of calculate the evolution of this function during time (as the measurement are getting closer to the break-off).

We agree that this paper should better address how uncertainty on the data affect the inferred rupture time, although this dataset is very accurate (1cm). However errors resulting from the fitting procedure are predominant. To illustrate this, we artificially added uniformly distributed random noise of different amplitude to our initial dataset, and performed the same fitting procedure. It appears that the error associated with fitting procedure is about one order of magnitude higher than those associated with data accuracy. (see new section 5.1)

As we are expecting to predict in near real time the occurrence of the break-off at a daily precision, such sophisticate analysis might not be relevant for our purpose.

• Because the paper do not really bring new insight about hanging glacier failure, I recommend to the authors to give, at least, a precise and clear methodology for predicting failure based on their expertise: Stakes emplacement ? How much stakes ? monitoring method ? Minimal resolution (time and space) for the displacement measurement ? Fit procedure ? Define a probability density function of the rupture time as the final result (see first general comment) ?

See new section 5.5

• I think the paper need some clarification about the choice of λ. Indeed, the logarithmic frequency can only be determined if the critical time is known (after the rupture occur) but the prediction of the failure need to fix a value for λ. I assume that it is possible to infer a value for λ without doing the Lomb periogram. λ seems also to be a universal value (set to 2d) [Failletaz et al., 2008], which is, by the way, confirmed in this paper. However, the authors show that the value of λ can be affected the geometrical change due to the first break-off (from λ=2 to λ=7.4, stake 2 and 13). So a discussion about the value of λ (constant for every glacier ?) and the sensitivity of the prediction to this parameter is needed.

Faillettaz et al. 2008 and the present study show that λ=2 for Weisshorn and Grandes Jorasses. Such a value has a physical explanation related to the dynamic interactions between newly developed micro-cracks. The appearance of other subharmonic frequencies before the last break-off is also discussed and possible physical explanation related to sudden geometry change was also found.

• As the authors claim their method as universal (P4938, lines 5-9), the transferability of the method to another glacier should be more discussed. Is the similar value of the threshold velocity (0.5 to 1 m/d) or λ (=2d) in several different studies could be link to the fact that all the three studied glaciers (Jorasse, Weisshorn, Monch) have similar geometry ? What could happen with totally different geometry ? Is the prediction method still valid ?

Cold hanging glaciers have alwaysa very similar geometry. This method was first developed and applied on Weisshorn and Monch and was shown to be a valuable tool for prediction purpose. For the first time, measurements could be performed up to the final break-off. Results confirm the appearance of logperiodic oscillations superimposed on the powerlaw acceleration, validating this prediction method.

Specific Comments

Abstract, line 5: this event was successfully ….

OK

P4927, lines 5 to 16 : Distinction between the two types of instabilities is not clear. I would speak first about temperate ice/bed interface (remove polythermal) and then about 'transition from cold to temperate ice/bed interface' rather than speak about 'partly temperate' ice/bed interface.

Fixed, see line 30-35

P4928, lines 16 to 23: Give more information about the glacier: accumulation rate, dimensions, temperature …

OK, see section 2.1

Figure 1 : Add a map that show the configuration of the valley bellow the glacier (topography, habitation, road, infrastructure ...), it would help to understand the context of this hazard. The limit where previous avalanches stopped could be also shown on this figure.

OK, see now Fig 1.

P4930, lines 3 to 14: What happen to the GPS measurement ?

See section 5.5

P4930, lines 23-24: Remove. (already say in next section).

OK

P4931, line 2: Which correction ? Maybe here a short description of the correction that have been done, even if already described in Faillettaz et al. [2008].

Ok see line 164-166

P4931, line 3: associated

OK

P4931: Point no 2: Be more precise about the geometry, which kind of geometry are the authors refer to ?

OK

P4931, line 20: replace fig 3 by fig 1 ?

OK, now Fig . 2

P4934, lines 5 to 7, the sentence sounds really unclear to me. Please reformulate.

OK see now lines 217-224

Figure 4 and 5: Unit is missing in the residual

Fixed

Figure 7: A grid would help to read the graph

OK

References

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Sornette, D., & Sammis, C. G. (1995). Complex critical exponents from renormalization group theory of earthquakes: Implications for earthquake predictions. Journal de Physique I, 5(5), 607-619.

Sornette, D. (2002). Predictability of catastrophic events: Material rupture, earthquakes, turbulence, financial crashes, and human birth. Proceedings of the National Academy of Sciences, 99(suppl 1), 2522-2529.

Reply to referee 2

This manuscript is a case study of a two-part failure of a portion of a hanging alpine glacier. Surface displacement measurements at several points on the glacier were recorded up to the time of failure. The displacement time series at two stakes was fit to two different power law relations, one with a superimposed log-periodic signal. The regression parameters from fitting these data are used to forecast the time of failure. The retrospective analysis indicates that the break off event could be forecast about 10 days in advance.

The manuscript reads as more of an engineering case study using existing methods rather than original scientific research. While it is undoubtedly useful and promising that the prediction of such a break off can be made well enough in advance to support an early warning system, I fail to see what research question or scientific hypothesis was addressed in the paper. The methods applied were all developed and published previously (indeed, the manuscript relies heavily on previous publications, to the point of lacking key details in some places). The manuscript could be bolstered by a more rigorous and quantitative analysis of the applied methods, especially when it comes to reporting uncertainties in the time forecast or a sensitivity analysis around some of the subjective choices made in the framework. Furthermore, some discussion or analysis of the physical implications of this framework–especially regarding the claims of “universal” behaviour–might add sufficient originality to warrant publication in The Cryosphere.

The reviewer is right when stating the methods applied in this study were all developed, but for the first time, we could gather data up to the break-off. Thanks to this dataset we could definitely confirm the presence of logperiodic behavior prior to break-off, enabling to forecast 10 days in advance the occurrence of the catastrophic event. Moreover, this dataset gave us the opportunity to validate previous conjectures on the physical processes during the onset of the instability.

General comments

1. The crevasse in the hanging glacier opened in autumn 2008, after which a monitoring system was set up. The break-off events occurred in autumn 2014. Can your analysis shed any insight on this 6-year time lag between the crevasse opening and the break off? What time lags have been observed for other events? Certainly the crevasse could be seen as a requisite precursor event for this type of break off, so there may be some important physical insight to be gleaned by thinking about this timescale as well, or the conditions that lead to this type of crevasse opening in the first place.

There are only few observations and monitoring of cold glacier break-off event. Pralong and Funk 2006 have observed a time lag of 2.5 years between the crevasse opening and the break-off event on the same glacier, with approximately similar geometry (see line 86). They also stated that the formation of the upper crevasse is related to the increase of the bedrock slope and not to the destabilization *process. Such a crevasse is therefore not necessarily observed on other cold ramp glaciers, which cling to a homogeneous face.*

2. More detail on methods is needed in a number of places. In fact, for a "methods" paper, there should probably be a Methods section to organize this material for the reader. For example, on p. 4931, what does "interpolated on a regular time step" mean? What is the time step? How sensitive are your regression results (and thus your time forecast for the break off) to your choice of data smoothing? A sensitivity analysis involving some of these choices could help to quantify the uncertainty in parameter values and thus forecast time, and would add some originality to the paper.

We modified the structure of the paper and added a new section (now section 3: "Previous findings on cold glacier break-off"). See also comments made to Reviewer 1.

3. Some more discussion and detail on the physics of damage accumulation would be welcome, especially if this case study supports the idea of damage accumulation at/near the base of the glacier as being the culprit in these break off events. For example, on p. 4927, line 22, this statement needs clarification or a reference: is it always the case that the failure occurs within a few meters above the bedrock? What evidence do you have for this? Are you discussing previous observations or model results (in which case a reference is needed) or your own original observations from this study? You mention this again on p. 4932, lines 1-2. Other than visually seeing ice left over after the break off rather than bedrock, how do you know the scale is a "few" meters? How does this align with other observations? If this is indeed related to the fundamental physics of damage accumulation, then this is very important! It would be helpful to discuss this in a bit more detail.

All the observations (Weisshorn 1973, Weisshorn 2005, Grandes Jorasses 1998 and Grandes Jorasses 2014) suggest that the final failure is not located at the bedrock but "few" meters above. Pralong and Funk 2006 (with the help of the model developed in Pralong et al 2006) noted that the position of the fracture over the bed is lower in the model than in nature, and associated this difference with bedrock irregularities (which are not considered in the model). We have added a discussion on damage evolution process lines 146-157.

4. You claim that the log-periodic relation (Eq. 2) fits the data better than the simpler power law relation (Eq. 1), but of course this is no surprise given that there are more free parameters in the log-periodic relation. Therefore comparing these two regression fits is not sufficient to justify that the log-periodic relation is more appropriate. You need to invoke some other physical evidence or line of reasoning here, especially if you want to conclude at the end of the manuscript that there is some "universality" for log-periodic behaviour (see related comment below).

Universality might not be the right term as it refers to constant critical exponents. However, we showed that such oscillating pattern is also confirmed in this break-off (with large amplitudes close to failure) and is to be common to all the observed break-off events. The complete understanding of the onset of the instability was already assess with surface displacement and seismic measurements (Faillettaz et al. 2011). We summarize the results lines 146-157.

5. Where do the 50 cm/day and 100 cm/day thresholds come from? How and why did you choose

these? You indicate that the time forecast is sensitive to the subjective choice of these parameters, so it seems that some more attention should be paid to why you chose these two values. Furthermore, why then do you recommend in the Discussion that 40 cm/day be used as a “conservative threshold”? Where did this number come from? Is this a subjective recommendation? It seems rather arbitrary when it is presented in the text. How much more conservative would a prediction be using this threshold? It might be helpful to describe this in more detail, and indicate such a prediction in your figures, especially if you are using the results of this analysis to inform future early warning systems.

As explained in the text, we arbitrary choose such thresholds based on the previous observations. We showed that taking a velocity threshold significantly improve the forecast (Fig 8).

6. At the very end of the manuscript, you claim that there is some “universality” to the log periodic oscillatory behaviour for this type of event. This is a bold claim, but it is unsubstantiated in the manuscript. This would be a very intriguing and important result, but it would take more discussion, evidence, and placing the analyzed event in context with other events to support such a claim.

See point 5. and comments reviewer 3.

7. I am not sure how to interpret the results presented in Table 1. You show regression parameters for the surface displacement data fit to Eq. 2. The results indicate different predictions, and different parameter values, for different stakes. The parameter values also differ for the same stake but using data over different time intervals. Is there anything in these results to support your universality claim? For a predictive forecasting framework, it would be useful to have uncertainties associated with your time forecast. You report t_c to four digits of precision, but certainly your uncertainty is on the order of days, not minutes.

We have added uncertainties in the table (it was in Fig 8 bottom) and leave t_c to a daily precision.

Specific comments

• p. 4929, lines 4–9: this is a speculative ice break-off, as you mention, but it’s a bit misleading to list it under the heading of glacier break off events that “have been observed and reported.” As such, you really only have two previous confirmed break off events.

• p. 4929, lines 16–19: these sentences are redundant from the Introduction

OK

• All of Section 3.1 is Background material, not Results

We rearranged the structure of the paper, now this section is located before the results section.

• p. 4929, lines 4–9: this is a speculative ice break-off, as you mention, but it’s a bit misleading to list it

under the heading of glacier break off events that “have been observed and reported.” As such, you really only have two previous confirmed break off events.

The reviewer is right but it is worth to mention this event as it reached the valley floor.

• p. 4929, lines 16–19: these sentences are redundant from the Introduction

OK we skip these sentences

• All of Section 3.1 is Background material, not Results

OK, see new structure.

• p. 4933, line 5: this is confusing, are you referring to Fig. 3 in the manuscript? Because Fig. 3 shows smoothed data, which implies post-processing. Or are you referring to Fig. 3 in a different manuscript related to the Whymper break off?

This was confusing. We remowed it.

• p. 4933, line 27: how is this 40 cm amplitude apparent from Fig. 5? Fig. 5 shows residuals from a regression, not oscillation amplitudes.

This is an oscillation superimposed on the general power law acceleration (see Eq 2), therefore 40cm refers to the amplitude of the oscillation in this figure.

• Much of Section 4.1 seems out of place as a Discussion section. It contains both background material (lines 5 to about 17) and results, with a bit of discussion. A bit more background material (and maybe Methods description) is needed to frame the results presented here.

See new structure

• p. 4935, lines 16–17: how much “more accurate” is the prediction when made using a threshold velocity rather than infinite displacement? It would be worth stating this in the text to justify this statement.

This was exactly what was Fig. 7 (now Fig. 8) about…

• p. 4935, lines 24–26: which regression is this based on? Eq. 1 or 2? You should probably explicitly state this here.

OK, Eq 2

• p. 4937, line 21: remove the term “significantly” since you did not perform a statistical analysis to show that using a threshold velocity produced a better forecast than an infinite displacement criterion (though such a statistical test could be done in this case)

No, using velocity threshold give the exact timing whereas infinite displacement overestimate the timing by more than 10 days (Fig. 8).

• p. 4937, line 24: similar comment, “highly probable” implies a probability, but you did not calculate probabilities. A subjective term such as “likely” would be more appropriate here.

OK

• Figure 2: I'm confused by the gap in the data in late September. In the text you make it sound like measurements were taken during this period despite a stretch of bad weather. Also, the lines for Stakes 2, 13, and 14 are difficult to distinguish (especially for Stake 14). Can you differentiate the curves with symbols, or different line types?

The surface displacements are similar and therefore not easy to be distinguished. See new Figure 3.

• Figures 4 and 5: These figures are a bit confusing. You're showing residuals to the regression fit, through time, which are plotted as points. A residual makes sense as a discrete measure of the distance, in model space, between an observation and the model. What, then, are the solid lines? I don't see physically what would be represented by a continuous function in residual space. You label these curves as the power law and log periodic "fit" in Figure 4, but these equations define surface displacements, so how are you plotting them in residual space? In Figure 5 you label the red curve as the residuals, so the description is inconsistent as well.

See new figure 5 and 6.

Reply to referee 3

This manuscript describes the procedure used for the successful prediction of the detachment of a hanging glacier. Impressively, through a combination of skill (and maybe a little luck) the authors have managed to obtain a record of displacements that extends right up to failure. This provides them with an extremely detailed dataset that they can analyze and use to make forecasts. There are two interrelated themes threaded throughout this manuscript. The first is the practical task of forecasting a likely time when the hanging glacier will detach based on measurements of surface displacement/velocity. This is no small task and is vitally important to those living in imminent danger of being crushed or at least inconvenienced by one of these events. Here, unlike many glaciological studies the authors were not only able to make a prediction that was verified, but this prediction had consequences. The second theme is more theoretical and in it the authors argue that surface velocities exhibit log-periodic oscillations and that this behavior is universal and the result of the discrete scale invariance. These two themes mesh together as the authors show that using the additional information associated with the log-periodic oscillations enables them to make more accurate predictions. I have some comments and questions (see below), but overall I enjoyed reading this manuscript and feel like it has the potential to make a significant contribution to avalanche forecasting and our understanding of rupture processes in general.

Thank you

One of the reviewers argued that this manuscript is not hypothesis driven and as such may not be appropriate for Cryosphere. I disagree. If we were forced to eliminate all manuscripts that aren't more clearly hypothesis driven half the manuscripts on the Discussion page would be eliminated. However, I do agree with most of the other comments posted and will echo some of them in my more detailed comments below.

Detailed comments: My detailed comments focus individual on the two main themes of the paper.

1. Time to rupture forecast. As the other reviewers noted, I think it is important to provide a more detailed description of the survey requirements and data processing algorithms. I have never been involved in avalanche forecasting so take my comments with some skepticism, but I would imagine that other practitioners would be interested in knowing more about the quality and quantity of data required for accurate time to failure forecasts. What kind of data collection rates are needed? How many/few stations are needed? What measurement precision/accuracy are needed to make accurate forecasts?

See new paragraph 5.5

How far in advance can forecasts be made?

See paragraph 5.4

The authors also make several claims about the unique quality of the data. That argues to me that the authors should make sure the data are archived somewhere they are publicly available so that others can examine their method and test their own prediction algorithms on this well studied case. (Although I make this claim in incomplete ignorance of standard practices in thefield.) I a little more interested in knowing more about the fitting algorithms. For example, Equation (1) has fewer parameters than Equation (2). Because of this Equation (2) can't (or at least shouldn't) generate larger residuals than Equation (1). A more statistically significant question is where Equation (2) performs in a statistically significant way better than Equation (1) **when the additional degrees of freedom are included**. That is a quantitative answer that the authors can provide. Similarly, assuming the authors are doing a standard least squares/maximum likelihood estimate of parameters, then it is possible to compute the uncertainty in each fitted parameter. This may be an especially useful quantify for the estimated rupture time. This type of analysis would allow the authors to address questions like: Does increasing the number of model parameters decrease the uncertainty in the predicted time to failure in a statistically meaningful way? Does increasing/decreasing the amount of time used in the time series used for fitting parameters affect the uncertainty of the predicted time to failure? I have some other minor questions, like what is the uniform time step that the data was interpolated to? How did the authors account for the effect of interpolating the data on the spectral analysis (or is it too small to bother with.)

Finally, I think the authors should provide more detail on their fitting algorithm, especially in regards to how they determine the power-law exponents. There is a long history in the geosciences of calculating exponents by fitting a straight line in log-space. We know now that this procedure can be dangerously inaccurate and much better procedures are available (see, for example: A. Clauset, C.R. Shalizi, and M.E.J. Newman, "Power-law distributions in empirical data" SIAM Review 51(4), 661-703 (2009). (arXiv:0706.1062, doi:10.1137/070710111.)

We described in more details the fitting procedures line 175-181. Associated errors are now included in Table 1. The errors in estimated rupture time for both regression are contained in Fig. 8b. We also checked the Degree-of-freedom adjusted coefficient of determination (dfa) for both fits: with eq. 1: dfa=1-1.7 10-3 and with Eq 2: dfa=1-1.1 10-4

See also new paragraph 5.1

Clauset et al 2009 deals with power law distributions, not with power law acceleration (when t_c is not known, without possibility to plot displacement as a function of tc-t).

2. Universality and log-periodic oscillations. This is the part of the manuscript I was most interested, but it was also the part that left me with the most questions. Some of these questions may not be too esoteric for this manuscript and I leave this decision with the authors and editor. Nonetheless, the universality claim is very interesting. However, I'm not sure that I understand the sense in which the authors are using the term "universal". The concept of universality (and criticality) that I'm familiar with originates in the statistical physics of phase transitions. Phase transitions were found to exhibit power-law fluctuations near a critical point in phase space and the exponents of the power-laws were found to be "universal" in the sense that many seemingly different systems exhibited the exact same exponent. The renormalization group was eventually used to show that all of these disparate systems with the same exponents lived in a broad "universality group". The crucial result being that details of

small-scale interactions between components were unimportant and the universality group was largely controlled by factors like dimensionality.

This history (and perhaps my own misinterpretation of the authors use of universality) is what feeds my confusion. As far as I can tell the authors find different critical exponents for each stake (Table 1). This would seem to indicate that either the critical exponents have large uncertainties and these differences are not statistically meaningful (does this have implications for forecasts?) or universality (at least as I'm used to using it) isn't supported by the data. I have similar questions about the critical exponents obtained for the Weisshorn glacier. If this really is universality then surely these two glaciers should surely belong to the same universality group and we should find the same exponents for both glaciers? Shouldn't there also be other systems that aren't hanging glaciers that live in the same universality class and exhibit the same critical exponents as for hanging glaciers? I apologize to the authors if I have misunderstood their intended usage through my own ignorance.

You are right concerning universality. In our case, the critical exponents are not the same for both glaciers, and therefore universality cannot be evoke in this study. However, we mentioned only once the term universal (in the last sentence: the present methods exploiting the log-periodic oscillating behavior are universal), but it was in the sense "general". Our mistake. We removed "universal" line 330-332.

A second, but more technical comment on the assumption of criticality and scale invariance is that scale invariance is a concept that breaks down at scales comparable to the fundamental scale of the interacting components of the system (actually much before). Presumably, the fundamental components here are interacting micro fractures within the glacier and then critically is obtained by taking the thermodynamic limit in which the system size tends to infinity (as compared to the fundamental scale of microcracks). Is the system actually large enough that you can have a large enough number of micro cracks interacting for the thermodynamic limit to be a valid approximation? What does this tell us about the size of micro cracks? Similarly-and this is what I'm more interested in-traditional assumptions break down as the scale of fluctuations approach the system scale and this gives rise to finite size effects. I would expect that as fractures start to penetrate a significant portion of the glacier that these finite size effects would begin to manifest themselves in deviations from criticality. But I don't see any evidence in the data for this. Why is this? Is it possible that much of the observations are corrupted by finite size effects and this is why the critical exponents fail to converge to a single value? Or is it possible that much of what is being observed is a consequence of finite size effects and not universal critical behavior? Is there a renormalization calculation that can be used to estimate exponents and/or finite size effects?

Such a behavior was investigated in the 2005 Weisshorn event (Faillettaz et al. 2011) with seismic measurements. It appears that just before failure a change in the size frequency distribution of icequake energies was detected: larger icequakes occurred as expected (signature of overcritical system?). Therefore a deviation from criticality was also observed in seismic as the reviewer conjectured, but no finite size effect was detected. We doubt that finite size effect manifest itself in this case.

Technical comments:

Section 3 results, 1st paragraph. I think the authors are saying that they interpolated the unevenly spaced measurements onto measurements that are evenly spaced in time. This can probably be rephrased to say this more clearly. What evenly spaced interval was used?

OK line 160-164

Page 4926: unique material -> single material?

OK

Page 4931: missing word? “Downstream this crevasse” ->Downstream **of** this crevasse

OK

Page 4932: Paragraph starting with Moreover should be joined with previous paragraph or introduced with a separate topic sentence.

OK

Section 3.2: Why apply the fitting procedure to 1 month of data? Does the analysis fail if, say 2 months of data are used or if 2 weeks are data are used? I would not be surprised to find that considering a longer time series doesn’t help. However, it is modestly interesting to ask how little data you need to make a predicting given that many glaciers may not be as consistently monitored.

We found that taking a longer time serie does not really help. Therefore we just used the last month of data to perform our analysis.

Page 4934: I suggest removing the exclamation point. This is indeed impressive and impressively large oscillation. I don’t think you need the exclamation to call readers attention to this.

OK

Section 4.2: Again, are these differences statistically significant?

See new section 5.1

Section 4.4 is what I was looking for earlier. You might want to point readers towards this section when you first describe the data analysis.

OK line 195-197

Manuscript prepared for The Cryosphere
with version 2015/04/24 7.83 Copernicus papers of the LaTeX class copernicus.cls.
Date: 11 January 2016

Time forecast of a break-off event from a hanging glacier

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Abstract.

A cold hanging glacier located on the south face of the Grandes Jorasses (Mont Blanc, Italy) broke off on the 23$^{\mathrm{rd}}$ and 29$^{\mathrm{th}}$ September 2014 with a total estimated ice volume of 105.000 m^3. Thanks to ~~very~~ accurate surface displacement measurements taken ~~right~~ up to the final break-off, this event ~~could be~~ was successfully predicted 10 days in advance, enabling local authorities to take the necessary safety measures. The break-off event also confirmed that surface displacements experience a power law acceleration along with superimposed log-periodic oscillations prior to the final rupture. This paper describes the methods used to achieve a satisfactory time forecast in real time and demonstrates, using a retrospective analysis, their potential for the development of early-warning systems in real time.

1 Introduction

Rockfalls, rock instabilities due to permafrost degradation, landslides, snow avalanches or avalanching glacier instabilities are gravity-driven rupture phenomena occurring in natural heterogeneous media. Such events have a potential to cause major disasters, especially when they are at the origin of a chain of processes involving other materials such as snow (snow avalanche), water (flood) and/or debris (mudflow). The reliable forecasting of such catastrophic phenomena combined with a timely evacuation of the endangered areas is often the most effective way to cope with such natural hazards. Unfortunately, accurate time prediction of such events remains a somewhat daunting task as (i) natural materials are heterogeneous, (ii) the heterogeneity is difficult to quantify and measure, and (iii) the rupture is a non-linear process involving such heterogeneities. Although often located in a remote high-mountain environment, avalanching glacier instabilities offer an interesting starting point for investigating early-warning perspectives of break-off events, as a glacier consists of a ~~unique~~ single material (ice) lying on well-defined bedrock. This relative simplicity of the system allows the focus to be placed on the rupture processes leading to the initiation of the instability. Recently, considerable efforts in monitoring, analyzing and modeling such phenomena have led to significant advances in understanding the destabilization process and in improving early-warning perspectives (Faillettaz et al., 2015).

In general, it is possible to distinguish three types of avalanching glacier instabilities according to the thermal properties of their ice/bedrock interface (Faillettaz et al., 2011b, 2012, 2015). If temperate~~or polythermal~~, the presence of liquid water in the glacier plays a key role in the initiation and the development of the instability as its presence influences the basal properties of the ice/bedrock interface (diminution of friction, lubrication or loss of support). In such cases, several preliminary conditions to be fulfilled can be identified, but an accurate time forecast of an impending break-off event is still far from being possible. If the ice/bed interface ~~is partly~~ experiences a transition from cold to temperate, the presence of melt water may reduce the basal resistance, which promotes the instability. No clear and easily detectable precursory signs are known in this case, and the only way to infer any potential instability is to monitor the temporal evolution of the thermal regime. If the ice/bedrock is cold, glaciers are entirely frozen to their bedrock. This situation appears in the case of high altitude hanging glaciers located entirely in accumulation zone. The snow accumulation is mostly compensated by periodic break-off of ice chunks (Pralong and Funk, 2006), occurring once a critical point in glacier geometry is reached. The instability results from the progressive accumulation of internal damage due to an increasing stress regime caused by glacier thickening. In this case, the rupture occurs within the ice, typically a few meters above the bedrock. The maturation of the rupture was shown to be associated with a typical time evolution of both surface velocities (Faillettaz et al., 2008) and passive seismic activity (Faillettaz et al., 2011a). This characteristic time evolution can theoretically be used to predict the occurrence of a catastrophic event. This was done a posteriori with data obtained prior to the 2005 break-off of the Weisshorn glacier.

In this context, the Whymper glacier, a cold hanging glacier located at the Grandes Jorasses (Mont Blanc, Alps, Italy), already broke off several times in the past, leading to major ice avalanches that occasionally reached ~~as far as~~ the bottom of the valley. In autumn 2008, the glacier recovered its previous critical geometry from the year 1998 and a crevasse opened in the lower part of the tongue, prompting the local authorities to initiate a monitoring program to enable a time forecast of the expected break-off event. The glacier finally broke off causing no damage in autumn 2014, after more than 5 years of monitoring. The break-off was successfully predicted 2 weeks in advance.

The aim of this paper is to confirm the validity of the time forecast procedure first developed in 2005 on the Weisshorn glacier and to apply it here in real time.

After describing the glacier and the monitoring system installed on the glacier, we analyze the time evolution of the surface displacement measurements in the context of a time forecast procedure. While comparing this break-off event with the Weisshorn ~~glacier break-off~~ event of 2005 we discuss the results obtained, with the goal of improving the understanding of this phenomenon.

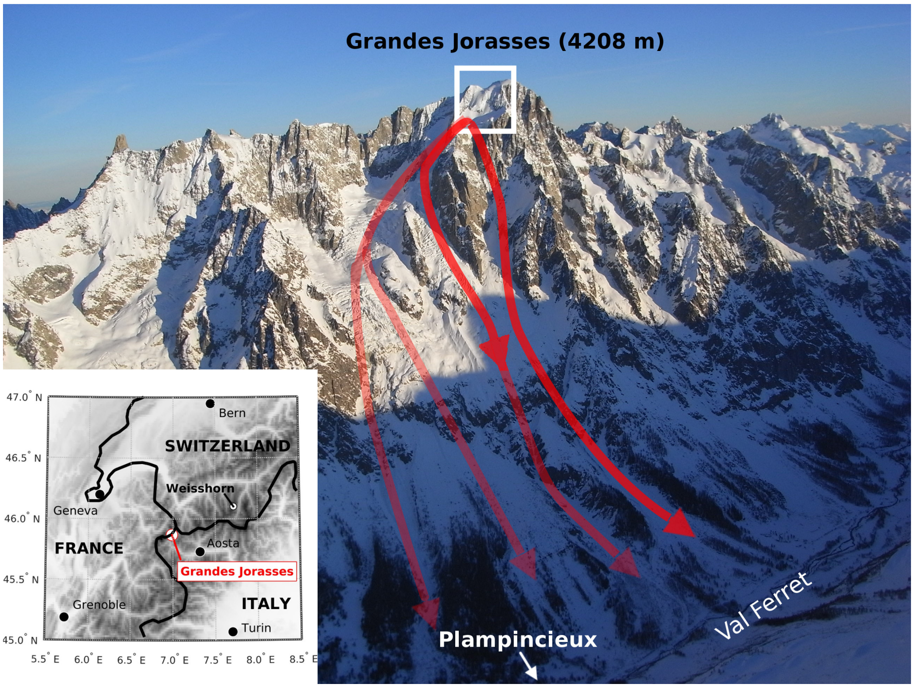

Figure 1. ~~(a) Geographical situation~~ Global view of the ~~studied glacier. (b)~~ Val Ferret with Grandes Jorasses~~(~~. White rectangle highlihghts Whymper ~~)~~ glacier~~before~~. Light red lines indicate possible avalanche flow path (~~23rd August 2014~~for more details see Margreth et al. (2011)), ~~(c) after~~ red lines indicate avalanche path from the ~~first~~ 1998 break-off ~~(23rd September 2014) and (d) after~~ event. Inset shows geographical situation of the ~~second break-off (30th September 2014)~~studied glacier.

2 Grandes Jorasses glacier

2.1 Study site

The Whymper glacier ~~(Fig. 2)~~ is located on the south face of the Grandes Jorasses (Mont Blanc massif, Italy) between 3900 and 4200 m asl (Fig. ~~2).~~ 1). The front of the glacier is about 90 m wide and its surface area amounts 25,000 m^2. This very steep cold hanging glacier (about 40 °) lies above the village of Planpincieux and the Italian Val Ferret, a famous and highly frequented tourist destination both in winter and summer. In 1997, six boreholes were drilled down to the bed and temperature profiles were measured, indicating basal temperatures below the freezing point (below $-1.6 \pm 0.4^{o}C$) at all locations (Pralong and Funk, 2006) . Historical data and morphological evidence indicate that the glacier experienced recurrent break-off events that can be dangerous, particularly in winter, when the initial ice avalanche can drag snow in its path. This hanging glacier periodically broke off in the past leading to large avalanches that flowed down into the valley.

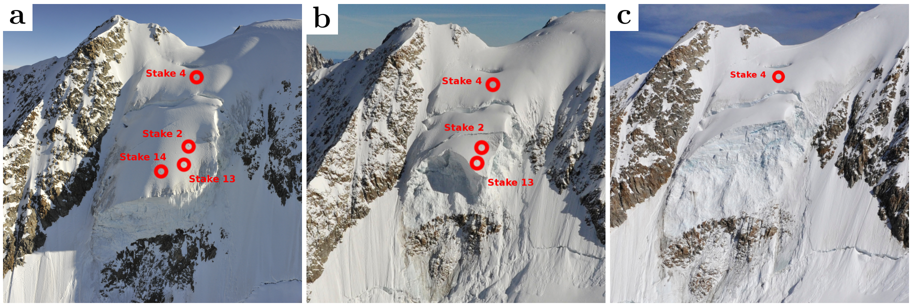

Figure 2. (a) Grandes Jorasses (Whymper) glacier before ($23^{\rm rd}$ August 2014), (b) after the first break-off ($23^{\rm rd}$ September 2014) and (c) after the second break-off ($30^{\rm th}$ September 2014)

2.2 Break-off event history

The glacier broke off several times during last 100 years. Some of these events have been observed and reported:

- On 21 December 1952, after an intensive snowfall period, a huge avalanche was released below the Grandes Jorasses which destroyed a 200-year old forest and blocked the bottom of the Val Ferret over a distance of more than 1 km. The avalanche volume was estimated at more than 1,000,000 m^3. It is not clear whether the snow avalanche was triggered by an ice avalanche from the Whymper glacier.
- In August 1993 and July 1996, the glacier released ice avalanches of 80,000 and 24,000 m^3, respectively. These ice avalanches did not reach the bottom of the valley.
- The last major break-off event occurred in the night of $31^{\rm th}$ May to $1^{\rm st}$ June 1998. Almost the entire Whymper glacier (around $150,000\ \mathrm{m}^3$) broke off at one time and the triggered ice avalanche reached the bottom of the valley, fortunately without causing damage ~~.~~ (Fig. 1). According to Pralong and Funk (2006) the formation of the upper crevasse was observed 2.5 years before failure .

~~In the following years, the hanging glacier has progressively re-formed, as it is located in an accumulation area. Ten years later, in 2008, the glacier almost recovered its 1998 geometry. In autumn 2008 a crevasse opened at the lower part of the glacier, prompting the local authorities to initiate a monitoring program.~~

2.3 Present monitoring: 2009-2014

The survey primarily consisted of surface displacement measurements with an automatic total station and GPS as well as close-range photogrammetry (Margreth et al., 2011) . Two reflectors set on the rock on both sides of the glacier were used as reference, and several reflectors mounted on stakes were directly drilled into the ice, so that their exact positions could be monitored (Fig. 2). Because of instrument problems, the seismic activity unfortunately could not be monitored as initially planned.

Starting in 2010, surface displacements were continuously recorded at several stakes at 2-hour intervals (~~if~~ when the prisms were visible, i.e., ~~in~~ good weather conditions) with the aim to timely detect an impending ice avalanche ~~in a timely manner~~ (Margreth et al., 2011). Using the same correction technique as described by Faillettaz et al. (2008), the surface displacements could be determined with an accuracy better than 1 cm, allowing surface velocities to be inferred.

In parallel to the monitoring program, a safety concept for the valley floor was developed considering several scenarios of falling ice volumes. The different ice avalanche scenarios were simulated using the 2-dimensional calculation model RAMMS. The necessary safety measures were defined according to the local avalanche danger level and the potential volume of a break-off event (Margreth et al., 2011).

2.4 The 2014 break-off event

From 2010 on, surface displacements were surveyed without interruption. The Whymper glacier finally broke off with an estimated ice volume ~~of same order of magnitude as~~ similar to the 1998 event (about 105,000 m^3). Contrary to the 1998 event, the glacier broke off in two events on September 23$^{\mathrm{rd}}$ and on September 29$^{\mathrm{th}}$ 2014, without reaching the valley (Fig. 2). At the final break-off, 4 reflectors were still active, 2 of them in place for more than 2 years. Despite poor weather conditions between the 16$^{\mathrm{th}}$ and 21$^{\mathrm{st}}$ of September, the monitoring was operational up to the final break-off. By chance, there was ~~at least~~ one reflector on each ~~part of the glacier (one on each unstable part~~ of the two unstable parts and one on the stable part, ~~Fig. 2). Note that contrary to previous studies, these constitute the first accurate surface displacement measurements on a hanging glacier up to the break-off event.~~

3 ~~Results~~

~~Fig. 3 shows the corrected surface displacements and Fig. 4 the associated derived surface velocities of the 4 stakes (Fig 2) prior to the break-off. The assocated derived surface velocities are computed taking the surface displacements interpolated on regular time step and smoothed on 5 points. Note that Stakes 13 and 14 have more than 2 years of nearly continuous measurements, the position of Stake 13 having been measured up to the final break-off event on September 29~~$^{\mathrm{th}}$~~. The accuracy of the measurements was less than a centimeter (Faillettaz et al., 2008) . Note that this constitutes a unique dataset not only because of the great accuracy and long measurement period but also due to available surface displacement measurements up to a few hours prior to the break-off event. Whereas the motion of Stake 4 is constant~~ (Fig. ~~3), the three other prisms show a clear acceleration prior to break-off. Surface displacement of the 4 stakes before the break-off using 19 July 2014 as reference~~

~~(when Stake 2 and Stake 4 were installed). Vertical red dashed lines indicate the occurrence of the two break-offs, on 23$^{\mathrm{rd}}$ and 29$^{\mathrm{th}}$ September 2014. Interrupted lines indicate a period of bad weather conditions without measurements. Note that Stake 14 was not surveyed after 16$^{\mathrm{th}}$ of September 2014, i.e., one week before the first break-off.~~

~~Smoothed surface velocity of the 4 stakes since 2012. Inset shows a closer view during the same period as that in Fig 3.~~ 2).

2.1 ~~Previous findings on cold glacier break-off~~

~~These observations exhibit striking~~ Striking qualitative analogies with those of the 2005 Weisshorn event (Faillettaz et al., 2008) can be highlighted.

1. This steep cold hanging glacier experiences periodic break-off events.

2. The geometrical configuration of the glacier is similar before each break-off~~. An~~ , with an upper crevasse spanning the whole glacier and a clear thickening of the glacier towards its tongue.

3. The upper crevasse marks a clear distinction between a stable upper part (where Stake 4 is located) and a downstream unstable part (where the other reflectors were located, Fig. ~~4~~2, section 4.1). A crude estimation of the volume of the unstable part is thus possible.

4. Downstream of this crevasse, surface displacements experience a typical acceleration prior break-off, whereas upstream this crevasse constant velocities are recorded (Stake 4 in Fig. 3).

5. The rupture did not occur at the ice/bedrock contact but a few meters above it, within the ice (Fig. 2), possibly because of bedrock irregularities (Pralong and Funk, 2006) .

6. The ~~total~~ whole break-off occurred ~~on two occasions~~in two steps; a minor ~~side section~~ section at the left side of the glacier was released first.

3 Previous findings on cold glacier break-off

Based on a retrospective analysis, the main conclusion drawn by Flotron (1977) and Röthlisberger (1981) was that the forecast of a break-off ~~occurrence~~ event from a hanging glacier was possible using surface displacements alone. The principle is to fit the characteristic acceleration of the surface ~~displacements~~ motion with a power law behavior of the form:

$$s(t) = s_0 + u_s t - a(t_c - t)^{\theta}, \tag{1}$$

where $s(t)$ is the displacement (in meters) at time t (in days), s_0 a constant in meters, u_s the constant velocity of the upstream stable part (in md^{-1}), t_c the critical time (in days), $\theta < 0$ (without units) and a (in $\mathrm{md}^{-\theta}$) the parameters characterizing the acceleration. In this way, the critical time t_c, i.e., time at which the theoretical displacement becomes infinite, could be evaluated ~~simply~~ using such empirical law. Although the break-off event would necessarily occur earlier, this critical time represents the upper limit of the break-off timing.

Moreover, an oscillating pattern superimposed on the power law acceleration of the surface displacements was evidenced prior to the 2005 Weisshorn event (Pralong et al., 2005; Faillettaz et al., 2008). ~~Such behavior~~ This peculiar glacier dynamics was shown to be a log-periodic oscillating ~~behavior~~ process superimposed on this acceleration (for appearance and interpretation see Faillettaz et al. (2015)). The time evolution of the surface displacement measurements can be described with the following equation (after Sornette and Sammis, 1995; Pralong et al., 2005):

$$s(t) = s_0 + u_s t - a(t_c - t)^{\theta}\left[1 + C\sin\left(2\pi\frac{\ln(t_c - t)}{\ln(\lambda)} + D\right)\right], \tag{2}$$

where C the relative amplitude (without units), λ the logarithmic frequency (in days) and D the phase shift of the log-periodic oscillation (without units).

~~Note that such oscillating behavior was also evident~~ Thanks to a combined analysis of surface displacement and seismic measurement, Faillettaz et al. (2011a) were able to obtain a coherent quantitative picture of the damage evolution process developing before the 2005 Weisshorn break-off. They have suggested three regimes in the evolution of the failure process leading to the break-off event:

(i) A first stable phase related to a self-organizing regime, where diffuse damage accumulates within the glacier, with a proliferation of dislocation-like defects.

(ii) A transitional phase where the damage process goes on, micro-cracks grow and start merging in a homogeneous way. Log-periodic oscillations appear and reveal the hierarchical structure of the fracture process under development.

(iii) A catastrophic regime where damage clusters are randomly activated. Damage clusters interact and merge with a preferential direction (i.e. preparing the final rupture pattern), in contrast to the previous regime.

4 Results

4.1 Surface displacements and associated velocities

Fig. 3 shows the corrected surface displacements and Fig. 4 the associated derived surface velocities of the 4 stakes (Fig 2) prior to the break-off. The associated derived surface velocities are computed taking the surface displacements (smoothed over 5 points) interpolated on regular time step of one day. Note that Stakes 13 and 14 have more than 2 years of nearly continuous measurements and the position of Stake 13 was surveyed up to the final break-off event on September 29$^{\text{th}}$. After processing the raw data with two reference points located near the glacier and additionally accounting for flow

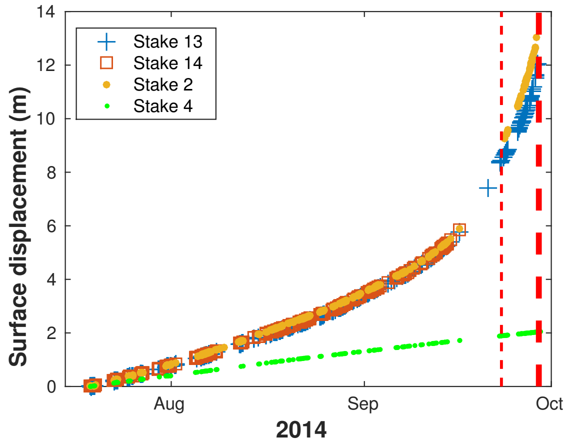

Figure 3. Surface displacements of the 4 stakes before the break-off using 19 July 2014 as reference (when Stake 2 and Stake 4 were installed). Vertical red dashed lines indicate the occurrence of the two break-offs, on 23$^{\mathrm{rd}}$ and 29$^{\mathrm{th}}$ September 2014. Interrupted lines indicate a period of bad weather conditions without measurements. Note that Stake 14 was not surveyed after 16$^{\mathrm{th}}$ of September 2014, i.e., one week before the first break-off.

direction, the accuracy of the results was less than a centimeter (Faillettaz et al., 2008) . Note that this constitutes a unique dataset not only because of the great accuracy and long measurement period but also due to available surface displacement data up to a few hours prior to the ~~2014 Whymper glacier~~ break-off ~~, as such oscillating patterns are clearly visible on the derived velocity without post-processing~~ event. Whereas surface velocities at Stake 4 are approximately constant (Fig. 4)~~.~~ , the three other stakes show a clear acceleration which is typical for an unstable situation. According to this observation we can expect that the glacier section around Stake 2, 13 and 14 will break-off, while the section around Stake 2 will remain stable (section 2.4).

4.2 Application to forecasting

Previous findings (section 3) were applied in order to forecast the ~~break-off~~ breaking-off event in real time. As soon as a significant increase in velocity was detected, the same procedure was followed as in Faillettaz et al. (2008). We periodically fitted surface displacements of all stakes to a power law (Eq. 1) and a log periodic oscillating behavior (Eq. 2). ~~Fig. ?? shows the residuals to the power law fit for two points (Stakes 13 and 14)~~ The nonlinear least-squares curve-fitting was performed using the Levenberg-Marquardt algorithm. Because the results depend on the initial parameter estimates, especially t_c and θ, we have systematically used different initial values with a prescribed bound and selected the results corresponding to the best root mean squared error and the degree-of-freedom adjusted coefficient of determination.

Fig. 5a and 6a show both power law (Eq. 1) and log-periodic (Eq. 2) fits using the last month of ~~data~~ available data, i.e up to 16$^{\mathrm{th}}$ September for Stake 14 and 29$^{\mathrm{th}}$ September for Stake 13. As

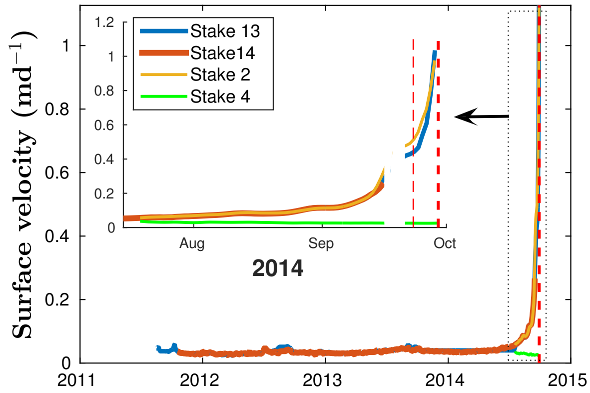

Figure 4. Surface velocities for 4 stakes since 2012. Inset shows a closer view during the same period as in Fig 3.

both fits are barely distinguishable, we have also plotted on Fig. 5b and 6b the residuals to the power law fit and show the associated log-periodic fit (minus the power law fit) as a dashed gray line ; Table 1 contains the values of the parameters in Eq. 2, taking $\lambda = 2$ d. Note that measurements are available up to the final break-off for 3 prisms (i.e., Stake 13, Stake 2 and Stake 4) and stopped on 16 September for Stake 14, i.e., 8 days before the first break-off.

It appears that the power law behavior describes well the surface displacements with ~~an accuracy~~ a maximum discrepancy of about 5 cm for Stake 14 (8 days before break-off), about the same order of magnitude as the one observed during the 2005 Weisshorn event (Fig. 5). However, residuals ~~show~~ indicate an oscillating pattern. When using the log-periodic function (Eq. 2), the ~~fit (shown in red~~agreement between measured and fitted values (dashed gray line) becomes significantly better, with an accuracy of the order of magnitude of the measurement accuracy (less than a centimeter). Results show that the critical time ~~ranges between 1 and 4 October~~ can be expected around the 3rd October for both stakes, which is fairly close to the observed break-off. Note that such an approach can be used to investigate how far in advance a reliable time forecast is possible (see section 5.4).

However, even if Stake 14 is located on a section that broke off earlier, no significant differences could be detected. Our approach is not able to detect whether the break-off ~~would happen~~ will occur all at once or ~~could occur~~ as successive small ~~break-offs~~events.

Now when ~~investigating~~ considering the entire dataset for Stake 13 (where measurements ~~were performed~~ could be recorded up to the break-off) using the same method, it appears that the amplitudes of ~~oscillations~~ the oscillations superimposed on the power law acceleration become even larger close to the break-off ~~-that is, they reach up to 40~~ - they reach values up to 30-40 cm (Fig. ~~??)!~~ 6). Such a broad oscillating pattern ~~had~~ has never been observed before, confirming that the jerky motion of the glacier (with oscillating nature) ~~has~~ might have a physical origin (see Section 5.2).

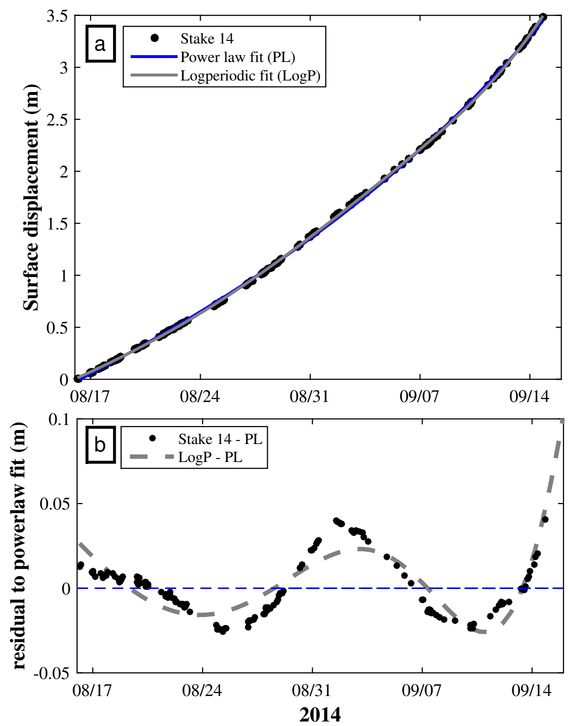

Figure 5. ~~Residuals (in meters) to the power law fit (in blue)~~ a. Surface displacements of Stake 14 for the period ~~17~~16th August- ~~17~~16th September (last measurement of Stake 14) ~~for both Stake 13~~ and the associated power law (~~black points~~in blue) and ~~Stake 14~~ log-periodic fit (in gray~~circles~~)~~and associated log-periodic~~. b. Residuals (in meters) to the power law fit (~~solid line~~ in blue) for ~~Stake 13 and~~ the same period. Log-periodic fit is also shown with dashed gray line~~for Stake 14)~~. Values for the parameters are shown in Table 1. ~~Inset shows the surface displacement (gray) and power law fit (blue) at Stake 14.~~

5 Discussion

5.1 Influence of data accuracy on the final result

To assess how the data accuracy influences the time forecast of the break-off, we artificially added two uniformly distributed random noise (between -1 and 1 cm and between -5 and 5 cm) to our dataset and to analyze how the obtained critical time depends on our fitting method. To ensure good statistical representation, this procedure was performed 100 times on Stake 14 up to 16.09.2014 and on Stake 13 up to the final break-off (29.09.2014). Results (see table 2) show that the forecasting errors are mainly due to the fitting procedure. Errors due to the data accuracy are about one order of magnitude lower than those generated by the fitting procedure.

5.2 Appearance of log-periodic behavior

Table 1. Values of the estimated coefficients of Equation 2 with λ = 2 d and the root-mean-square error (RMSE) of the fit, first two columns corresponding to the parameters of the fit used in Fig. ~~??~~ 5 for the period 16.08-16.09, the last two columns corresponding to the parameters of the fit used in Fig. ~~??~~ 6 for the period 30.08-30.09. t_c is given in days after the first ~~days~~ day of the investigated period.

Parameter	Units	Stake 13 (~~up to~~ 16.08 - 16.09)	Stake 14 (~~up to~~ 16.08 - 16.09)	Stake 13 (~~up to~~ 29.08 - 29.09)	Stake 2
t_c	d	~~45.23~~48.02 ± 5.13	~~48.93~~48.11 ± 5.6	~~41.76~~41.93 ± 0.91	~~44.~~
	date	~~01-Oct-2014 05 AM~~03-Oct-2014	~~04-Oct-2014 10 PM~~03-Oct-2014	10-Oct-2014~~6 PM~~	~~13-Oct-20~~
θ	-	~~-0.21~~ -0.24	~~-0.48~~ -0.25	~~-1.04~~ -0.99	
s_0	m	~~-1.86~~ -1.47 $\cdot 10^4$	~~-1.83~~ -1.47 $\times 10^4$	~~-2.52~~ -2.03 $\times 10^4$	~~-1.~~
u_s	md^{-1}	~~2.53~~ 2.00 $\times 10^{-2}$	~~2.48~~ 2.00 $\times 10^{-2}$	~~3.43~~ 2.99 $\times 10^{-2}$	~~2.0~~
a	$md^{-\theta}$	~~25.41~~ 27.88	~~33.12~~ 27.72	~~1 466.22~~ 141.73	~~5~~
C	-	~~2.68~~ 2.9 $\times 10^{-3}$	~~5.75~~ 2.3 $\times 10^{-3}$	~~3.27~~ 3.0 $\times 10^{-2}$	~~3.~~
D	-	~~2.90~~ 2.25	~~1.46~~ 1.97	~~2.26 $\times 10^{-5}$~~ 6.13	
RMSE	md^{-1}/m	8.7 $\times 10^{-3}$	~~8.4~~ 7.9 $\times 10^{-3}$	~~3.14~~ 3.05 $\times 10^{-2}$	~~1.6~~

Stake	Initial data	$\pm$ 1cm noise	$\pm$5cm noise
13	$t_c = 41.93 \pm 0.91$ d	$t_c = 41.90 \pm 0.038$ d	$t_c = 41.86 \pm 0.041$ d
14	$t_c = 48.11 \pm 5.6$ d	$t_c = 48.55 \pm 0.56$ d	$t_c = 49.33 \pm 0.55$ d

Table 2. Critical time t_c evaluated with our dataset and with a uniformly distributed random noise of $\pm$ 1 cm and $\pm$ 5 cm.

~~Faillettaz et al. (2011a, 2015) explain the~~ The origin of the log-periodic oscillating behavior ~~as the result of~~ is likely due to a Discrete Scale Invariance (DSI), a weaker kind of scale invariance according to which the system obeys scale invariance only at a specific scaling factor scale (Sornette and Sammis, 1995; Sornette, 1998; Zhou and Sornette, 2002a; Sornette, 2006). ~~This~~ Whereas the hallmark of Continuous Scale Invariance is the existence of power law, the signature of DSI is the presence of power laws with complex exponents which manifests itself in data by log-periodic corrections to scaling. Several mechanisms may lead to this partial breaking of the continuous symmetry~~is a result of~~. Thanks to a combined analysis of surface displacements and seismic measurements, Faillettaz et al. (2011a) suggest that it results from the dynamic interactions between newly developed micro-cracks, as shown by Huang et al. (1997) and Sahimi and Arbabi (1996).

To identify the log-frequency, we analyzed the data in the same way as Faillettaz et al. (2008) with a Lomb periodogram analysis (Press, 1996; Zhou and Sornette, 2002b), which is designed to analyze non-uniformly sampled time series. This method enables us to determine f_{Lomb} as a function of $cos(2\pi f_{Lomb} t)$. The parameter λ in Equation 2 can then be evaluated easily as $\lambda = e^{1/f_{Lomb}}$. Unfortunately, the critical time t_c has to be known to perform this analysis, i.e., this analysis can only

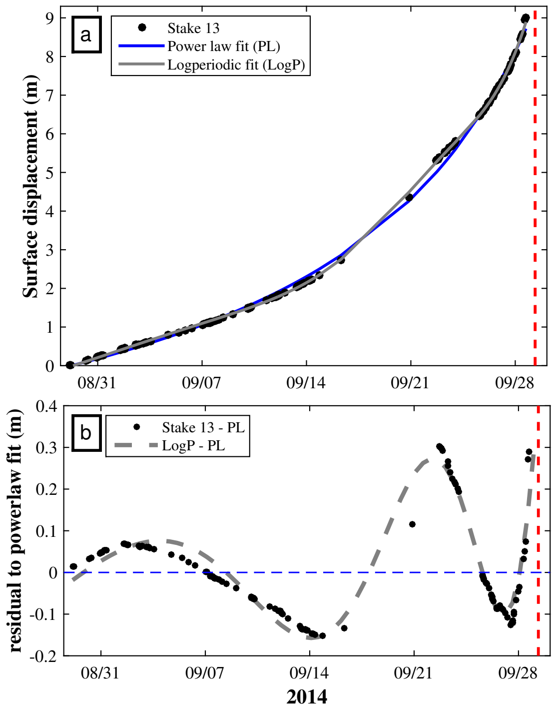

Figure 6. a Surface displacement of Stake 13 for the period 29th August 2014 - 29th September 2014 and associated power law (in blue) and logperiodic (in gray) fits. b. Residuals (in meters) to the power law fit (black point) ~~and log-periodic fit (red line)~~ for ~~Stake 13 based on~~ the ~~last month of data prior to the break-off~~same period. Log-periodic fit is shown with gray dashed line. Values of the parameters are shown in Table 1.

be ~~an a posteriorianalysis~~performed a posteriori. It clearly shows (Fig. 7a) peaks in Lomb power (power spectral density) at $\lambda \sim 2$ d for the three analyzed points, confirming that the oscillating behavior is not a measurement artefact but has physical origins, such as the merge of newly developed micro-cracks. Note that another strong log frequency appears at $\lambda \sim 7.4$ d for Stakes 2 and 13 (Fig. 7b), after the first break-off. The reason for the appearance of such peak is not clear, but is probably induced by the occurrence of the first break-off that changes the geometry of the glacier: Using experimental data, Moura et al. (2005, 2006) suggested that grain size and loading rate directly influence log-periodic oscillations. A possible explanation would thus be that the first release led to a sudden change in the global loading of the remaining section of the glacier, i.e., loading rate change, introducing ~~then~~ another subharmonic log frequency and perturbing the overall behavior of the remaining section of the glacier where Stakes 2 and 13 stand.

5.3 ~~Power law vs. Log-periodic~~

~~Besides a more accurate fit (Fig. ?? and ??), Fig. 8 (bottom) shows that errors (given as 95 % confidence interval) in the determination of the critical time t_c are generally smaller for log-periodic~~

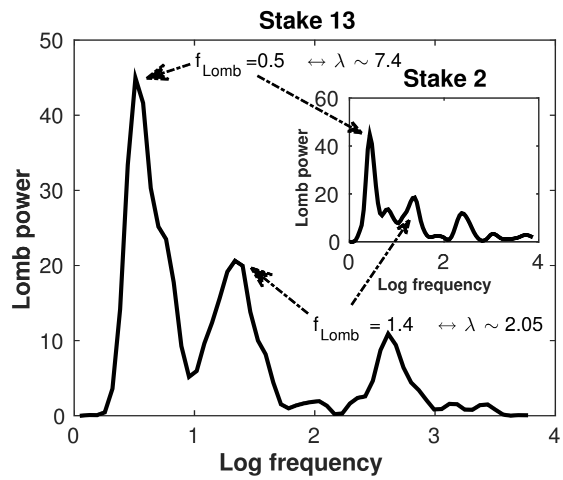

Figure 7a. Lomb periodogram for Stakes 13 and 2 (in inset) as well as the corresponding log frequencies (λ) of the peaks.

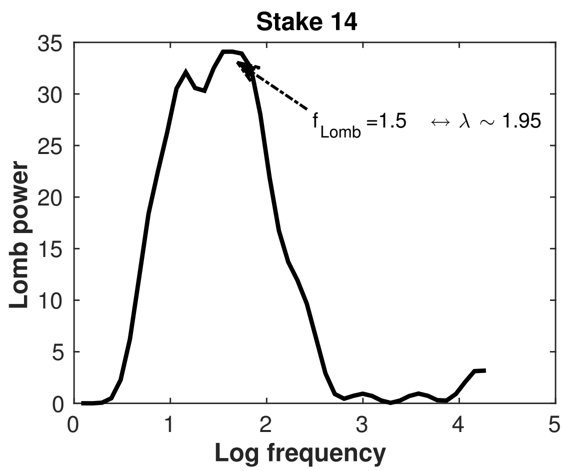

Figure 7b. Lomb periodogram for Stake 14 as well as the corresponding log frequencies (λ) of the peaks.

~~fit than power law fit, confirming once again a more reliable log-periodic fit. Usually power law evaluates a larger (later) critical time than log-periodic law.~~

5.3 Accurate determination of break-off occurrence

As critical time t_c given by power law or log-periodic fit indicates ~~time at which surface displacements are theoretically infinite, real~~ when surface displacements become theoretically infinite. However, the break-off event is expected before t_c. When fitting in real time the surface ~~displacement~~ displacements with both power law and log-periodic behavior, it is not only possible to assess the critical time but also the time at which the derived velocities are expected to reach a given threshold (for example 50 $\mathrm{cm\ d^{-1}}$ or $1\ \mathrm{m\ d^{-1}}$). Fitting and estimating the time at which the ~~associated~~ velocity reaches a given threshold provides a more accurate way to predict the ~~real~~ break-off event. We developed a software based on this idea by fitting in real time the measurements with both power law and log-periodic behavior and thus provide an estimate of the break-off time.

~~From~~ According to our knowledge, it is not possible to know in advance the velocity at which break-off will occur. However, from previous events (Weisshorn 1973 and 2005 event, Flotron (1977); Röthlisberger (1981); Faillettaz et al. (2008)), it seems that break-off occurs between 50 $\mathrm{cm\ d^{-1}}$ to 1.2 $\mathrm{m\ d^{-1}}$, but this is based on a restricted number of events.

Taking threshold surface velocities of 50 $\mathrm{cm\ d^{-1}}$ and 1 $\mathrm{m\ d^{-1}}$, our analysis (using Eq. 2) performed every days from the 12 September to 16 September suggested that break-off could occur between the 23 September ($v_{th} = 50\ \mathrm{cm\ d^{-1}}$) and the 29 September ($v_{th} = 1\ \mathrm{m\ d^{-1}}$). Note that ~~this method provided the exact timing of the real break-offs, around~~ the two breaking-off events occurred exactly at these two days, which were forecasted 10 days in advance. Following this analysis, alert was immediately sent to the authorities leading them to close the endangered area one week before the event. Note that the definition of the velocity threshold has an influence on the prediction itself, as we saw nearly one week is needed for the glacier to accelerate from 50 $\mathrm{cm\ d^{-1}}$ to 1 $\mathrm{m\ d^{-1}}$. The precise prediction would also not only be based on a correct fit of the surface displacement data but also on a guess of this parameter. We suggest to choose 40 $\mathrm{cm\ d^{-1}}$ as a conservative threshold to define a ~~high~~ safe break-off danger time ~~zone~~interval.

5.4 How ~~much~~ far in advance ~~can be the break-off predicted~~are time forecasts possible?

~~Surface displacement was~~ Surface displacements were analyzed retrospectively based on the last month of data for each ~~prism~~stake, and the critical time as well as the time at which the fitted velocity reached 50 $\mathrm{cm\ d^{-1}}$ (v_{50}) and 1 $\mathrm{m\ d^{-1}}$ (v_{100}) were plotted as a function of the time ~~of analysis~~ (Fig. 8). Associated errors (Fig. 8 bottom) account for the fitting procedure.

First, the prediction is better when using log-periodic fit than power law fit. This retrospective analysis shows that the prediction is correct after 12 September, i.e., 11 and 17 days before the break-off with a confidence interval becoming less than than 10 days ~~for~~ with a log-periodic fit.

This analysis points out the great prediction potential - and early warning ~~perspectives~~ perspective - of this method, as the exact time of the break-off could be ~~forecast~~ forecasted almost 2 weeks ~~before its occurrence~~in advance. Note that both the power law and the log-periodic fits become less accurate after the first break-off for Stake 13. ~~Such effect~~ This might be related to the sudden change in glacier geometry that may influence the surface displacements at Stake 13. However, note that the time at which ~~estimated derived velocity reaches~~ a velocity of 1 $\mathrm{m\ d^{-1}}$ (v_{100}) is ~~stable~~expected remains unaffected, still pointing at September 29$^{\mathrm{th}}$.

5.5 Overall recommendations

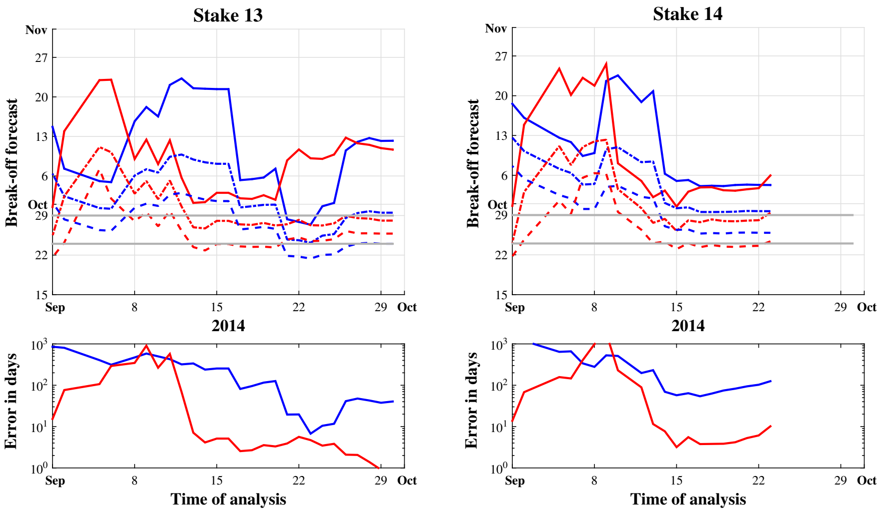

Figure 8. Top: Thick lines: evaluated critical time t_c for power law (blue) and log-periodic (red) fit for Stakes 13 (left) and 14 (right) as a function of the time of analysis. Interrupted lines indicate time at which estimated derived velocity from power law and log-periodic fit reaches 50 $\mathrm{cm\ d^{-1}}$ (dashed lines, v_{50}) and 1 $\mathrm{m\ d^{-1}}$ (dot-dash line, v_{100}). Horizontal grey lines represent the observed break-off (23$^{\mathrm{rd}}$ and 29$^{\mathrm{th}}$ September)~~, inclined gray line indicates the time of analysis~~. Bottom: Error in days on critical time fitted with power law (blue) and log-periodic (red) estimated from the 95% confidence interval. Errors on v_{50} and v_{100} are similar to the errors on critical time, as they are directly derived from these fits.

According to the knowledge gained from the different studies on Weisshorn, Mönch and Grandes Jorasses glaciers, accurate data are required to forecast an impeding break-off event. As the amplitudes of the log-periodic oscillations are increasing towards the break-off (from 5 cm one week before the break-off to 40 cm at the break-off), the confidence of the time forecast strongly depends on the precision of the surveying data. To ensure a satisfactory forecast about one week in advance, a surveying accuracy better than half of the expected log-periodic amplitudes, i.e., 2.5 cm, is required. In this study an accuracy of 1 cm was achieved with an automatic total station (Leica theodolite TM1800 combined with the DI3000S Distometer). The sampling rate needs to be adapted to the oscillating pattern in order to enable its detection. Moreover, in such rapid changing meteorology where clouds can momentarily hindered measurements, several measurements need to be performed each days. A sampling rate of 2 hours was chosen in this study, ensuring thus several opportunities to obtain data every day. This technique can be performed in near real time and several measurements can be performed every day with a sufficient accuracy. Note that GPS measurements would be a valuable alternative but this technique requires a long acquisition time and additional processing to achieve to required accuracy. Although independent of weather conditions, the power supply and data transmission are problems to be solved. This procedure based on power law/log-periodic oscillations regression requires at least two measurements points on the potentially unstable part of the glacier, so that the time evolution of surface motion at different points could be compared. It also ensures that the results are not affected by stake/prism stability issues.

An alternative surveying technique is terrestrial Insar. The advantage of this technique is that no installation on the glacier (potentially dangerous) is required. However the data accuracy which can be expected with this monitoring system is not completely clear yet (Preiswerk et al., 2016)

6 Conclusions

Grandes Jorasses glacier broke off twice, on 23$^{\mathrm{rd}}$ and 29$^{\mathrm{th}}$ September 2014. In 2008, as it was suspected that ~~this glacier~~ a large part of this glacier is becoming unstable, a ~~long-term~~ monitoring program was initiated. At the time of the break-off, 4 ~~prisms spread over~~ stakes covering a large part of the glacier enabled surface ~~displacements to be measured in a very accurate way~~ displacement measurements up to the time of the break-off. By regularly analyzing the dataset, it was possible to forecast the event ten days in advance~~, enabling local authorities to close off the endangered areas and thus prevent catastrophic outcomes~~. In the following the local authorities closes the endangered area up to the final rupture.

It was possible to confirm ~~definitely that surface displacement~~ for an impeding ice fall that a time series of surface displacements exhibits strong log-periodic ~~oscillating behavior~~ oscillations superimposed on a global power law acceleration~~prior to its break-off~~, as first discovered for the Weisshorn event (Faillettaz et al., 2015). In the immediate vicinity of the break-off, such oscillations reached an amplitude of more than 40 cm, almost one order of magnitude larger than revealed in previous findings. By fitting ~~surface displacements to this behavior~~our recorded surface displacements, the critical time, i.e. time at which surface displacement become infinite, can be determined. ~~The surface velocities at~~ Using this critical time value as an upper bound, a good time forecast could be achieved.

The inferred surface velocities immediately prior the two events were $0.5\ \mathrm{m\ d^{-1}}$ and $1.2\ \mathrm{m\ d^{-1}}$, in the same range as for the Weisshorn event, suggesting that break-off of a cold hanging glacier could occur as soon as surface velocities reached $0.5\ \mathrm{m\ d^{-1}}$. ~~By taking critical time as an upper time bound of the event occurrence, this method provides a good estimate of the timing of the break-off.~~ We showed that evaluating the time at which extrapolated velocities (based on the log-periodic fit) reach a ~~given~~ prescribed threshold ($0.5\ \mathrm{m\ d^{-1}}$ and $1\ \mathrm{m\ d^{-1}}$) provides a significantly better forecast. However, in the present case, ~~the time needed for the glacier to increase its velocity by~~ surface velocity increased from 50 to 100 cm/d ~~was~~ in the order of ~~a~~ one week. In practice, we suggest ~~that~~ to use a critical velocity of v=$0.4\ \mathrm{m\ d^{-1}}$ ~~be applied~~ to determine the period of highly ~~probable~~ likely break-off occurrence. A retrospective analysis based on this method showed that an accurate prediction of the phenomenon can be ~~made~~ achieved two weeks before its occurrence using the last month of surface displacement data and $0.5\ \mathrm{m\ d^{-1}}$ and $1\ \mathrm{m\ d^{-1}}$ as velocity thresholds. Although

~~the crude volume can be estimated, provided that a sufficient number of measurements points is available, this method does not seem to be able to detect whether the break-off will occur as a single large event or as a series of~~ enabling a crude estimation of the total unstable ice volume, this point based surveying procedure is not appropriate to determine whether the unstable ice mass will fall down in one event or disaggregate and give rise to several smaller events, as no differences in the evolution of surface displacements were detected. This has ~~of course important consequences for~~ consequences for the risk evaluation, as the resulting ice avalanche (and also the chain of processes resulting from its release) depends on the ~~initial ice volumereleased~~falling ice volume. To conclude, our results suggest that the ~~present methods~~ presented monitoring and data processing techniques exploiting the log-periodic oscillating behavior ~~are universal and thus~~ can be applied in real time to forecast a break-off event on any cold unstable hanging glacier.

Acknowledgements. The authors thank Susan Braun-Clarke for proofreading the English. The authors thanks also J. Bassis and two anonymous reviewers for their useful comments that significantly improved the manuscript.

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