Response to reviewers

Each of the reviewer's comment are included and the response and altered section from the manuscript below in italic.

Review 1

One significant issue is that it was somewhat unclear what is being measured / modelled.
It kind of seems like magic: one measurement (passive voltage) tells us about both water content and meltwater flux? As written, it is unclear to me how these are parsed, exactly.

The section introducing self-potentials in the introduction has been rewritten to try and make this clearer, the section now reads,

'The self-potential technique is a passive geo-electrical method that exploits the presence of naturally-occurring electrical potentials in the subsurface generated as a result of dipolar charge separation when water flows through a porous matrix ('streaming potential'; Darnet et al., 2003, Revil et al., 2006). The self-potential method has a unique ability in delineating, monitoring, and quantifying the flow of subsurface water in groundwater aquifers and unsaturated media (e.g., Revil et al., 2006, and references therein), and for numerous cold regions application (e.g., French et al., 2006; Kulessa, 2007, and references therein). This ability is due on the fact that pore waters generally have an excess of electrical charge due to the electrical double layer at the interface between the solid matrix (in this case snow grains) and pore water. The advective drag of this excess of electrical charge is responsible for a streaming current, whose divergence generates a quasistatic electric field known as the streaming potential (Sill, 1983; Revil et al., 2003). More recently, streaming potential theory has been extended for unsaturated conditions (Linde et al., 2007; Revil et al., 2007; Jougnot et al., 2012)'.

Another point without clarity just comes from language: The word "model" is thrown around, but a qualifier is needed: there is no numerical model presented here, but rather equation fitting. Some clarification is needed early in the paper and throughout. I kept waiting for an integrated, physically-based model to appear.

In all instances the terms model/modelling have been removed from the manuscript and replaced with calculation/estimation where appropriate.

My biggest problem with this paper is the sensitivity analysis. As conducted, it appears that all the variables were varied independently, which suggests no feedback between them. Is this true? If so, that should be explained. If not, a more robust sensitivity analysis should be considered.

Originally the sensitivity analysis figure was included in a supplementary materials document. This has now been included in the main manuscript (Figure 7) and Section 5 regarding sensitivity has been re-written for clarity; Section 5 now reads,

'We evaluate the sensitivity of calculated liquid water contents to both individual and combined parameter uncertainties. For each parameter a range of uncertainty values was created, with the respective minima and maxima approximately twice that of the uncertainty (Table 1). Repeat water content calculations were carried out initially by changing each parameter individually for a range of values between the respective minima and maxima. The results cluster broadly in three categories, including the zeta potential (up to ~ 20 % change

in liquid water content within the 50 % uncertainty range), followed by grain diameter, survey area width, electrical conductivity, snow depth and snow density (~ 3 – 4 % change) and bulk discharge, and self-potential (2 % change) (Fig. 6). These three categories readily reflect our knowledge of or ability to measure in-situ the respective parameters, with surprisingly low sensitivity to cross-sectional area despite our simplistic calculation and significant inherent assumptions (i.e. 1 – 4 in Section 4). Self-potential magnitudes are readily measured in the field with minimum uncertainty (Fig. 6), although the strongly enhanced sensitivity to the zeta potential highlights the need for focused research to tightly constrain possible values of this parameter in in-situ snow packs.

While this gives a good indication of the parameters to which water content calculations are most sensitive, it does not indicate possible feedbacks between parameters. Feedbacks were therefore evaluated by calculating liquid water contents for all possible combinations of the best estimates and minimum and maximum parameter values (Table 1), giving over 6500 solutions (Fig. 7). The minimum and maximum outputs were then adopted as the lower and upper uncertainty bounds (Fig.3). Due to the large potential uncertainty in the zeta potential, the sensitivity range was arbitrarily set to ± 50 % for illustrative purposes (Section 4).

Despite our consideration of extreme potential error bounds, calculated uncertainties in liquid water contents are restricted to a relatively small range (~ 20 % for large assumed uncertainty in the zeta potential, and ~ 3 – 4 % otherwise) at both Rhone Glacier and Jungfraujoch Glacier, and absolute values remain within the pendular regime where water bodies in the pore space remain isolated. At the latter site the daily evolution of liquid water contents thus is well captured even if uncertainty is taken into account (Fig. 5b), and likewise at Rhone Glacier calculated liquid water contents plus uncertainties still fall within the range of field measurements (Fig. 5a). Our inferences thus not only support Kulessa et al.'s (2012) notion that existing snow hydrological relationships are robust for modelling purposes, but also suggest that they may apply to in-situ field surveys. These inferences can also provide an explanation for the relatively large self-potential magnitudes generated by relatively low bulk discharge at Jungfraujoch Glacier (Fig. 2). Because we did not observe or infer any consistent or statistically-significant differences between Rhone Glacier and Jungfraujoch Glacier in dielectric permittivity (ε), zeta potential (ζ), saturation (S_w S_e^{-n}), electrical conductivity (σ_w) or cross-sectional area (A), the only remaining parameter that could facilitate the observed relative difference is permeability (k). Indeed, using an average snow density of 564 kg m^{-3}, the differences in mean snow grain sizes between Rhone Glacier (1.5×10^{-3} m) and Jungfraujoch Glacier (1×10^{-3} m) translate into respective permeabilities of 9.7×10^{-5} m^2 and 4.3×10^{-5} m^2. The relatively reduced permeability of Jungfraujoch Glacier's accumulation-area snow-pack therefore likely supported the presence of self-potential magnitudes that were markedly elevated relative to Rhone Glacier's ablation-area snow-pack (equation (4)). This inference emphasises the sensitivity of the self-potential method to permeability as a fundamental snow-hydrological property, along with its observed sensitivity to bulk melt water discharge and inferred sensitivity to liquid water content'.

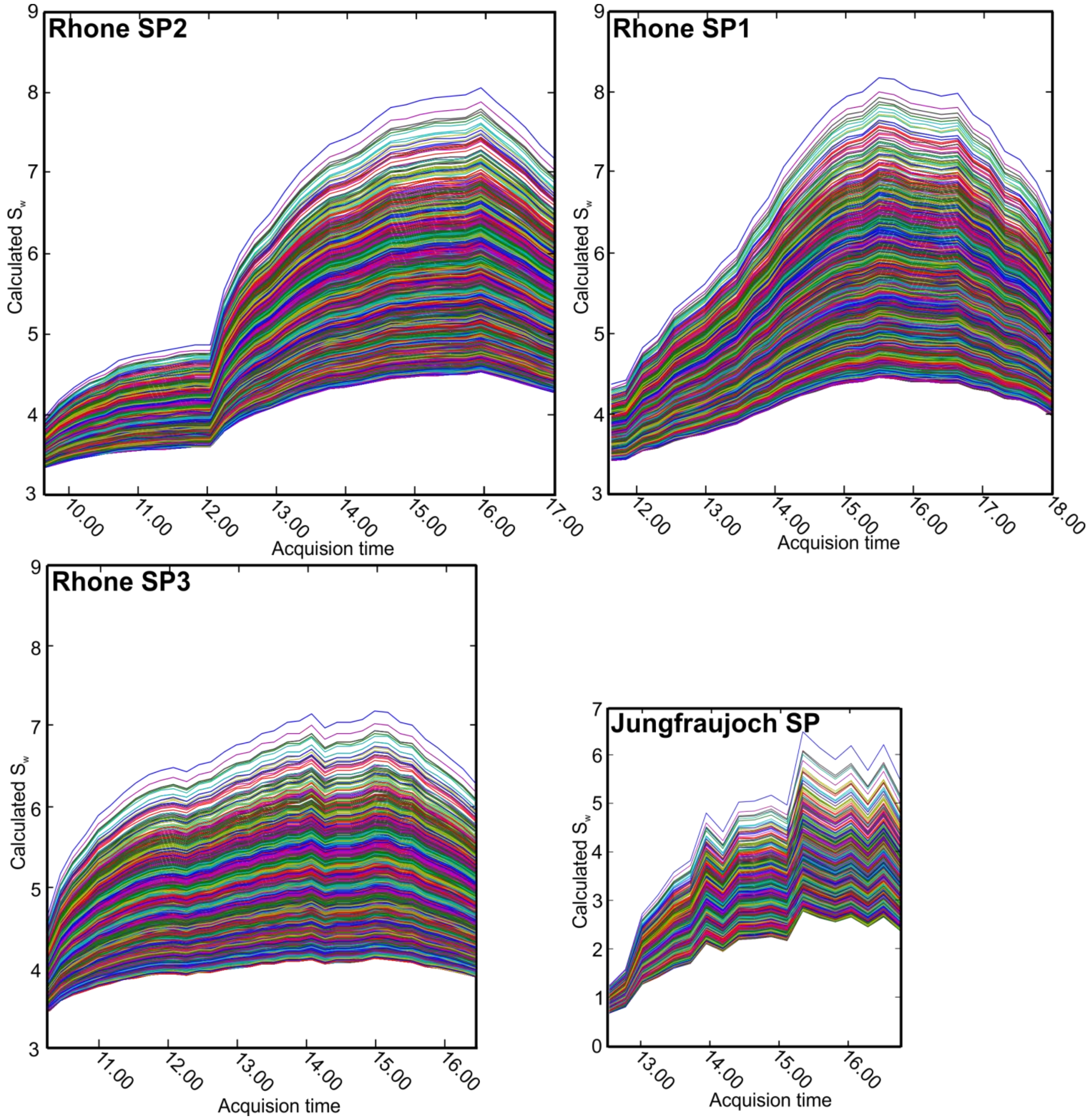

Figure 7: *Full sensitivity analysis for each of the four data sets. Each graph shows the full range of calculated Sw values of every combination of min, model input and max for each of the input parameters.*

Also, why are there only data for one day in the results? It would have been instructive to see the melt/freeze cycle over 24 hours. As is, I don't know how to interpret the meaningfulness of the estimated values.

This is a feasibility study and we were subject to time limitations. For future work we must of course consider 24-hr and continuous monitoring. However, it is clear that there are consistent changes through the days, even without 24-hr data.

Lastly, more is needed to explain why it correct to assume that the properties of snow and meltwater are temporally invariant, and how important that is to the analyses here. This would be a great line of discussion for a conclusions section. The paper just kind of dies off with a list of possible future needs, without a clear indication of how to step forward on these, or without a clear wrap up of the work that has been done. A conclusions section would be really valuable to this paper, especially since the abstract itself is quite poor. It is much too vague, and don't focus on quantitative results of study.

The conclusions section has been completely re-written, in reference to this comment and comment P8 L3-16. It now reads,

'The ability of the electrical self-potential method to sense meltwater flow in in-situ snowpacks is unique, where self-potential magnitudes scale directly with discharge and are zero in the absence of flow. The scaling factor depends principally on the liquid water content of the snowpack, its permeability and the water chemistry (Kulessa et al., 2012). We have shown here that diurnal variations in the liquid water content of in-situ snowpacks can be derived from electrical self-potential data and bulk discharge measurements with a simple lysimeter. This derivation was subject to four key assumptions (Section 4) which we now examine in turn to identify what, if any, constraints arise for future applications.

The Reynolds number (Re) is a common measure of the mode of fluid flow through porous media, as discussed in a relevant cryospheric context by Kulessa et al. (2003a):

$$Re = \frac{\rho_s v L}{\eta} \qquad (9)$$

where v and L are respectively characteristic fluid flow velocity (in m s^{-1}) and characteristic length scale of flow (in m), and ρ_s and η are respectively snow density (in kg m^{-3}) and dynamic viscosity (in Pa s). To a first approximation the transition from laminar to turbulent flow nominally occurs when $Re \approx 10$, although laminar flow can persist at much higher values of Re (for comparison, in open channels transition occurs at $Re \approx 2300$). For our purposes v can be assumed to correspond to the average linear velocity of flow, $v = Q A^{-1} n^{-1}$, where n is effective porosity (ratio of snow and ice densities). In porous media such as snow L corresponds to the average pore diameter, and in the absence of direct evidence is assumed to be equal to grain size; in practice an overestimation of pore diameter. For the respective snow properties and their uncertainties reported in Table 1 values of Re between ~ 0.1 and ~ 50.7 are obtained, with a best estimate of $Re \approx 1.1$. These values pertain to times of highest measured meltwater discharge when the Reynolds number is likely be greatest. Despite the unrealistically large uncertainty bounds considered in Table 1, and the overestimation of pore diameter (L) and associated inflation of the Reynolds number (equation (9)), we can therefore conclude that meltwater flow in our snowpacks was laminar. The absolute and relative inclinations of the snow surface and base will vary to different degrees within different field areas, thus generating differences in discharge and potentially preferential flow. Indeed, it is an exciting attribute of self-potential measurements that they will, in practice, aid to delineate such differences in meltwater flow.

Persistent meltwater runoff at the snow surface is uncommon, and meltwater flow through underlying soils or ice will normally be negligible or small compared to flow through or at the base of snowpacks. We have also shown that the inversion of self-potential data for snow properties such as liquid water content is insensitive to the area of snowpack contributing meltwater flow to the measured signals. Uncertainties in the area of origin of water contributing to measured bulk discharges and thus measured self-potential data are not therefore expected to be a major hindrance to future applications of the self-potential method to snow problems. We have also shown that with the exception of the zeta potential, sensitivity to uncertainties in the snow properties governing the relationship between self-potential data *and liquid water contents are small (~ 3-4% in our feasibility study). Future work must ascertain to what extent longer-term monitoring studies are affected by the preferential elution of ions and the associated impacts on meltwater pH, EC and thus the zeta potential. Even if such effects were found to be of concern, meltwater EC and pH are readily monitored in-situ with automated probes and could be measured alongside self-potential data at a calibration location, and subsequently be assimilated in snow models.*

The final consideration focused on the assumption that the spatial pattern of self-potential magnitudes, measured during the day across our survey areas, was due to temporal changes in the liquid water content of the snowpack. This assumes that any spatial pattern due to elevation changes between the bottom and top of our survey areas is comparatively small and indeed negligible. Kulessa et al. (2003a) showed that elevation-driven changes in the self-potential fields measured between upstream (Ψ_{up}) and downstream (Ψ_{down}) locations (z_{up}, z_{down}) can be approximated by

$$\psi_{up} - \psi_{down} = -\frac{\varepsilon\zeta}{\eta\sigma_w} S_w \left(z_{up} - z_{down}\right), \tag{10}$$

here translated to our notation and adjusting for meltwater saturation according to equation (2). Even for the maximum daily values of saturation inferred from our measurements the elevation-driven spatial pattern has small magnitudes, estimated to be ~ -16.0 mV and -8.4 mV respectively for Jungfraujoch Glacier and Rhone Glaciers. These values are an order of magnitude smaller than daily changes measured at the two glaciers (Fig. 2) and are therefore considered to be insignificant for the purpose of the present feasibility study. In similar future applications the relevance of such spatial changes should be assessed on a case by case basis, and would in fact readily be incorporated into quantitative inferences of snow properties from self-potential data where they are of concern'.

More minor issues are below:

P3 L1: uncertainty in what?

Uncertainty refers to that inherent in the operational models used in snow and hydrological forecasting discussed in the previous sentence, the sentence now reads,

'This uncertainty in operational models is rooted principally in the inability of traditional snow-hydrological techniques to provide automated attribute measurements non-invasively and on spatial scales that match those used in operational snow models'.

L20: remove semicolon, inappropriate use and not needed

Removed semicolon.

L 23: Don't we know that the answer to Q1 is "yes" based on previous work? Maybe we specific about what processes/parameters instead.

We know that the method has potential from laboratory tests carried out by Kulessa et al. (2012) but we do not know how well the technique performs in the field. To clarify this question now reads, *'Can the self-potential method serve as a non-intrusive field sensor of temporally evolving bulk meltwater fluxes and liquid water contents of snow?'*.

L26: "hydrological implications" of what?

This question was removed following the comments of reviewer 2 and now reads,

'Lastly we discuss the implications and possibilities of the technique for future snow measurement and modelling research and practice'.

P4 L6: This equation has been around long before Kulessa et al. 2012. Another ref should be used here if one is needed.

Reference was removed.

L19. Why would h0 and psi_0 have negligible magnitudes?

The magnitudes should be negligible as care was taken in locating the reference electrode where no streaming potential occurred, or where the potential was considered constant, see the later description of the survey set up at each site. The section now reads

'At a given time, t_n, the measured self-potential field, $\Psi_m(t_n)$, in our survey area is the difference between the locally produced self-potential field, $\Psi_l(t_n)$, and the self-potential field at the reference electrode, $\Psi_0(t_n)$. The latter is unknown in our field feasibility study, although our method of emplacing the reference electrode is elaborate and designed to eliminate, or at least minimise, any streaming potentials at the reference electrode. Once the reference electrodes have settled in their environments, we further expect any electrochemical or thermal potentials to be negligible. We can therefore expect $\Psi_0(t_n)$ to be close to zero, but nonetheless apply caution and take a two-step approach. Initially we eliminate the reference self-potential fields by considering temporal changes in measured self-potentials only before, subsequently, considering absolute self-potential magnitudes'.

P5 L1: What is the meaning of this saturation exponent? This appears to just be an empirical fitting factor.

The value comes from Albert et al. (1998) who state, 'Denothe et al. (1979) calculated that in snow, n attains values in the range 2.16 ± 4.59, and observed a dependence of the derived value of n on grain size, but concluded that no clear relationship exists between any snow parameter and n. For the current work we simply use a constant, user-supplied value for n, with a default value of 3.3.' The reference to Albert has been added to the sentence, which now reads,

'$n \approx 3.3$ is the saturation exponent (after Albert et al., 1998, Kulessa et al., 2012).

L3-6: This sentence is so awkwardly written that I'm not sure what is happening. What "experimental concept"? That simulates what in situ? And "all" attributes? What are these?

The sentence has been rewritten for clarity and now reads, *'To address the specific objectives set out in the introduction through data-driven testing of this model, we developed an experimental survey design to simulate the geometry of Kulessa et al. (2012) laboratory snow column (Fig. 1b). It was therefore our aim to characterise lateral bulk meltwater fluxes in inclined snowpacks at two glaciers in Valais, Switzerland, measuring all relevant snow pack attributes for ground truth'.*

L20: How is meltwater bulk discharge measured? (I later see, on P6 line 8. Move up.)

This was moved from the later location and the sentence now reads,

'At both sites more than 100 self-potential measurements were made at the snow surface, and meltwater bulk discharge in a lysimeter, pH and electrical conductivity, and snowpack characteristics including thickness, density, grain size and liquid water content were recorded.'

L24: Awkward wording: "Execution followed the potential amplitude method"

The sentence was reworded and now reads,

'The survey was carried out following the potential amplitude method (Corry et al., 1983); this employs a reference electrode in a fixed location and a roving electrode which is moved through the survey area at 0.5 m intervals.'

P6 L19: What is 0.4m? The depth of the snow pack? Not clear how measurements were made….at 0.4 m depth?

The Denoth instrument was inserted into the snow pack at a depth of 0.4 m in the same location as each of the SP measurements, the sentence has been rewritten and now reads,

'Liquid water content was estimated using two different techniques, including the hand test (Colbeck et al., 1990, Fierz et al., 2009) in the surface and base layers of Rhone Glacier's snow pit, and the Denoth Capacitance Meter (Denoth, 1994) in the surface and base layers of the snow pit at Jungfraujoch. The latter were acquired across a 2D grid where the instrument was inserted into the snowpack at a depth of 0.4 m following the same survey spacing as the self-potential measurements'.

L22-23. First sentence here is awkward.

The sentence was reworded and now reads,

'The drift-corrected self-potential magnitudes and meltwater bulk discharges both increase with time through the day until a peak in late afternoon, after which they both begin to decrease.'

L24. Magnitude of what?

Magnitude of the measured self-potential, the sentence now reads,

'There is no distinguishable time lag between the measured self-potential magnitude and discharge data.'

L27. What is an "even day"?

This was a typo, the sentence now reads,

'Intriguingly bulk discharge at Jungfraujoch was akin to day 3 at Rhone glacier but self-potential magnitudes at Jungfraujoch were much higher than days 1 and 2 at Rhone glacier.'

P7 L3. This is fluid electrical conductivity, right?

Changed to 'Fluid electrical conductivity'.

L14. Most of these measurements seem to have no consistent pattern. Perhaps tie up this paragraph by noting what actually had value to the model.

It is the small range in the values of the measurements that are of most interest, we are assuming that the snowpacks at Rhone and Jungfraujoch are mature, as first suggested earlier in Section 2 (p5, l13-18) where we state

'We therefore expect them to be physically mature in terms of enhanced grain size and density due to metamorphosis, and chemically mature in terms of invariant meltwater pH and electrical conductivity as preferential elution of solutes has been completed (Kulessa et al., 2012, and references therein)'. This section now includes clarification, and reads, 'The very small variability range of the snowpack characteristics measured is consistent with mature snowpacks, as assumed above with reference to prior meteorological conditions'.

L 17. I have trouble believing there are no surface undulations in any field setting. How was this confirmed? If snow covered, how is it even known? Or do you mean surface of the snow?

This is referring to the snow surface, the sentence has been rewritten and now reads,

'Both survey areas were south facing, topographically-inclined but otherwise had no visibly distinguished snow surface undulations'.

P8 L3-16. It's really great that the authors have listed the assumption of their model here. However, some of these seem really constraining and also hard to validate. Somewhere in this paper, the implications of having some of these assumptions wrong seems important to believing the results. Another thought of the conclusions section.

The conclusion section has been rewritten to include an assessment of the 4 assumptions, the full section was addressed with this in mind in response to the earlier comment regarding the conclusions.

L20. How is cross-sectional area measured? Is this just the area of the snow pack? If so, does the ground below the snow have no impact?

This is the area of the snowpack, the ground beneath is assumed not to have an impact as there is no detectable flow going on beneath the survey area. At the Rhone Glacier site the area beneath the snowpack was glacier ice, the interface with which no melt was identified. At

Jungfraujoch the base of the cross section was the limit of the diurnal melt penetration. The sentence has been reworded and now reads,

'cross-sectional area (A) (survey area width × snow depth) was measured directly'.

L21. Isn't the dielectric permittivity of water around 80 (unitless)? What is the value given here? Also, this is permeability of the snow, correct?

This variable should have been the dielectric permittivity (F m^{-1}) of pore meltwater and the sentence has been rewritten fully. It now reads,

'Assuming that water at 0 °C has a dielectric permittivity of ε_r = 88, the dielectric permittivity (F m^{-1}) of pore meltwater is $\varepsilon = \varepsilon_r \varepsilon_0$ = 7.8 x 10^{-9} Fm_1, where ε_0 = 8.85 x 10^{-12} F m^{-1} is the dielectric permittivity of vacuum'.

The equation used to derive snow permeability is commonly used thought to be robust for our purposes, the basis is now explained in the text which now reads,

'The commonly used equation was derived from a fit to laboratory data collected with small rounded grains and a starting grain diameter of ~0.33 mm (Shimizu, 1970). However, later work ascertained experimentally that Shimizu's [1970] empirical formula does in fact apply to a much larger range of grain diameters expected to be encountered in practice (less than 0.5 mm to greater than 2 mm) (Jordan et al., 1999). We can therefore expect equation (7) to be robust for our purposes'.

P9. In general, readers shouldn't have to look at another paper to understand the one we're reading. Bring in the equations/figures from the other paper if needed to tell the story here.

The equation from Kulessa et al 2012 has been included as a new equation 8, the section now reads,

'Recent 'natural snowmelt' laboratory experiments were consistent with a progressive increase of pH from 4.3 to 6.3 and a simultaneous decrease in electrical conductivity from ~ 1 × 10^{-1} S m^{-1} to ~ 6 × 10^{-7} S m^{-1}, as the elution of ions follows a well-known sequence (Kulessa et al., 2012)). Upon conclusion of the Kulessa et al.'s (2012) laboratory experiments, modelled rates of change of pH and electrical conductivity were minimal and the snow column mature. The zeta potential is principally a function of pH and electrical conductivity:

$$\zeta(\sigma_w, pH) = [\alpha + \beta log_{10}\sigma_w]\left(sin\frac{\pi}{12}[pH_w - pH_w(pzc)]\right), \quad (8)$$

where α and β depend on the chemical composition of the pore fluid and can be determined empirically (Revil et al., 1999). Kulessa et al. (2012) inferred the zeta potential changed from ~ -7.5 × 10^{-2} V at the start of the natural snowmelt experiments to +1.5 × 10^{-2} V at the end, when the rate of change of the zeta potential was minimal.

The final values of pH and electrical conductivity that Kulessa et al. (2012) calculated from equation 8 were similar to those measured at Rhone Glacier and Jungfraujoch Glacier (respectively ~ 6.5 – 6.9 and ~ 1 – 5 × 10^{-6} S m^{-1}), suggesting that these in-situ snow packs were likewise mature as expected (Section 2). This inference is corroborated by the absence of consistent spatial or temporal changes in either pH or electrical conductivity throughout the survey periods. In Kulessa et al.'s (2012) laboratory study, the pH-corrected zeta *potential had values around zero for the range of electrical conductivities (1 – 5 × 10^{-6} S m^{-1}) measured at Rhone Glacier and Jungfraujoch Glacier (1 – 5 × 10^{-6} S m^{-1}), and its rate of change became minimal along with those of pH and electrical conductivity. We can therefore expect a small and invariant zeta potential value to apply to the snowpacks at Rhone Glacier and Jungfraujoch Glacier'.*

L21. What "indeed agrees"? The pH and EC data with themselves? That's what the sentence implies as written. Confusing.

Agrees with the suggestion that the snowpack is mature, this was re-worded for clarification and the section now reads,

'The final values of pH and electrical conductivity that Kulessa et al. (2012) calculated from equation 8 were similar to those measured at Rhone Glacier and Jungfraujoch Glacier (respectively ~ 6.5 – 6.9 and ~ 1 – 5 × 10^{-6} S m^{-1}), suggesting that these in-situ snow packs were likewise mature as expected (Section 2). This inference is corroborated by the absence of consistent spatial or temporal changes in either pH or electrical conductivity throughout the survey periods'.

P10. L 24. I don't like the word "modeled" here for putting numbers into an equation. So despite the huge variability in the measured parameters, the moisture content only values by 1-3%? How is that possible in the linear equation I assume is being used (Eq 3,5)?

The term modelling/model has been changed in this instance and others to calculating/calculate.

L27. Period missing.

Added period.

P 11 L21. Is there no feedback between the tested variables? Again, I'm surprised by the small variability in parameters of interest given the huge uncertainties in measurements. Somehow, this needs to be explained so that it's accessible to your readers.

Yes, this is perhaps surprising / counter-intuitive, but the sensitivity analysis varying all possible combinations of parameters does support this and the self-potential method is well known to be robust for hydrological applications.

P 12 L1. Definition of how snow pack is measured should be moved way up to when first mentioned.

This was moved and explained in the earlier comment.

L8. 's is missing after the citation.

Added

L11. So what is the benefit of SP if other measurements are needed to confirm? To more fully explore in space or time? Some information is needed here to help the reader. I also don't still understand how water content and flux are distinguished from a single data set.

This has been more fully described in both the abstract and the conclusions, the last section of the abstract now reads,

'We conclude that the electrical self-potential method is a promising snow and firn hydrological sensor owing to its suitability for [1] sensing lateral and vertical liquid water flows directly and minimally invasively, [2] complementing established observational programs through multidimensional spatial mapping of meltwater fluxes or liquid water content, and [3] low-cost autonomous monitoring. Future work should focus on the development of self-potential sensor arrays compatible with existing weather and snow monitoring technology and observational programs, and the integration of self-potential data into analytical frameworks'.

The first section of the synthesis and conclusions now reads,

'The ability of the electrical self-potential method to sense meltwater flow in in-situ snowpacks is unique, where self-potential magnitudes scale directly with discharge and are zero in the absence of flow. The scaling factor depends principally on the liquid water content of the snowpack, its permeability and the water chemistry (Kulessa et al., 2012). We have shown here that diurnal variations in the liquid water content of in-situ snowpacks can be derived from electrical self-potential data and bulk discharge measurements with a simple lysimeter'.

Table 1. Somewhere in the text, more description of uncertainty vs sensitivity as defined here is needed.

The uncertainty / sensitivity analysis section (5) has been rewritten to include this point and the full section is included in reference to the initial sensitivity comment above. In addition Table 1 has been altered to improve clarity and now reads,

Measured / estimated parameters	***Rhone SP2 input value***	***Uncertainty range***	***Sensitivity range***
Self-potential ψ_m (V)	*Variable*	$\psi_m \pm 40\%$	$\psi_m \pm 20\%$
Discharge Q ($m^3 s^{-1}$)	*Variable*	$Q \pm 40\%$	$Q \pm 20\%$
Electrical conductivity σ_w ($S m^{-1}$)	5×10^{-6}	$10^{-7} – 10^{-4}$	$\sigma_w \pm 5 \times 10^{-7}$
Zeta potential ζ (V)	-1×10^{-5}	$10^{-4} – 10^{-6}$	$\zeta \pm 50\%$
Permeability from;			
Grain diameter d (m)	*0.00175*	*d ± 0.001*	*d ± 0.0005*
Density ρ ($kg m^3$)	*555.5*	*ρ ± 140*	*ρ ± 70*
Cross sectional area from;			
Width w (m)	*12.5*	*w ± 10*	*w ± 5*
Depth dp (m)	*1.45*	*dp ± 1*	*dp ± 0.2*

Table 1: *Best estimate of each parameter for Rhone Glacier SP2 (Day 2) and relative assumed uncertainty and sensitivity ranges. The sensitivity ranges are based on the measurement accuracy of each measured parameter or the confidence of estimates parameters. The uncertainty ranges are exaggerated from the sensitivity values to highlight the effect of poor measurement or estimation.*

Figure 4. I'm confused. Why isn't there a range of estimated Sw here? Isn't each parameter being varied from a min to max value such that there should be a range of outcomes?

In the original manuscript Figure 4 (now Figure 6) did illustrate the difference between the minimum and the maximum Sw calculation for each variable. The figure has been change to include the range of values for each variable. This is a greatly exaggerate range of uncertainty associated with the measured values to show the parameters that we need to be most careful with. The new Figure is shown below,

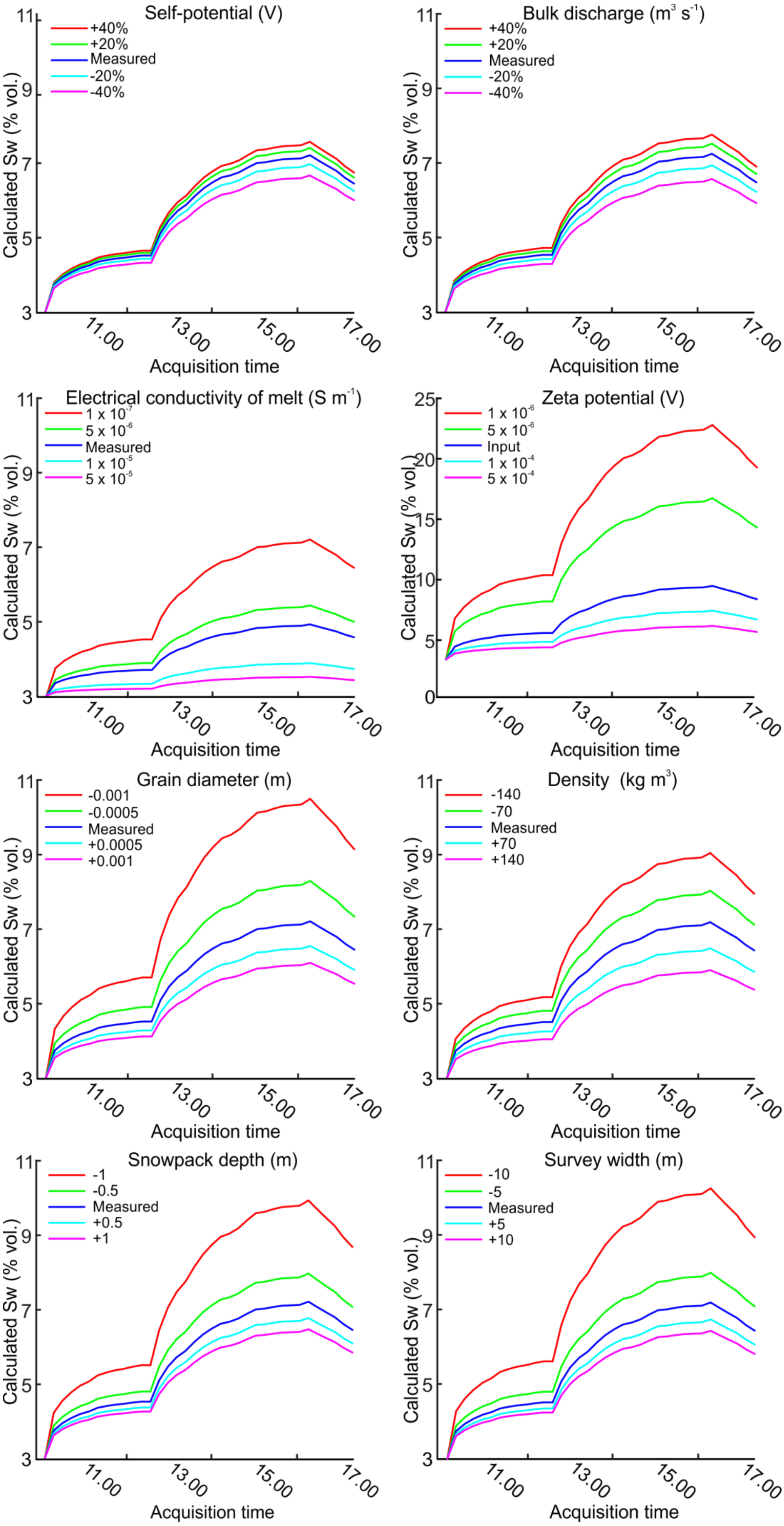
Self-potential (V)
+40%
+20%
Measured
-20%
-40%
Bulk discharge (m3 s-1)
+40%
+20%
Measured
-20%
-40%
Electrical conductivity of melt (S m-1)
1 x 10-7
5 x 10-6
Measured
1 x 10-5
5 x 10-5
Zeta potential (V)
1 x 10-6
5 x 10-6
Input
1 x 10-4
5 x 10-4
Grain diameter (m)
-0.001
-0.0005
Measured
+0.0005
+0.001
Density (kg m3)
-140
-70
Measured
+70
+140
Snowpack depth (m)
-1
-0.5
Measured
+0.5
+1
Survey width (m)
-10
-5
Measured
+5
+10
Calculated Sw (% vol.)
Acquisition time
11.00
13.00
15.00
17.00

Figure 6: *Sw calculations for a range of values for each input parameter, using Rhone Glacier SP2 as an example. In each case the range is an exaggerated uncertainty range (Table 1), highlighting the effect of each individual parameter on the calculated Sw output.*

<u>Review 2</u>
I suggest to remove objective 3, which is not really an objective, but the perspectives that conclude a scientific communication.

Objective three has been removed and replaced with a sentence that reads,

'Lastly we discuss the implications and possibilities of the technique for future snow measurement and modelling research and practice.'

The introduction and the objectives are clearly explained, as well as the brief description of the SP theory in the case of snow (based on previous wroks by Kulessa et al., 2012).

From equation (3), it is clear that the SP signal strongly depends on snow properties, such as water saturation, conductivity, pH (through zeta), permeability, among others. The relation between the measured electrical potential and the water content is thus absolutely not straightforward, all the more as these properties may be not well determined - and this is the difficulty of the question.

This has now been more fully addressed in the synthesis and conclusions, please see the response to the comments from reviewer 1 regarding the implications of the 4 assumptions (comment P8 L3-16) and strengthening the conclusions.

To test the SP methods, the authors performed two experiments in two natural sites, where the snowpack has encountered significant melting. The protocole are well described.
Some results are given in figure 2 (discharge and SP): if discharge clearly evolves with time, the correlation with the SP signal is not so clear, whereas equation (3) predicts a linear relation, if all other parameters are kept constant. Would it be possible to add a subplot SP vs. Q, to evidence a correlation (or not)?

To illustrate the temporal evolution of SP with bulk discharge a new figure (3) has been added showing SP/BD.

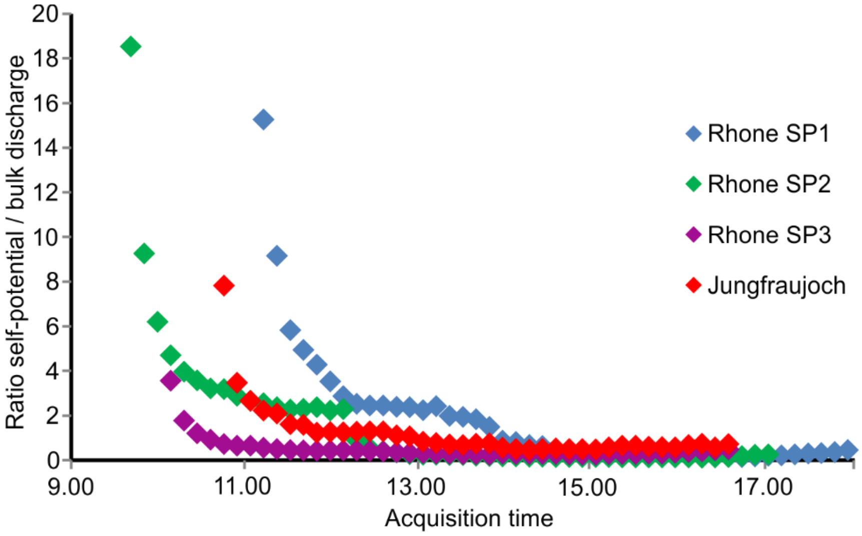

Figure 3: *Ratio between self-potential (V) and bulk discharge (m^3 s^{-1}) for each of the four surveys through time, illustrating the ratio changes consistently over time.*

For applying equation (3), all parameters were recorded or estimated with well-known relations. The main difficulties is the estimation of the zeta potential, which strongly changes with pH and conductivity. I am somehow confused with the method used here. Indeed, it seems that the authors chose the value of zeta so that equation (3) gives a value for the water content in agreement with the measured value (see Figure 3). To my mind, this is not modelling, but trials and errors. For a better understanding, I suggest to add a new graph superimposing in the different Sw curves predicted by equation (3) for different values of zeta.±

We did not do any trial and error fitting with the zeta potential but selected the value from the work carried out in Kulessa et al (2012) as discussed in section 4. The very large uncertainty bounds used in the uncertainty analysis reflect the possible error associated with this modelled value but the output range from this is still only ~ 20%.

The section about the sensivity is not clear and somehow hard to understand. In particular, the sense of figure 4 is unclear to me. What was the method? For a considered parameter, all the others were kept constant at their average value, and Sw was estimated with the maximal and minimal value of the considered parameter??? If yes, it provides uncomplete estimate. The N parameters should varies together... This part should be reconsidered and rewritten for clarity.

The whole section on sensitivity has been rewritten, figure 4 (now figure 6) has been expanded and a new figure 7 has been added. Please see the response to reviewer 1 regarding rewriting the sensitivity analysis.

The conclusion present the future works to be achieved in order to make SP a routine method. To my mind, the most important is the laboratory study of the zeta potential in function of snow properties...

Yes, this is a very important point and should be the focus of future work, this is stated in Section 5 which now reads,

'Self-potential magnitudes are readily measured in the field with minimum uncertainty (Fig. 6), although the strongly enhanced sensitivity to the zeta potential highlights the need for focused research to tightly constrain possible values of this parameter in in-situ snow packs'.

The weakest part is the sensitivity analysis, which deserves rewritting.

The whole section on sensitivity has been rewritten, figure 4 (now figure 6) has been expanded and a new figure 7 has been added. Please see the response to reviewer 1 regarding rewriting the sensitivity analysis.

p3 line 9: "modelling" (i.e., SP equation 3) instead of "numerical modelling"

All instances of the terms model/modelling have been changed in response to comments from reviewer 1.

p10 line 7: is the small, negative value of zeta determined by Sw fitting coherent with what we know about the pH and the conductivity?

Yes, this is coherent with the laboratory work carried out by Kulessa et al (2012), this is discussed in part of section 4 which reads,

'Earlier work on artificial ice samples, of fixed bulk electrical conductivity, ascertained that the zeta potential reverses sign from ~ +0.01 V to ~ -0.02 V as equilibrium pH increases from less than 3 to greater than 8 (Drzymala et al., 1999, Kallay et al., 2003). The electrochemical properties of the electrical double layer at the snow grain surfaces, and thus also the magnitude and potentially the sign of the zeta potential, will change over time in a fresh snowpack as the snow is affected by melt, recrystallisation and the preferential elution of ions (Meyer and Wania, 2008, Meyer, 2009, Williams et al,. 1999b). Recent 'natural snowmelt' laboratory experiments were consistent with a progressive increase of pH from 4.3 to 6.3 and a simultaneous decrease in electrical conductivity from ~ 1×10^{-1} S m^{-1} to ~ 6×10^{-7} S m^{-1}, as the elution of ions follows a well-known sequence (Kulessa et al., 2012)). Upon conclusion of the experiments, modelled rates of change of pH and electrical conductivity were minimal and the snow column mature'.

Figure 2a: The spatial variability of the SP measurements is well estimated by averaging each profile. The value of this variability are in the classical ranges for the Rhone glacier, but it rather high for the Jungfraujoch. How this difference can be explained?

This difference is explained at the end of Section 5, which reads,

'Because we did not observe or infer any consistent or statistically-significant differences between Rhone Glacier and Jungfraujoch Glacier in dielectric permittivity (ε), zeta potential (ζ), saturation (S_w S_e^{-n}), electrical conductivity (σ_w) or cross-sectional area (A), the only remaining parameter that could facilitate the observed relative difference is permeability (k). Indeed, using an average snow density of 564 kg m^{-3}, the differences in mean snow grain sizes between Rhone Glacier (1.5×10^{-3} m) and Jungfraujoch Glacier (1×10^{-3} m) translate into respective permeabilities of 9.7×10^{-5} m^2 and 4.3×10^{-5} m^2. The relatively reduced permeability of Jungfraujoch Glacier's accumulation-area snow-pack therefore likely supported the presence of self-potential magnitudes that were markedly elevated relative to Rhone Glacier's ablation-area snow-pack (equation (4))'.

Please find the track changes version of the corrected manuscript below.

Bulk meltwater flow and liquid water content of snowpacks mapped with the electrical self-potential (SP) method

~~The electrical self-potential method is a non-intrusive snow-hydrological sensor~~

S. S. Thompson[1, *], B. Kulessa[2], R. L. H. Essery[3], M. P. Lüthi[4, *]

(1) Department of Arctic Geology, University Centre in Svalbard (UNIS), Svalbard

(2) College of Science, Swansea University, UK

(3) The School of Geosciences, University of Edinburgh, UK

(4) University of Zurich, Switzerland

(*) Formerly at Versuchsanstalt für Wasserbau, Hydrologie und Glaziology (VAW), ETH Zürich, Switzerland

Correspondence to S. S. Thompson (Sarah.Thompson@unis.no)

ABSTRACT

Our ability to measure, quantify and assimilate hydrological properties and processes of snow in operational models is disproportionally poor compared to the significance of seasonal snowmelt as a global water resource and major risk factor in flood and avalanche forecasting. ~~Encouraged by recent theoretical, modelling and laboratory work, w~~We show here that strong electrical self-potential fields are generated in melting in-situ snowpacks at Rhone Glacier and Jungfraujoch Glacier, Switzerland. In agreement with theory the diurnal evolution of ~~aerially distributed~~ self-potential magnitudes (~ 60 – 250 mV) relates to ~~closely track~~ those of bulk meltwater fluxes (0 – 1.2 × 10^{-6} m^3 s^{-1}) principally through the permeability and the content, electrical conductivity (EC) and pH of liquid water. Previous work revealed that

when fresh snow melts, ions are eluted in sequence and EC, pH and self-potential data change diagnostically. Our snowpacks had experienced earlier stages of melt, and complementary snow pit measurements revealed that EC (~ 1-5 × 10^{-6} S m^{-1}) and pH (~ 6.5 – 6.7) as well as permeabilities (respectively ~ 9.7 ×10^{-5} m^2 and ~ 4.3 ×10^{-5} m^2 and Rhone and Jungfraujoch glaciers) were invariant. This implies, first, that preferential elution of ions was complete and, second, that our self-potential measurements reflect daily changes in liquid water contents. These were calculated to increase within the pendular regime from ~ 1 – 5 % and ~ 3 – 5.5 % respectively at Rhone Glacier and Jungfraujoch Glacier, as confirmed by ground truth measurements. We conclude that the electrical self-potential method is a promising snow and firn hydrological sensor owing to its suitability for [1] sensing lateral and vertical liquid water flows directly and minimally invasively, [2] complementing established observational programs through 2-D or 3-D spatial mapping of either meltwater fluxes or chemistry, or liquid water content or permeability, and [3] low-cost 2-D or 3-D autonomous monitoring. Future work should focus on the development of self-potential sensor arrays compatible with existing monitoring technology and observational programs, and the integration of self-potential data into analytical frameworks.

in melting in-situ snowpacks at Rhone and Jungfraujoch glaciers, Switzerland. Numerical modelling infers temporally-evolving liquid water contents in the snowpacks on successive days in close agreement with snow-pit measurements. Muting previous concerns, the governing physical and chemical properties of snow and meltwater became temporally invariant for modelling purposes. Because measurement procedure is straightforward and readily automated for continuous monitoring over significant spatial scales, we conclude that the self-potential geophysical method is a highly-promising non-intrusive snow-hydrological sensor for measurement practice, modelling and operational snow forecasting.

1. Introduction

More than a sixth of the world's population relies on melt from seasonal snow and glaciers for water supply (Barnett et al., 2005). Snow, and runoff from snow, are also major resources for the hydroelectric, tourism and inland fishery industries, and furthermore represent hazards from flooding and avalanches (Mitterer et al., 2011). The availability of snow models constrained by a reliable observational basis, for the forecasting of snow hydrological properties and processes in climate, resource and hazard applications is therefore of considerable socio-economic significance (Wever et al., 2014). However, the parameterisation of fundamental snow-hydrological attributes, such as liquid water content and flux, is a well-recognised major source of uncertainty in operational models used in snow and hydrological forecasting (Livneh et al., 2010, Essery et al., 2013). This ~~U~~uncertainty in operational models is rooted principally in the inability of traditional snow-hydrological techniques to provide automated attribute measurements non-invasively and on spatial scales that match those used in operational snow models. Relevant traditional techniques include dielectric (Denoth, 1994) or 'hand' tests (Fierz et al., 2009) of snow liquid water contents, lysimeter measurements of discharge, temperature and pH and electrical conductivity of bulk meltwaters (Campbell et al., 2006, Williams et al., 2010), and manual observation or measurement of snow density and grain size (Fierz et al., 2009). Even cutting edge upward-looking radar measurements of snowpack structure and liquid water content (Heilig et al., 2010; Mitterer et al., 2011; Schmid et al., 2014) compare unfavourably with model predictions of wetting front propagation (Wever et al., 2014), attributed to inherent limitations of 1-D approach in capturing preferential flow.

By combining field measurements with a theory and model of self-potential signals associated with unsaturated flow in melting snow (Kulessa et al., 2012), ~~numerical modelling~~ we show here that electrical self-potential geophysical data integrated with ~~a combination of~~

traditional with electrical self-potential geophysical traditional snow measurements can address these limitations. The self-potential technique is a passive geo-electrical method that exploits the presence of naturally-occurring electrical potentials in the subsurface generated as a result of dipolar charge separation when water flows through a porous matrix ('streaming potential'; Darnet et al., 2003, Revil et al., 2006). The self-potential method has a unique ability in delineating, monitoring, and quantifying the flow of subsurface water in groundwater aquifers and unsaturated media (e.g., Revil et al., 2006, and references therein), and for numerous cold regions application (e.g., French et al., 2006; Kulessa, 2007, and references therein). This ability is due on the fact that pore waters generally have an excess of electrical charge due to the electrical double layer at the interface between the solid matrix (in this case snow grains) and pore water. The advective drag of this excess of electrical charge is responsible for a streaming current, whose divergence generates a quasistatic electric field known as the streaming potential (Sill, 1983; Revil et al., 2003). More recently, streaming potential theory has been extended for unsaturated conditions (Linde et al., 2007; Revil et al., 2007; Jougnot et al., 2012). The technique is well established for a number of subsurface hydrological problems, including aquifer characterization, mapping pollutant plumes and monitoring seepage in earth dams (Revil et al., 2003, Sheffer and Oldenburg, 2007, Doherty et al., 2010). A new theory and numerical model of self-potential signals associated with unsaturated flow in melting snow, along with laboratory tests, strongly promoted the technique as a non-intrusive hydrological sensor of water fluxes (Kulessa et al., 2012); at spatial scales intermediate between snow pits and satellite footprints or, given independent flux measurements, of evolving physical and chemical properties of snow and snow-melt.

We answer three two fundamental questions: 1) Can the self-potential method serve as a non-intrusive field sensor of temporally evolving bulk meltwater fluxes and liquid water contents of snow hydrological properties and processes? 2) What are the ambiguities introduced into estimates of liquid water contents from self-potential and bulk discharge data, by uncertainties inherent in the governing ~~How sensitive are retrievals of liquid water content from self-potential to~~ snow physical and chemical properties? Lastly we discuss the implications and possibilities of the technique ~~3) What are the hydrological implications~~ for future snow measurement and modelling research and practice.~~?~~ Our study thus takes a significant step towards the in-situ implementation of the self-potential method for improved characterization and monitoring of snow liquid water contents and melt water fluxes.

2. ~~Model~~Theory, field sites and methods

The Poisson equation relates the electrical field ψ to the source current density in a partially or fully-saturated snow pack,

$$\nabla \cdot (\sigma \nabla \psi) = \nabla \cdot \mathbf{j}_S, \tag{1}$$

where σ is the bulk electrical conductivity of the porous material (in S m^{-1}), and $\mathbf{j}_S$ is the source current density (in A m^{-2}) (Kulessa et al., 2012). Equation (1) applies only in the low-frequency limit of the Maxwell's equations without external injection or retrieval of charges, or charge storage in the snowpack. Extending the classic Helmholtz-Smoluchowski theory for unsaturated flow in snow, the one-dimensional solution to Eq. (1) is given by

$$\psi_m - \psi_0 = -\frac{\varepsilon\zeta}{\eta\sigma_w} S_w (H_m - H_0), \tag{2}$$

where ψ_m and H_m are respectively the electrical and hydraulic potentials at the measurement electrode, ψ_0 and H_0 are the corresponding potentials at the reference electrode, ζ is the zeta potential (V), and ε, η, σ_w and S_w are respectively the dielectric permittivity (F m^{-1}), electrical conductivity (S m^{-1}), dynamic viscosity (in Pa s) and relative saturation (dimensionless) of the melt or rainwaters in the snowpack's pore space (Kulessa et al., 2012). The zeta potential is the voltage across the electrical double layer at the interface between the ice matrix and the pore waters, as controlled by these constituents' physical and electrical properties. If ψ_0 and H_0 have negligible magnitudes compared to the self-potential field ψ, the relationship between ψ and bulk discharge Q (m^3 s^{-1}) in the snow pack through cross-sectional area A (m^2) is:

$$\psi_m = \frac{\varepsilon\zeta}{\sigma_w}\frac{S_w}{S_e^n}\frac{1}{kA}Q, \qquad (3)$$

where S_e is effective saturation and n ≈ 3.3 is the saturation exponent (Kulessa et al., 2012).

To address the three specific objectives set out in the introduction through data-driven testing of this model, we developed an experimental concept was developed thatsurvey design to simulates in-situ at two glaciers in Valais, Switzerland, the geometry of Kulessa et al.'s (2012) laboratory snow column (Fig. 1b and numerical model It was therefore our aim to characterise lateral bulk meltwater fluxes in inclined snowpacks at two glaciers in Valais, Switzerland, measuring all relevant snow hydrologicalpack attributes for ground truth. Self-potential and traditional snow-hydrological measurements were acquired on 13th, 14th and 15th June 2013 from the ablation area snowpack at Rhone Glacier, and 5th September 2013 from the glacial accumulation area at Jungfraujoch Glacier (Fig.1a). At Rhone Glacier and Jungfraujoch glaciers Glacier site elevations were respectively 2340 and 3460 m.asl., with surface gradients of ~ 8° and 17°. At the Rhone Glacier all three days experienced comparable air temperature, although 15th June was noticeably cloudier with a very low sunshine duration. Because daily average temperatures were between 5 and 15 °C with no fresh snowfall (MeteoSuisse), the snowpacks would have experienced significant melting in the weeks before the surveys. We therefore expect them to be physically mature in terms of enhanced grain size and density due to metamorphosis, and chemically mature in terms of invariant meltwater pH and electrical conductivity as preferential elution of solutes has been completed (Kulessa et al., 2012, and references therein).

At both sites more than 100 self-potential measurements were made at the snow surface, and meltwater bulk discharge in a lysimeter, pH and electrical conductivity, and snowpack characteristics including thickness, density, grain size and liquid water content were recorded. Adopting our established acquisition procedures (Thompson et al., 2012), we conducted all self-potential surveys using a pair of lead/lead chloride 'Petiau' non-polarising electrodes (Petiau, 2000). The survey was carried out~~Execution~~ followinged the potential amplitude method (Corry et al., 1983); this~~,~~ ~~employing~~ employs a reference electrode in a fixed location and a roving electrode ~~moving~~ which is moved through the survey area at 0.5 m intervals (Fig.1a~~b~~). Self-potential surveys were conducted in profiles of 25 data points perpendicular to the principal direction of water flow, where the latter was assumed to follow the gradient indicated by snow surface topography. All self-potential measurements were taken as differential readings relative to the reference electrode, minimizing streaming, electrochemical and thermal potentials at the latter by grounding them outside the survey areas (Fig. 1a), submerged in a glass jar, open at the top and filled with water-saturated local media (Kulessa et al., 2003a). The jar was then buried upright ~1 m deep to avoid exposure to surface temperature variations. Surveys were carried out with a fixed tie-in point (measured every second line) at the reference electrode, allowing for correction of the effects of electrode polarisation and drift (Doherty et al., 2010, Thompson et al., 2012).

Bulk discharge through a snowpack is preferably measured with a lysimeter (Campbell et al., 2006, Williams et al., 2010), in this case made up of a series of smaller (guttering) areas joined together to prevent freezing and compaction ~~emplaced according to~~ (after Campbell et al., ~~(~~2006) at the base of Rhone Glacier's snowpack, and at the limit of the diurnal melt penetration depth at Jungfraujoch Glacier (determined by daily dye tracing experiments). Snow density (by balance) and average snow grain size (crystal card and lens) were measured, at the start and end of each self-potential survey to reveal any intermittent snow metamorphism, using standardised techniques within the top and basal layers of snow pits freshly excavated at the survey sites (Fierz et al., 2009). Liquid water content was estimated using two different techniques, including the hand test (Colbeck et al., 1990, Fierz et al., 2009) in the surface and base layers of Rhone Glacier's snow pit, and the Denoth Capacitance Meter (Denoth, 1994) in the surface and base layers of the snow pit at Jungfraujoch Glacier. The latter were acquired ~~and~~ across a 2D grid where the instrument was inserted into the snowpack at a depth of ~~in the surface layers (~~0.4 m~~) at Jungfraujoch,~~ following the same survey spacing as the self-potential measurements.

3. Field measurement results

The d~~D~~rift-corrected self-potential magnitudes and meltwater bulk discharges both increase with time through the day until a peak in late afternoon, after which they both begin to decrease ~~begins in late afternoon~~ (Fig. 2).~~,~~ There is no ~~without a~~ distinguishable time lag between the measured self-potential magnitude and discharge data (Fig. 2b)~~.~~ and the ratio between self-potential and bulk discharge changes consistently over time (Fig. 3). Days 1 and 2 at Rhone G~~g~~lacier were characterised by higher discharges and self-potential magnitudes compared to day 3~~,~~. ~~although i~~Intriguingly bulk discharge at Jungfraujoch Glacier was akin to day 3 at Rhone G~~g~~lacier but self-potential magnitudes at Jungfraujoch Glacier were much higher than even days 1 and 2 at Rhone GGlacier (Fig. 2). The pH, electrical conductivity and temperature of meltwater, recorded with each bulk discharge measurement, show no consistent temporal or spatial variation across any of the four field surveys. Electrical conductivity values generally ranged between 1 $\times 10^{-6}$ S m^{-1} and 5 $\times$ 10^{-6} S m^{-1} without spatial or temporal consistency, while pH ranged between 6.5 and 6.9. Snow grain size remained constant at ~ 1.5 mm at Rhone Glacier and ~ 1 mm at Jungfraujoch Glacier, while snow densities ranged between 555 kg m^{-3} and 573 kg m^{-3} without spatial or temporal consistency. The very small variability range of the snowpack characteristics measured is consistent with mature snowpacks, as assumed above with reference to prior meteorological conditions. At Rhone Glacier the liquid water content of snow had a wetness index of 3 irrespective of measurement time or location at the surface or base of the snow pit, associated with a liquid water content range of 3 – 8 % vol. (Colbeck et al., 1990). At Jungfraujoch Glacier liquid water content, measured using the Denoth meter, gave profile-averaged values of 1.5 to ~5.0 % vol., increasing consistently throughout the survey period. These measurements and inherent uncertainties are used below for snow liquid water content calculations, uncertainty analysis andmodelling purposes, sensitivity testing and error analysis..

4. Objective 1: Self-potential as a snow-hydrological sensor

Both survey areas were south facing, topographically-inclined but otherwise had no visibly distinguished surface undulations, and any snow thicknesses variations were minimal. We therefore expect changes in self-potential magnitudes to be pronounced in the downslope direction, and minimal across-slope along any individual profile (Fig. 1a). Averaging all 25 self-potential data points acquired along any particular profile, a one-dimensional upslope-downslope series of self-potential magnitudes is produced for a given survey area on a given day, together with uncertainty estimates reflecting natural spatial and temporal variability along the profile (Supporting Information). For each profile the acquisition time of the central data point was assigned to it, and all measurements of snowpack and meltwater properties were averaged over the same time period (~ 20 mins). The upslope-downslope series of average self-potential magnitudes thus emulate measurements along a strongly inclined version of the one-dimensional snow column used in Kulessa et al. (2012) (Fig. 1b)., facilitating the application of Eq. (3) to them.

This application is dependent on four key assumptions, including; 1) water flow within the survey areas' snowpacks is laminar and homogenous (where any inhomogeneities average out over the survey grids) in three dimensions, where snowpack surface and base have thus bounded by an impermeable layer at the base, which has a constant and equal inclination and thus maintain to that of the surface, providing a spatially constant hydraulic gradient; 2) all water contributionsng to the measured self-potential signal from flow below the base of the snowpack, runoff at the surface of the snowpack, and flow outside the lateral boundaries of the survey areas' snowpacks are negligible, and all water contributing to the measured self-potential signals is adequately within the survey area is captured by the bulk discharge measurements, thus assuming no flow across survey area boundaries; 3) contributions to the measured self-potential signal from flow below the base of the snowpack, runoff at the surface of the snowpack, and flow outside the lateral boundaries of the survey areas' snowpacks are negligible, and the integrated long-wavelength self-potential signal generated at the surface adequately captures the bulk 3-D flow; 34) all snow physical and chemical propertiesparameters controlling the self-potential magnitude (right hand side of Eq. 3) do not vary spatially across the survey areas' snowpacks, so that our ground-truth snow-pit data apply uniformly across them, and 4) any spatial changes in self-potential magnitudes are dominated by temporal changes in snow or meltwater properties, while static elevation driven spatial changes are negligible. We assess the implications of any potential violations to these assumptions in Section 6.

At a given time, t_n, the measured self-potential field, $\Psi_m(t_n)$, in our survey area is the difference between the locally produced self-potential field, $\Psi_l(t_n)$, and the self-potential field at the reference electrode, $\Psi_0(t_n)$. The latter is unknown is our field feasibility study, although our method of emplacing the reference electrode is elaborate and designed to eliminate, or at least minimise, any streaming potentials at the reference electrode. Once the reference electrodes have settled in their environments, we further expect any electrochemical or thermal potentials to be negligible. We can therefore expect $\Psi_0(t_n)$ to be close to zero, but nonetheless apply caution and take a two-step approach. Initially we eliminate the reference self-potential fields by considering temporal changes in measured self-potentials only before, subsequently, considering absolute self-potential magnitudes.

Temporal changes in self-potential magnitudes.

We can eliminate the reference field by differencing two self-potential measurements acquired at two successive times

$$\psi_m(t_n) - \psi_m(t_{n-1}) = \psi_l(t_n) - \psi_l(t_{n-1}) \tag{3}$$

Equation (3) assumes that Ψ_0 and H_0 are temporally invariant, a reasonable supposition for drift-corrected self-potential data if the reference electrode is correctly emplaced. Recognising that $\psi_0 = H_0 \approx 0$ for their snow column experiment, Kulessa et al. (2012) reformulated equation (2) to show that the self-potential field at a measurement electrode, $\Psi_l(t_n)$, can be approximated by:

$$\psi_l(t_n) = \frac{\varepsilon\zeta}{\sigma_w}\frac{S_w(t_n)}{S_e^n(t_n)}\frac{1}{kA}Q(t_n) \quad (4)$$

~~.~~where Q ($m^3\ s^{-1}$) is bulk discharge in the snow pack through cross-sectional area A (m^2), k is permeability, S_e is effective saturation and n ≈ 3.3 is the saturation exponent (after Albert et al., 1998, Kulessa et al., 2012). Assuming that any temporal changes in the self-potential field at the reference electrodes in our field experiments are negligible, the difference between successive field self-potential measurements in time can be approximated by

$$\psi_m(t_n) - \psi_m(t_{n-1}) = \frac{\varepsilon\zeta}{\sigma_w}\frac{1}{kA}\left(\frac{S_w(t_n)}{S_e^n(t_n)}Q(t_n) - \frac{S_w(t_{n-1})}{S_e^n(t_{n-1})}Q(t_{n-1})\right). \quad (5)$$

In the present case we have measured $\Psi_m(t_n)$ and $\Psi_m(t_{n-1})$ as well as $Q(t_n)$ and $Q(t_{n-1})$. We have also measured, or can estimate from well-established empirical relationships, all other parameters coupling the temporal difference in self-potential fields ($\Psi_m(t_n)$ and $\Psi_m(t_{n-1})$) to that of discharge (expression in the large parentheses on the right-hand side of equation(5)). To demonstrate the usefulness of self-potential measurements in snow research and practice, we can therefore evaluate equation (5) at successive times, t_n and t_{n-1}, to calculate temporal changes in the liquid water content, S_w, of the snowpacks at our field sites. This evaluation is subject to assumptions (1) to (4) above, and is ground-truthed using snow pit measurements of liquid water contents.

~~In modelling liquid water content (S_w) we must measure or estimate all of the parameters included in Eq. (3), whilst satisfying assumptions 1 to 4 above.~~ At both Rhone Glacier and Jungfraujoch self-potential magnitude (Ψ_m), bulk discharge (Q), electrical conductivity (σ_w) and cross-sectional area (A) (survey area width × snow depth) were measured directly.~~,~~ Assuming that water at 0 °C has a dielectric permittivity of ε_r = 88, the dielectric permittivity (F m^{-1}) of pore meltwater is $\varepsilon = \varepsilon_r\varepsilon_0$ = 7.8 x 10^{-9} F m^{-1}, where ε_0 = 8.85 x 10^{-12} F m^{-1} is the dielectric permittivity of vacuum. ~~and the dielectric permittivity of water at ~ 0 °C is well known to be 7.8 x 10^{-9} F m^{-1}.~~ Permeability (k) can be derived from our snow density (ρ_s) and grain size (d) measurements using Shimizu's (1970) empirical relationship

$$k = 0.077 d^2 e^{-0.0078 \rho_s} \qquad (6~~4~~)$$

where k is in m^2, d is in m and ρ_s in kg m^{-3}. This~~,~~ commonly used equation was derived from a fit to laboratory data collected with small rounded grains and a starting grain diameter of ~0.33 mm (Shimizu, 1970). However, later work ascertained experimentally that Shimizu's [1970] empirical formula does in fact apply to a much larger range of grain diameters expected to be encountered in practice (less than 0.33 mm to greater than 2 mm) (Jordan et al., 1999). We can therefore expect equation (13) to be~~and~~ robust for ~~modelling~~our purposes. ~~(Kulessa et al., 2012).~~ Effective saturation (S_e) and S_w are related through the irreducible water saturation S_w^{ir} by

$$S_e = \frac{S_w - S_w^{ir}}{1 - S_w^{ir}} \qquad (7~~5~~)$$

In the absence of direct measurements we adopt the commonly used values of S_w^{ir} = 0.03 and n ≈ 3.3 (Kulessa et al., 2012), and assume that these values are invariant in space and time at our study sites.

~~T~~A significant challenge arises however in that there is one remaining parameter the zeta potential (ζ) which is unknown here and poorly constrained in general. Earlier work on artificial ice samples, of fixed bulk electrical conductivity, ascertained that the zeta potential reverses sign from ~ +0.01 V to ~ -0.02 V as equilibrium pH increases from less than 3 to greater than 8 (Drzymala et al., 1999, Kallay et al., 2003).). The electrochemical properties of the electrical double layer at the snow grain surfaces, and thus also the magnitude and potentially the sign of the zeta potential, will change over time in a fresh snowpack as the snow is affected by melt, recrystallisation and the preferential elution of ions (Meyer and Wania, 2008, Meyer, 2009, Williams et al,. 1999b). Recent 'natural snowmelt' laboratory experiments were consistent with a progressive increase of pH from 4.3 to 6.3 and a simultaneous decrease in electrical conductivity from ~ 1 × 10^{-1} S m^{-1} to ~ 6 × 10^{-7} S m^{-1}, as the elution of ions follows a well-known sequence ~~(Fig. 6b in~~ (Kulessa et al., ~~(~~2012)). Upon conclusion of Kulessa et al.'s (2012) laboratory~~the~~ experiments, modelled rates of change of pH and electrical conductivity were minimal and the snow column mature. The zeta potential is principally a function of pH and electrical conductivity

$$\zeta(\sigma_w, pH) = [\alpha + \beta log_{10}\sigma_w]\left(sin\frac{\pi}{12}[pH_w - pH_w(pzc)]\right), \qquad (8)$$

where α and β depend on the chemical composition of the pore fluid and can be determined empirically (Revil et al., 1999). Kulessa et al. (2012) inferred the zeta potential ~~(Kulessa et al., 2012; their eq. 18), and was inferred to~~ changeed from ~ -7.5 × 10^{-2} V at the start of their natural snowmelt experiments to +1.5 × 10^{-2} V at the end, when the rate of change of the zeta potential ~~consistently~~ was minimal. ~~(Fig. 7a in Kulessa et al. (2012)).~~

The final values of pH and electrical conductivity that Kulessa et al. (2012) calculated from equation 8 were similar to those measured at Rhone Glacier and Jungfraujoch (respectively ~ 6.5 – 6.9 and ~ 1 – 5 × 10^{-6} S m^{-1}), suggesting that these in-situ snow packs were likewise mature as expected (Section 2). This inference is corroborated by~~, and indeed agrees with~~ the absence of consistent spatial or temporal changes in either pH or electrical conductivity throughout the survey periods. In Kulessa et al.'s (2012) laboratory study ~~T~~the pH-corrected zeta potential ~~(Fig. 7b in Kulessa et al. (2012))~~ had values around zero for the range of electrical conductivities (1 – 5 × 10^{-6} S m^{-1}) measured at Rhone Glacier and Jungfraujoch Glacier (1 – 5 × 10^{-6} S m^{-1}), and its rate of change became minimal along with those of pH and electrical conductivity. ~~(Figs 6b and 7b in Kulessa et al. (2012)).~~ We can therefore expect a~~A~~ small and invariant zeta potential value ~~therefore~~ to apply~~lies~~ to the snowpacks at Rhone Glacier and Jungfraujoch Glacier. Indeed, ~~the best~~an excellent fit ($R^2 \approx 0.85$) between liquid water contents measured at Jungfraujoch with the Denoth meter and that ~~modelled~~ based on ~~Eq. (3)~~equation (5) is obtained when the zeta potential is assigned a value of ~ -1 × 10^{-5} V (Fig. ~~3b~~4). This excellent fit suggests that in-situ measurements or empirically derived estimates of the parameters affecting coupling between measured self-potential magnitudes and discharges in equation (5) are robust for practical purposes.

Absolute changes in self-potential magnitudes.

The same parameters affect the coupling between temporal changes in self-potential magnitudes and discharge (equation 5), and absolute changes therein as described by equation (4) derived by assuming that the reference potential is zero. We are therefore encouraged to calculate absolute liquid water contents from our self-potential data using equation (4). We do this initially for Jungfraujoch glacier because here we have detailed ground-truth measurements of liquid water content made with a Denoth meter. Encouragingly we find that calculated and measured ground-truth data match each other very well (Fig. 5a), attesting to the fact that the reference potentials at Jungfraujoch may not only be temporally invariant as confirmed earlier, but generally have negligible magnitudes.

We can apply the same expectation of negligible reference self-potential magnitudes to our surveys at Rhone Glacier on the three successive days. We find that absolute ~~The range of~~ liquid water contents inferred from equation (4) generally fall well within the range of ~ 3

– 8% inferred from our ground-truth hand tests. We can therefore conclude that given careful emplacement of the reference electrode, the simple empirical relationship between self-potential magnitudes, discharge and liquid water content is robust not only in a laboratory setting (Kulessa et al., 2012), but also for application to in-situ snowpacks. ~~our hand tests at Rhone Glacier is also matched well by the model for all three days when this value of the zeta potential is used (Fig. 3a). Because this 'best estimate' of zeta potential (-1×10^{-5} V) is small and negative, and a single zeta potential value produces an excellent fit with all of our liquid water content measurements (Fig. 3), we conclude that~~ T~~t~~he self-potential method ~~does indeed~~therefore shows considerable promise as a non-intrusive snow-hydrological sensor.

5. Objective 2: Self-potential sensitivity to uncertainty in snow properties

We evaluate the sensitivity of ~~predicted~~ calculated liquid water contents to both ~~combined~~ individual and ~~individual~~ combinedl parameter uncertainties. ~~The former was achieved by running our model based on Eq. (3) numerous times for each of our four surveys (i.e. one day at Jungfraujoch and three consecutive days at Rhone Glacier); first~~ For each parameter a range of uncertainty values was created, with the respective minima and maxima approximately twice that of the uncertainty (Table 1). Repeat water content calculations were carried out initially by changing each parameter individually for a range of values between the respective minima and maxima. The results cluster broadly in three categories, including the zeta potential (up to ~ 20 % change in liquid water content within the 50 % uncertainty range), followed by grain diameter, survey area width, electrical conductivity, snow depth and snow density (~ 3 – 4 % change) and bulk discharge, and self-potential (2 % change) (Fig. 6). These three categories readily reflect our knowledge of or ability to measure in-situ the respective parameters, with surprisingly low sensitivity to cross-sectional area despite our simplistic calculation and significant inherent assumptions (i.e. 1 – 4 in Section 4). Self-potential magnitudes are readily measured in the field with minimum uncertainty (Fig. 6), although the strongly enhanced sensitivity to the zeta potential highlights the need for focused research to tightly constrain possible values of this parameter in in-situ snow packs.

While this gives a good indication of the parameters to which water content calculations are most sensitive, it does not indicate possible feedbacks between parameters. Feedbacks were therefore evaluated by calculating liquid water contents for all possible combinations of the best estimates and minimum and maximum parameter values (Table 1), giving over 6500 solutions (Fig. 7). The minimum and maximum outputs were then adopted as the lower and upper uncertainty bounds (Fig.3). Due to ~~with our best estimates as measured in-situ and inferred from Eq. (4) and (5) and our zeta-potential considerations, and then sequentially with all possible combinations of the model, minimum and maximum values of the uncertainty range (respectively field data minus and plus uncertainty) (Fig. 3 and Supplementary Material). These ranges were based on the uncertainties inherent in measured parameters (Section 3, Table 1) and t~~the large potential uncertainty in the zeta potential, the sensitivity range was arbitrarily ~~assigned~~ set to ± 50 % for illustrative purposes (Section 4). ~~The two latter model runs thus provide reasonable upper and lower bounds on predicted liquid water contents for comparison with our field measurements.~~

Despite our consideration of extreme potential error bounds, ~~modelled~~ calculated uncertainties in liquid water contents are restricted to ~~the~~a relatively small range (~ 20 % for large assumed uncertainty in the zeta potential, and ~ 3 – 4 % otherwise) ~~of ~ 1 – 3 %~~ at both Rhone glacier and Jungfraujoch Glacier, and absolute values remain within the pendular regime where water bodies in the pore space remain isolated. At the latter site the daily evolution of liquid water contents thus is well captured even if uncertainty is taken into account (Fig. 5~~3~~b), and likewise at Rhone glacier modelled liquid water contents plus uncertainties still fall within the range of field measurements (Fig. 5~~3~~a). Our inferences thus not only support Kulessa et al.'s (2012) notion that existing snow hydrological relationships are robust for modelling purposes, but also suggest that they may apply to in-situ field surveys. These inferences can also provide an explanation for the relatively large self-potential magnitudes generated by relatively low bulk discharge at Jungfraujoch Glacier (Fig. 2). Because we did not observe or infer any consistent or statistically-significant differences between Rhone glacier and Jungfraujoch in dielectric permittivity (ε), zeta potential (ζ), saturation (S_w S_e^{-n}), electrical conductivity (σ_w) or cross-sectional area (A), the only remaining parameter that could facilitate the observed relative difference is permeability (k). Indeed, using an average snow density of 564 kg m^{-3}, the differences in mean snow grain sizes between Rhone glacier (1.5 × 10^{-3} m) and Jungfraujoch (1 × 10^{-3} m) translate into respective permeabilities of 9.7 ×10^{-5} m^2 and 4.3 ×10^{-5} m^2. The relatively reduced permeability of Jungfraujoch's accumulation-area snow-pack therefore likely supported the presence of self-potential magnitudes that were markedly elevated relative to Rhone glacier's ablation-area snow-pack (~~Eq~~equation. ~~(3~~(4)). This inference emphasises the sensitivity of the self-potential method to permeability as a fundamental snow-hydrological property, along with its observed sensitivity to bulk melt water discharge and inferred sensitivity to liquid water content.

~~Model sensitivities to individual parameter uncertainties were evaluated by running our model separately for the maximum and minimum values considered for each individual parameter (Table 1) and subsequently differencing the outputs, whilst keeping the other parameters constant. The results cluster broadly in three categories of sensitivity, including the zeta potential (up to ~ 12 % change in liquid water content within the 50 % uncertainty range), followed by grain diameter, survey area width and snow density (~ 1 – 3 % change) and bulk discharge, electrical conductivity, snow depth and self-potential (< 1 % change) (Fig. 4). These three categories readily reflect our knowledge of or ability to measure in-situ~~

the respective parameters, with surprisingly low sensitivity to cross-sectional area (survey area width × snow depth) despite our simplistic modelling approach and significant inherent assumptions (i.e. 1 – 4 in Section 4). Self-potential magnitudes are readily measured in the field with minimum uncertainty (Fig. 4), although the strongly enhanced sensitivity to the zeta potential highlights the need for focused research to tightly constrain possible values of this parameter in in-situ snow packs.

6. Objective 3: Implications for future snow hydrological research and practiceSynthesis and conclusions

The ability of the electrical self-potential method to sense meltwater flow in in-situ snowpacks is unique, where self-potential magnitudes scale directly with discharge and are zero in the absence of flow. The scaling factor depends principally on the liquid water content of the snowpack, its permeability and the water chemistry (Kulessa et al., 2012). We have shown here that diurnal variations in the liquid water content of in-situ snowpacks can be derived from electrical self-potential data and bulk discharge measurements with a simple lysimeter. This derivation was subject to four key assumptions (Section 4) which we now examine in turn to identify what, if any, constraints arise for future applications.

The Reynolds number (*Re*) is a common measure of the mode of fluid flow through porous media, as discussed in a relevant cryospheric context by Kulessa et al. (2003a):

$$Re = \frac{\rho_s v L}{\eta} \qquad (9)$$

where v and L are respectively characteristic fluid flow velocity (in m s^{-1}) and characteristic length scale of flow (in m), and ρ_s and η are respectively snow density (in kg m^{-3}) and dynamic viscosity (in Pa s). To a first approximation the transition from laminar to turbulent flow nominally occurs when *Re* ≈ 10, although laminar flow can persist at much higher values of *Re* (for comparison, in open channels transition occurs at *Re* ≈ 2300). For our purposes *v* can be assumed to correspond to the average linear velocity of flow, $v = Q\ A^{-1}\ n^{-1}$, where n is effective porosity (ratio of snow and ice densities). In porous media such as snow L corresponds to the average pore diameter, and in the absence of direct evidence is assumed to be equal to grain size; in practice an overestimation of pore diameter. For the respective snow properties and their uncertainties reported in Table 1 values of Re between ~ 0.1 and ~ 50.7 are obtained, with a best estimate of *Re* ≈ 1.1. These values pertain to times of highest measured meltwater discharge when the Reynolds number is likely be greatest. Despite the unrealistically large uncertainty bounds considered in Table 1, and the overestimation of pore diameter (L) and associated inflation of the Reynolds number (equation (9)), we can therefore conclude that meltwater flow in our snowpacks was laminar. The absolute and relative inclinations of the snow surface and base will vary to different degrees within different field areas, thus generating differences in discharge and potentially preferential flow. Indeed, it is an exciting attribute of self-potential measurements that they will, in practice, aid to delineate such differences in meltwater flow.

Persistent meltwater runoff at the snow surface is uncommon, and meltwater flow through underlying soils or ice will normally be negligible or small compared to flow through or at the base of snowpacks. We have also shown that the inversion of self-potential data for snow properties such as liquid water content is insensitive to the area of snowpack contributing meltwater flow to the measured signals. Uncertainties in the area of origin of water contributing to measured bulk discharges and thus measured self-potential data are not therefore expected to be a major hindrance to future applications of the self-potential method to snow problems. We have also shown that with the exception of the zeta potential, sensitivity to uncertainties in the snow properties governing the relationship between self-potential data and liquid water contents are small (~ 3-4% in our feasibility study). Future work must ascertain to what extent longer-term monitoring studies are affected by the preferential elution of ions and the associated impacts on meltwater pH, EC and thus the zeta potential. Even if such effects were found to be of concern, meltwater EC and pH are readily monitored in-situ with automated probes and could be measured alongside self-potential data at a calibration location, and subsequently be assimilated in snow models.

The final consideration focused on the assumption that the spatial pattern of self-potential magnitudes, measured during the day across our survey areas, was due to temporal changes in the liquid water content of the snowpack. This assumes that any spatial pattern due to elevation changes between the bottom and top of our survey areas is comparatively small and indeed negligible. Kulessa et al. (2003a) showed that elevation-driven changes in the self-potential fields measured between upstream (Ψ_{up}) and downstream (Ψ_{down}) locations (z_{up}, z_{down}) can be approximated by

$$\psi_{up} - \psi_{down} = -\frac{\varepsilon\zeta}{\eta\sigma_w} S_w \left(z_{up} - z_{down} \right), \tag{10}$$

here translated to our notation and adjusting for meltwater saturation according to equation (2). Even for the maximum daily values of saturation inferred from our measurements the elevation-driven spatial pattern has small magnitudes, estimated to be ~ -16.0 mV and -8.4 mV respectively for Jungfraujoch Glacier and Rhone Glaciers. These values are an order of magnitude smaller than daily changes measured at the two glaciers (Fig. 2) and are therefore considered to be insignificant for the purpose of the present feasibility study. In similar future applications the relevance of such spatial changes should be assessed on a case by case basis, and would in fact readily be incorporated into quantitative inferences of snow properties from self-potential data where they are of concern.

Overall our findings imply that in principle, self-potential data could be inverted for spatial or temporal variations in any one desired parameter (i.e. discharge, liquid water content, permeability or water chemistry), if independent estimates of the respective remaining parameters are available. Self-potential data are therefore well suited for assimilation in snow models along with meteorological and snowpack observations. We have shown in previous cryospheric applications that self-potential monitoring is readily effected with autonomous arrays of low-cost non-polarising electrodes connected to a high-impedance data logger (Kulessa et al., 2003a, 2003b, 2012). In operational practice for instance, 2-D vertical arrays of electrodes and data loggers could be installed along with meteorological stations and upward-looking radar instrumentation, where the latter is used to monitor snow structure and 1-D liquid water contents. Assimilation of self-potential data along with complementary meteorological and radar data could then facilitate unique insights into daily and longer-term variations in 2-D vertical, lateral and preferential meltwater flows, or in liquid water contents. We conclude that the integration of self-potential measurements into existing snow measurement and data assimilation routines shows considerable promise in supporting a reduction of uncertainty in quantifying snow-atmosphere energy exchanges, or in predictive modelling used in operational snow forecasting.

Building on Kulessa et al.'s (2012) fundamental theoretical and laboratory work, our study implies that the self-potential method can respectively characterize bulk meltwater fluxes in or liquid water contents of in-situ snowpacks, if independent water content or flux estimates are available. The method's ability to sense bulk meltwater fluxes in snow directly is unique because theyare not readily measureable with existing techniques. The acquisition of self-potential data promises to be readily automated for snow hydrological monitoring (Kulessa et al., 2003a, 2003b, Kulessa et al., 2012), and once a snow pack has experienced initial stages of melt, uncertainty in the snow physical and chemical properties on which self-potential magnitudes depend becomes small for measurement and modelling purposes. Four key areas of future development can be identified, including:

- The determination of absolute values of the zeta potential in in situ snowpacks for modelling purposes.
- The experimental confirmation that the impact on self-potential magnitudes of the preferential elution of ions from and metamorphosis of freshly fallen snow is time-limited to initial stages of melt.
- The development of a rugged bespoke system for multi-dimensional self-potential monitoring in snow-hydrological research and practice.
- The experimental identification of the impact of small-scale variations in snow properties (e.g. structural inhomogeneity, anisotropy in hydraulic conductivity, micro-topography) on self-potential magnitudes.
- The stochastic assimilation of self-potential data in leading snow models such as JULES (Best et al., 2011), CROCUS (Vionnet et al., 2012) or SNOWPACK (Bartelt and Lehning, 2002, Lehning and Fierz, 2008).

We conclude that the integration of self-potential measurements into existing snow measurement and data assimilation routines shows considerable promise in supporting a reduction of uncertainty in predictive models used in operational snow forecasting.

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TABLES AND FIGURES

Tables and figures

Table 1: Best estimate of each parameter for Rhone Glacier SP (Day 2) and relative assumed uncertainty and sensitivity ranges. The sensitivity ranges are based on the measurement accuracy of each measured parameter or the confidence of estimates parameters. The uncertainty ranges are exaggerated from the sensitivity values to highlight the effect of poor measurement or estimation.

Measured parameter	Uncertainty range	Sensitivity values
Self-potential ψ_m (V)	$\psi_m \pm 20\%$	$\psi_m \pm 20\%$
Discharge Q ($m^3 s^{-1}$)	Q ± 20%	Q ± 40%
Electrical conductivity of melt σ_w ($S\ m^{-1}$)	$\sigma_w \pm 5 \times 10^7$	$\sigma_w \pm 1 \times 10^6$
Zeta potential ζ (V)	ζ ± 50 %	10^{-3} – 10^{-7}
Permeability from;		
Grain diameter d (m)	d ± 0.0005	d ± 0.001
Density ρ ($kg\ m^3$)	ρ ± 70	ρ ± 140
Cross sectional area from;		
Width w (m)	w ± 5	w ± 10
Depth dp (m)	dp ± 0.2	dp ± 0.4

Table 1: Model input parameters and their relative maximum uncertainty and sensitivity ranges.

Measured / estimated parameters	Best estimate	Uncertainty range	Sensitivity range
Self-potential ψ_m (V)	Variable	$\psi_m \pm 40\%$	$\psi_m \pm 20\%$
Discharge Q ($m^3 s^{-1}$)	Variable	Q ± 40%	Q ± 20%
Electrical conductivity σ_w ($S\ m^{-1}$)	5×10^{-6}	10^{-7} – 10^{-4}	$\sigma_w \pm 5 \times 10^{-7}$
Zeta potential ζ (V)	-1×10^{-5}	10^{-4} – 10^{-6}	ζ ± 50%
Permeability from;			
Grain diameter d (m)	0.00175	d ± 0.001	d ± 0.0005
Density ρ ($kg\ m^3$)	555.5	ρ ± 140	ρ ± 70
Cross sectional area from;			
Width w (m)	12.5	w ± 10	w ± 5
Depth dp (m)	1.45	dp ± 1	dp ± 0.2

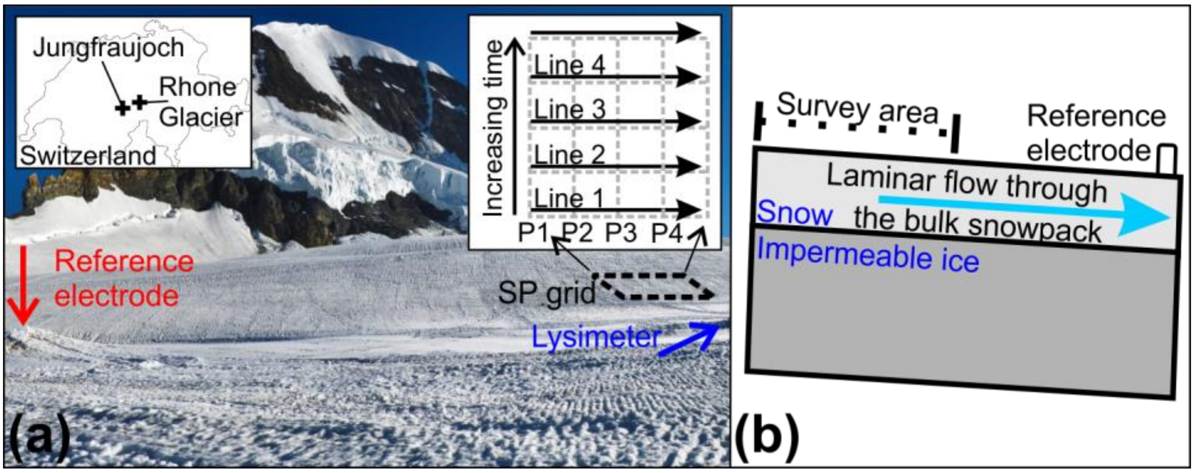


Figure 1: (a) Example survey set up. Insert left show the location of both fieldsites. Insert right illustrates the self-potential survey design; to provide each self-potential data value, a profile of 25 data points (P1, P2, etc.) was collected (Line 1, Line 2, etc.), perpendicular to assumed bulk water flow. (b) Schematic of the self-potential experiment developed by Kulessa et al. (2012) for the situ snowpack surveys.

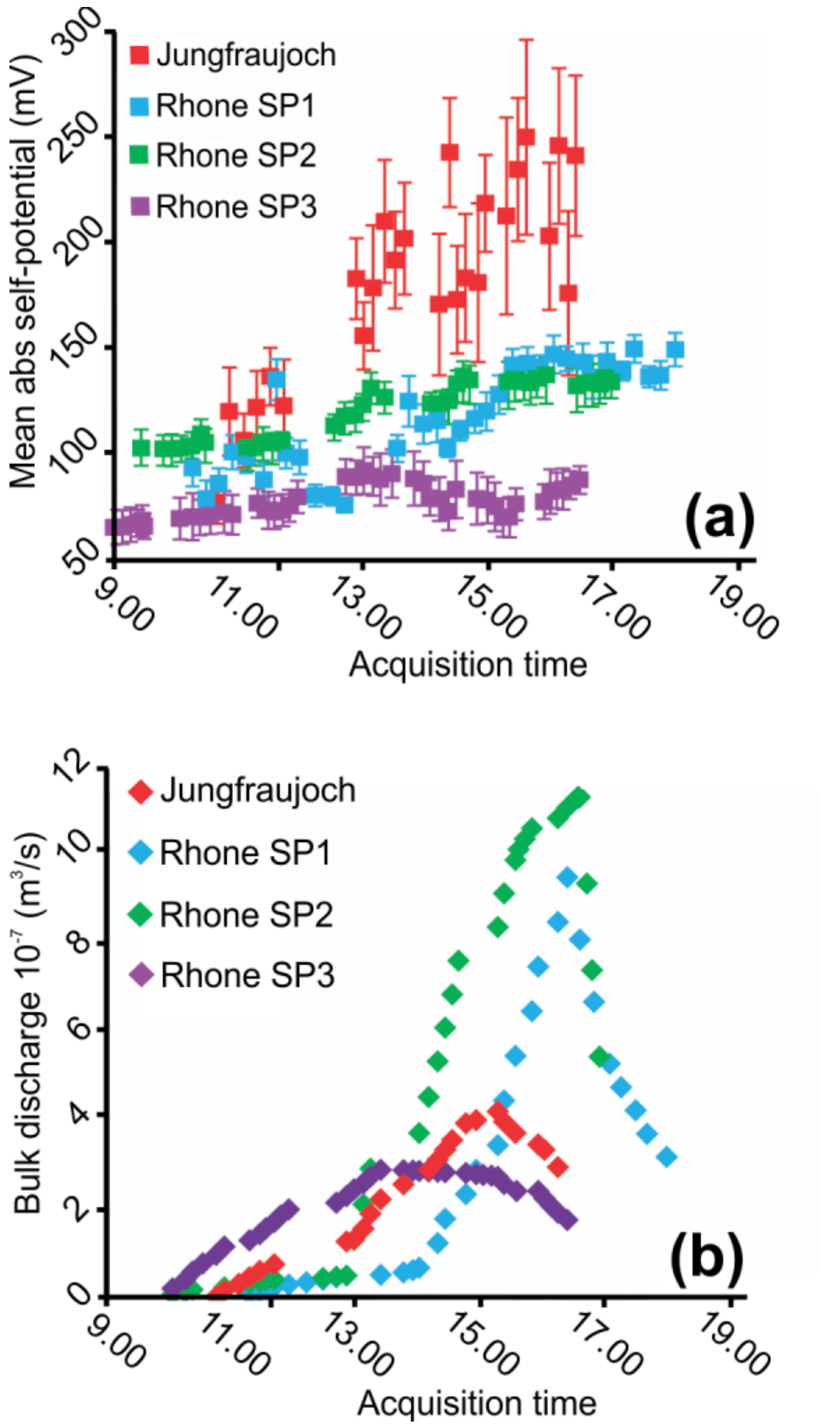


Figure 2: Time series of (a) bulk self-potential measurements and (b) bulk discharge measurements for the three Rhone Glacier surveys and the Jungfraujoch Glacier survey. Each self-potential data point represents the mean value of a profile (consisting of 25 data points); the error bars illustrates the variability over each profile. Bulk discharge was measured over each profile by the lysimeter.

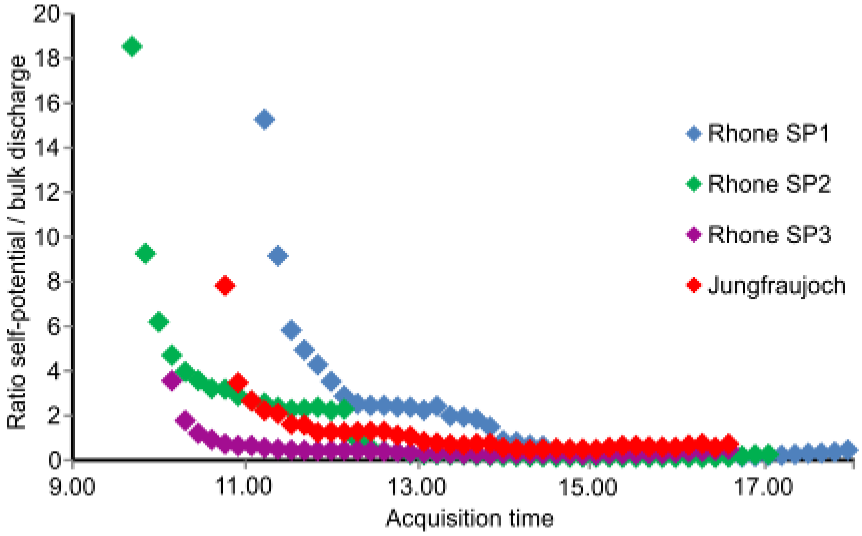


Figure 3: Ratio between self-potential (V) and bulk discharge (m^3 s^{-1}) for each of the four surveys through time, illustrating the ratio changes consistently over time.

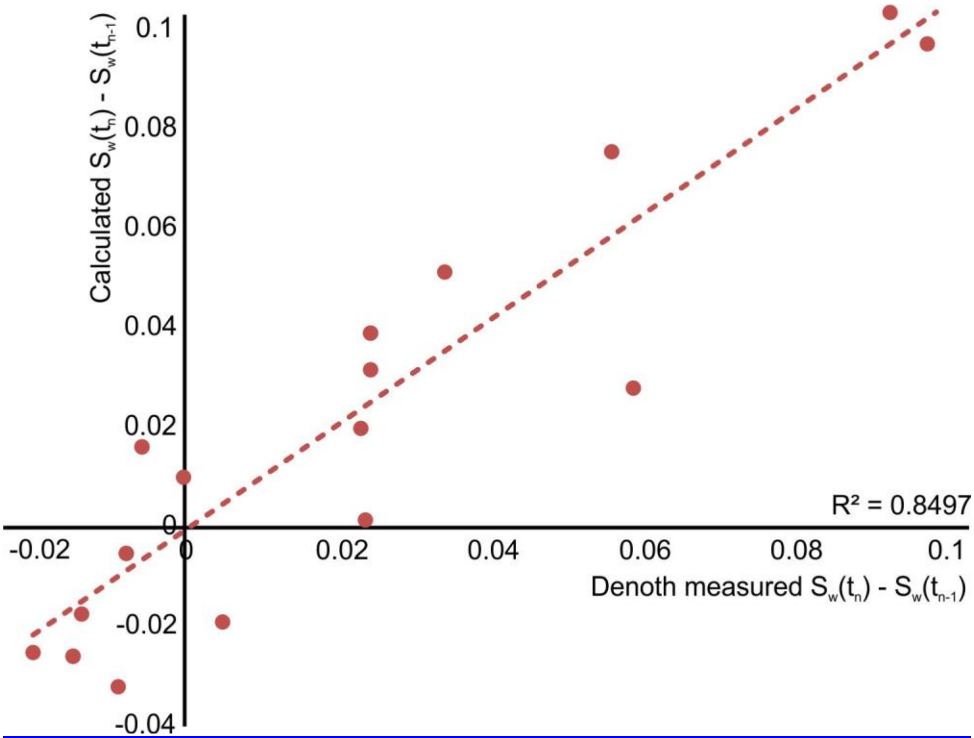
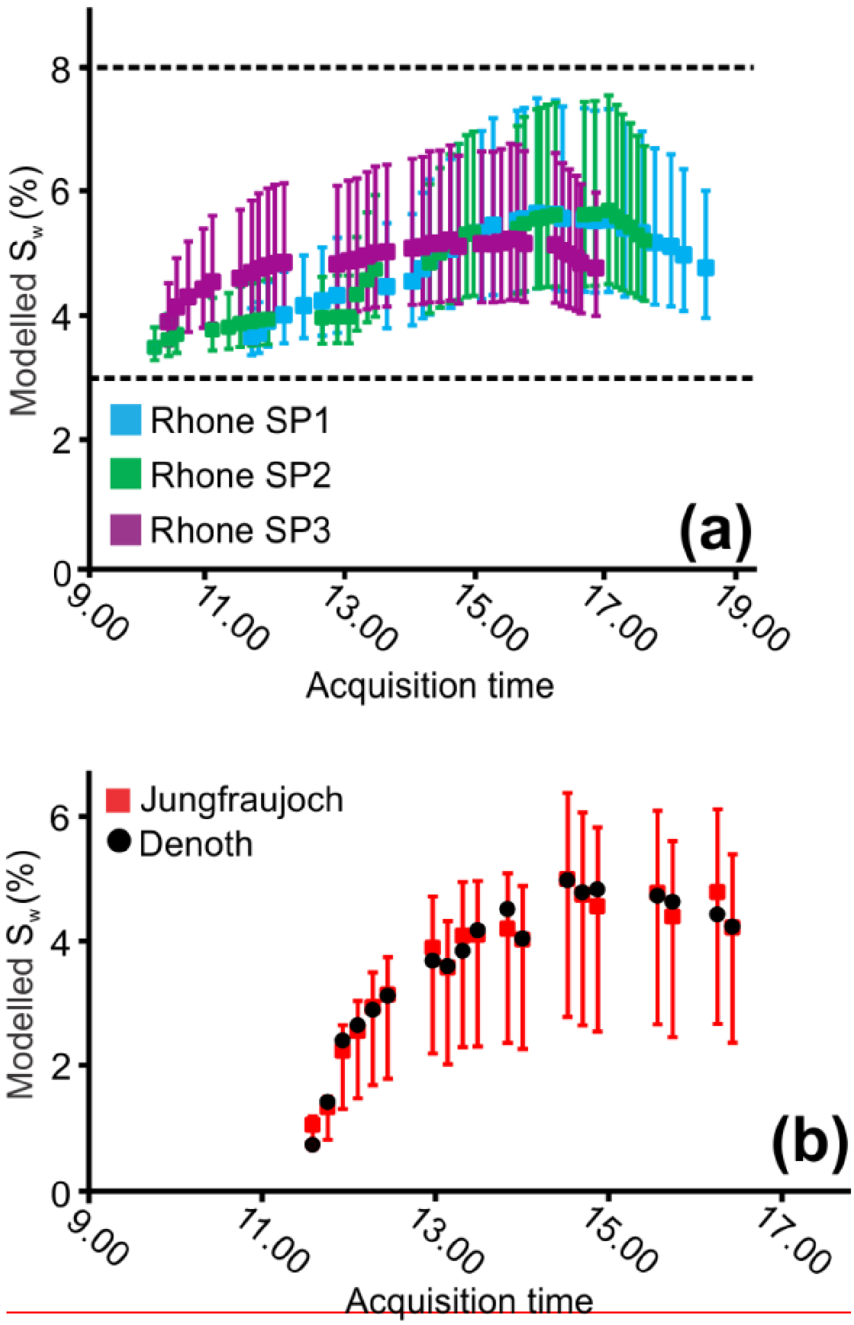


Figure 4: Temporal differences in S_w inferred from self-potential data against temporal differences in the Denoth measured S_w at Jungfraujoch Glacier, according to equation (5).



Modelled S_w (%)
Rhone SP1
Rhone SP2
Rhone SP3
(a)
9.00
11.00
13.00
15.00
17.00
19.00
Acquisition time
Jungfraujoch
Denoth
Modelled S_w (%)
(b)
9.00
11.00
13.00
15.00
17.00
Acquisition time

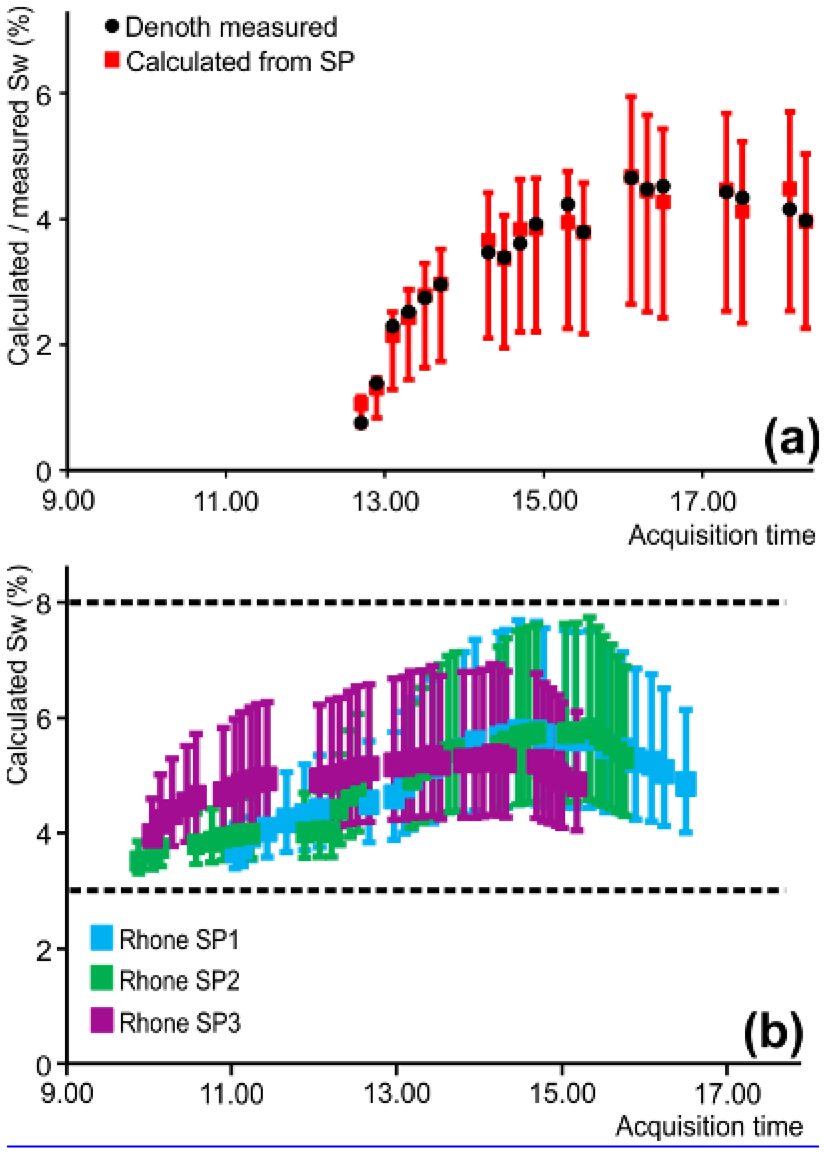
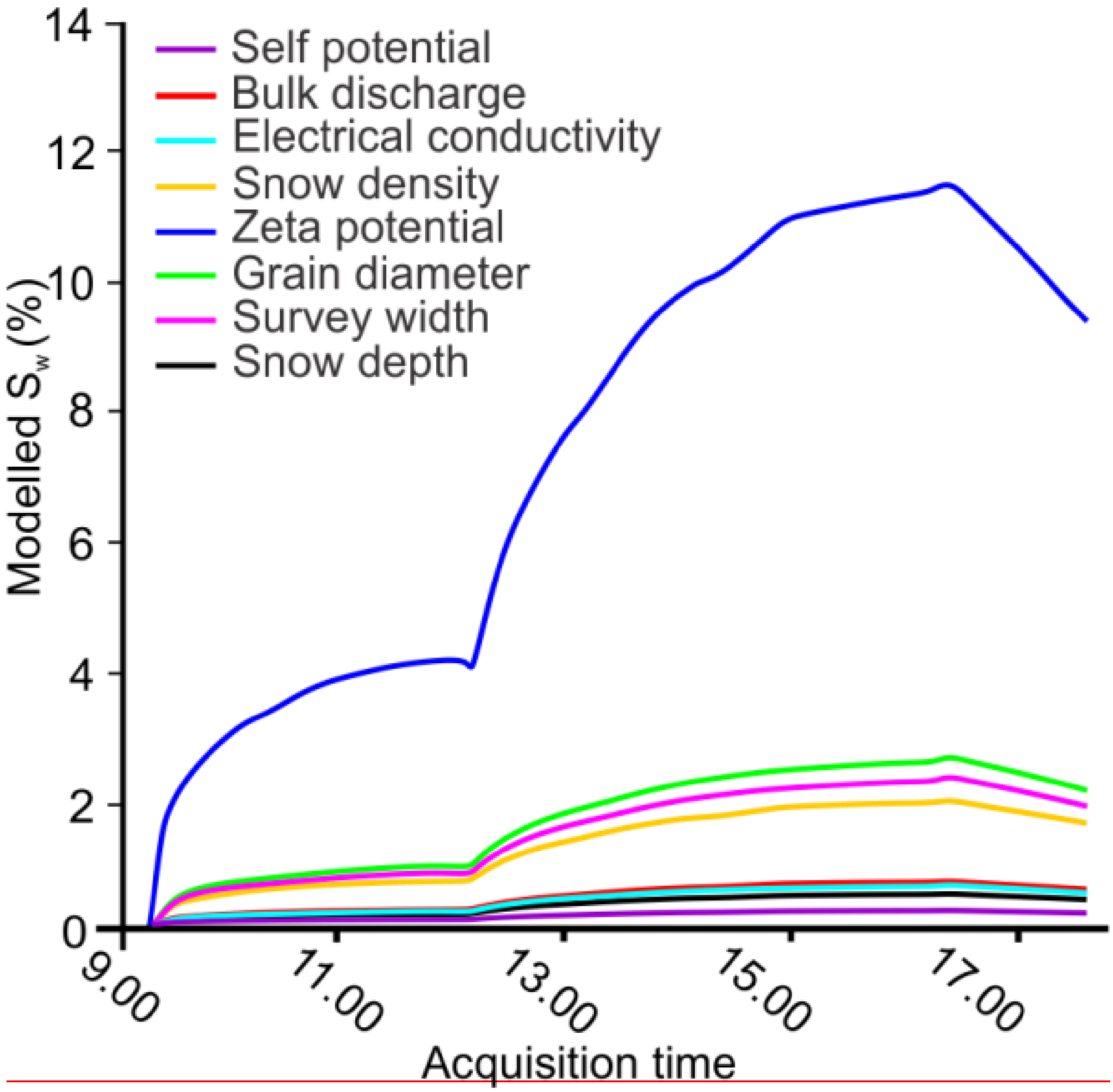


Figure ~~3~~5: (a) ~~Modelled l~~Liquid water content calculated from equation(4) for ~~each of~~ the ~~three~~ self-potential survey~~s~~ carried out at ~~Rhone~~ Junfraujoch Glacier, with the corresponding Denoth measurements. The uncertainty range illustrates the minimum and maximum model results for the range of input parameters (Table 1)~~, Supplementary Material). All results are within the range of liquid water content (% vol) estimated by the hand tests (black dashed lines).~~ (b) Liquid water content calculated from equation 4 for each of the three self-potential surveys carried out at Rhone Glacier. All results are within the range of liquid water content (% vol) estimated by the hand tests (black dashed lines in b).

728 Model results for the self-potential survey carried out at Jungfraujoch, with the corresponding
729 Denoth measurements.



732 **Figure 4:** The difference in model results to the minimum and maximum parameter value
733 from the uncertainty range (Table 1), highlighting the model sensitivity to each of the
734 measured input parameter individually.

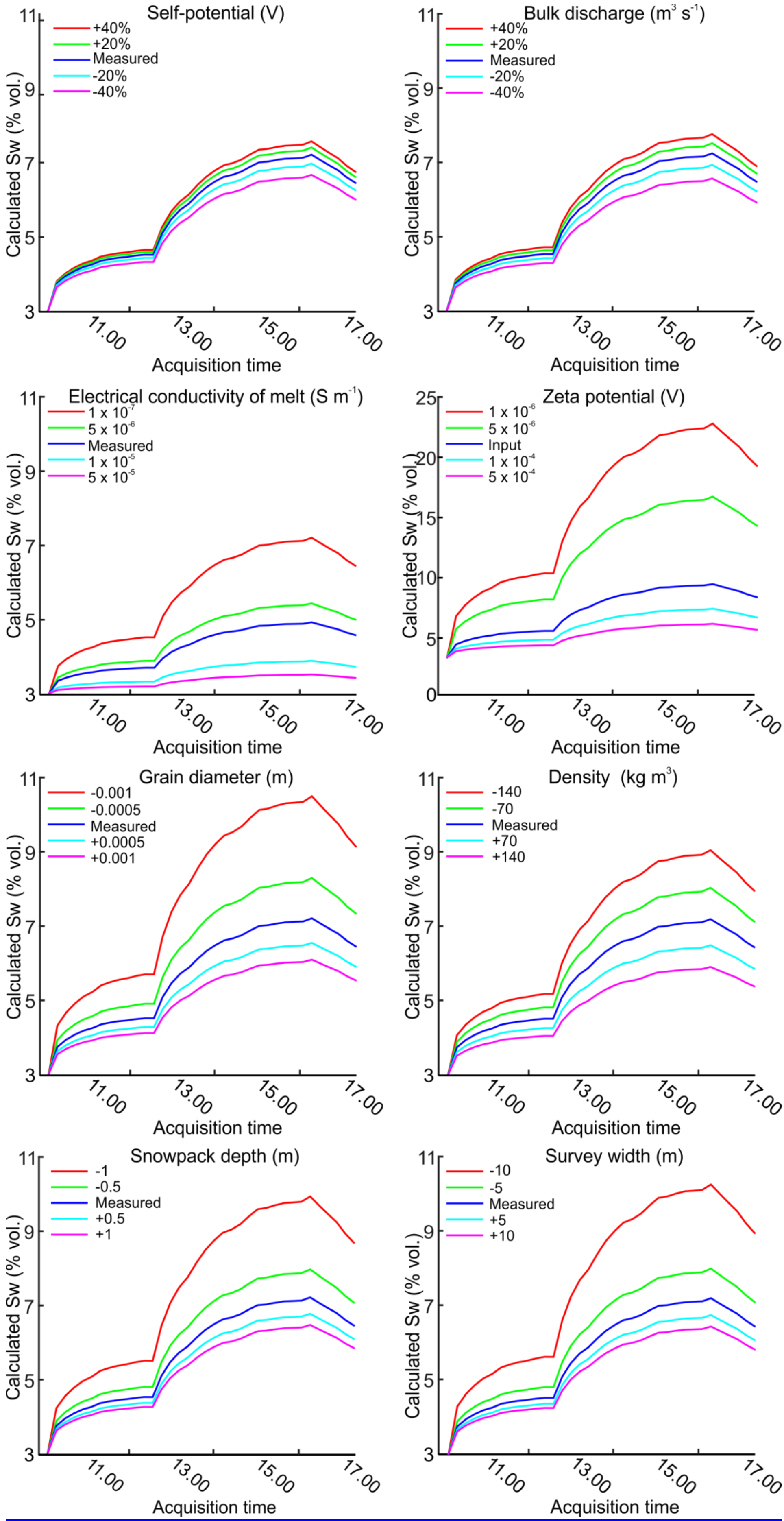

Self-potential (V)
+40%
+20%
Measured
-20%
-40%
Bulk discharge (m3 s-1)
+40%
+20%
Measured
-20%
-40%
Electrical conductivity of melt (S m-1)
1 x 10-7
5 x 10-6
Measured
1 x 10-5
5 x 10-5
Zeta potential (V)
1 x 10-6
5 x 10-6
Input
1 x 10-4
5 x 10-4
Grain diameter (m)
-0.001
-0.0005
Measured
+0.0005
+0.001
Density (kg m3)
-140
-70
Measured
+70
+140
Snowpack depth (m)
-1
-0.5
Measured
+0.5
+1
Survey width (m)
-10
-5
Measured
+5
+10
Calculated Sw (% vol.)
Acquisition time
11.00
13.00
15.00
17.00

Figure 6: S_w calculations for a range of values for each parameter. In each case the range is an exaggerated uncertainty range (Table 1), highlighting the effect of each individual parameter on the calculated S_w output, using Rhone Glacier SP2 as an example.

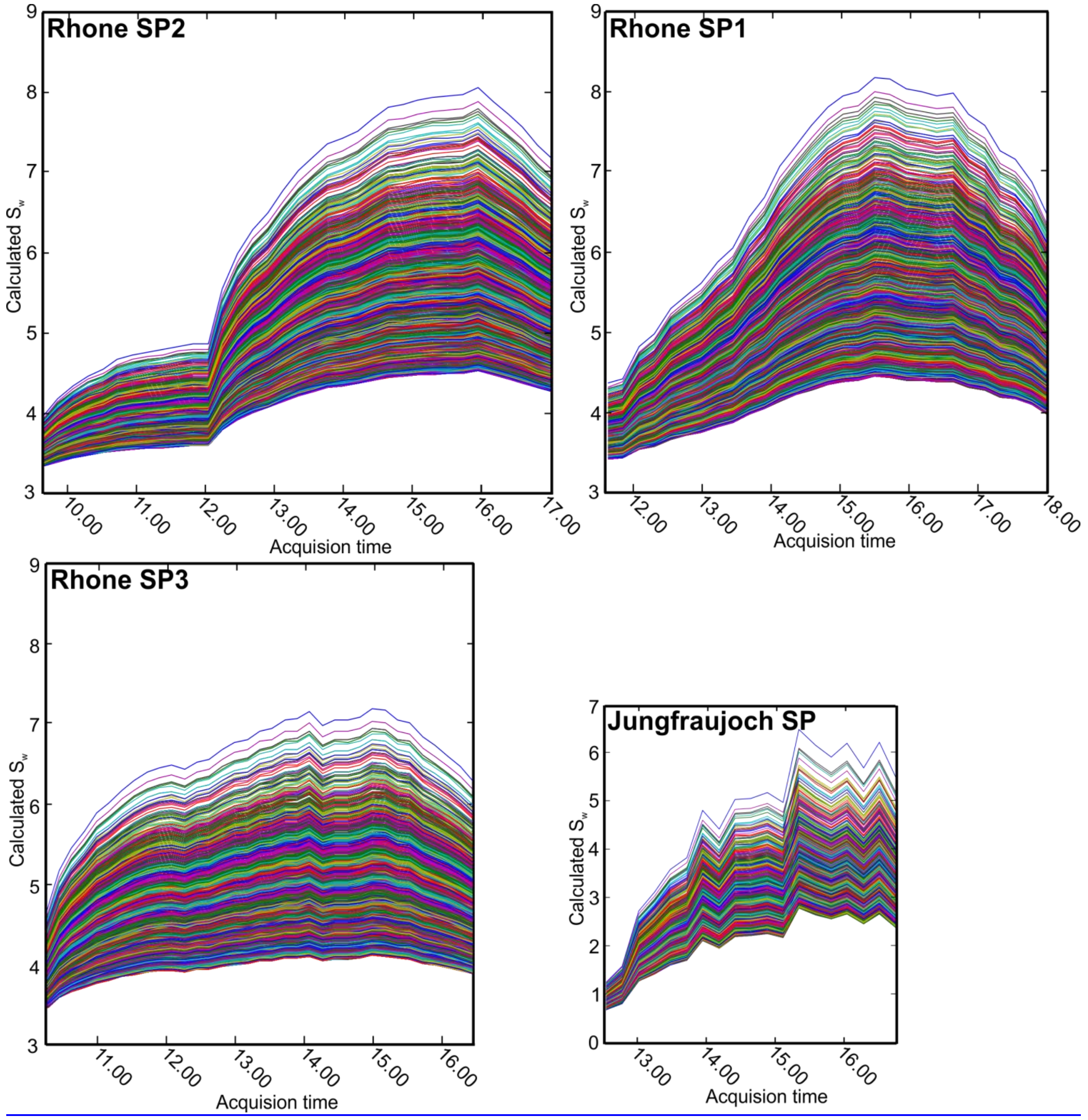


Figure 7: Full sensitivity analysis for each of the four data sets. Each graph shows the full range of calculated liquid water content (S_w) values of every combination of minimum, best estimate and maximum for each of the parameters.