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, 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 (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. (3). 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'.

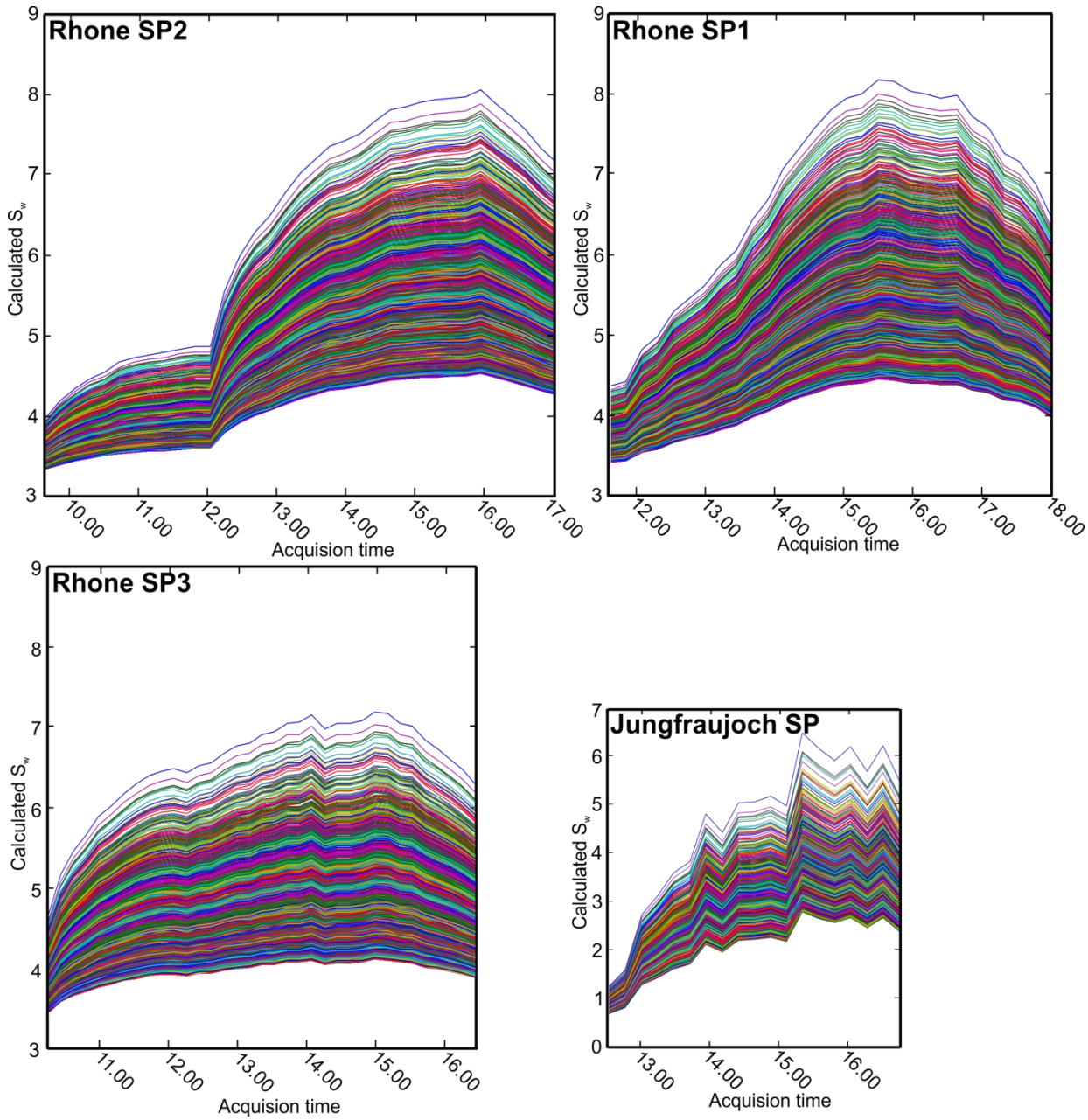

Figure 7: *Full sensitivity analysis for each of the four data sets. Each graph shows the full range of calculated Sw values of every combination of min, model input and max for each of the input parameters.*

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. 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. In operational practice, 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 monitoring 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 and lateral meltwater flows or liquid water contents.

Future research must ascertain whether, and if so to what degree, the four key assumptions introduced in Section 4 affect the application of the self-potential method in snow practice. Here we consider assumptions 1 to 4 in turn.

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)

$$Re = \frac{\rho_s v L}{\eta} \qquad (10)$$

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 a gross 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. Despite the unrealistically large uncertainty bounds considered in Table 1, and the gross overestimation of pore diameter and associated inflation of the Reynolds number, 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 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 the application of the self-potential method in snow practice. 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, 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

$$\psi_{up} - \psi_{down} = -\frac{\varepsilon\zeta}{\eta\sigma_w} S_w \left(z_{up} - z_{down}\right), \qquad (11)$$

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 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 the 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 sentence now reads - If ψ_0 *and* H_0 *have negligible magnitudes compared to the self-potential field* ψ *(expected if the reference electrode is correctly positioned outside of the survey site)'.*

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 ≈ 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 $\varepsilon_r = 88$, the dielectric permittivity (F m^{-1}) of pore meltwater is $\varepsilon = \varepsilon_r\varepsilon_0 = 7.8 \times 10^{-9}$ Fm_1, where $\varepsilon_0 = 8.85 \times 10^{-12}$ 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 6, the section now reads, 'The zeta potential is principally a function of pH and electrical conductivity (after Kulessa et al., 2012)

$$\zeta(\sigma_w, pH) = [\alpha + \beta log_{10}\sigma_w]\left(sin\frac{\pi}{12}[pH_w - pH_w(pzc)]\right) \qquad (6)$$

where α and β depend on the chemical composition of the pore fluid and can be determined empirically (Revil et al., 1999).'

Specific references to figures in the Kulessa et al., 2012 paper have been removed while the relevant information is retained in the paper, 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 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 (after Kulessa et al., 2012)

$$\zeta(\sigma_w, pH) = [\alpha + \beta log_{10}\sigma_w]\left(sin\frac{\pi}{12}[pH_w - pH_w(pzc)]\right) \quad (9)$$

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 consistently was minimal. The final values of pH and electrical conductivity calculated from equation 6 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), the absence of consistent spatial or temporal changes in either pH or electrical conductivity throughout the survey periods further suggests that the snowpacks were mature. 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 (1 – 5 × 10^{-6} S m^{-1}), and its rate of change became minimal along with those of pH and electrical conductivity (Kulessa et al., 2012)'.

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 modelled from equation 6 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), the absence of consistent spatial or temporal changes in either pH or electrical conductivity throughout the survey periods further suggests that the snowpacks were mature'.

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 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’.

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. 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. In operational practice, 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 monitoring 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 and lateral meltwater flows or liquid water contents’.

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*	*ψ_m ± 40%*	*ψ_m ± 20%*
Discharge Q (m^3 s^{-1})	*Variable*	*Q ± 40%*	*Q ± 20%*
Electrical conductivity σ_w (S m^{-1})	*5 x 10^{-6}*	*10^{-7} –10^{-4}*	*σ_w ± 5 x 10^{-7}*
Zeta potential ζ (V)	*-1 x 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*

Table 1: *Best estimate of each parameter for Rhone 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,

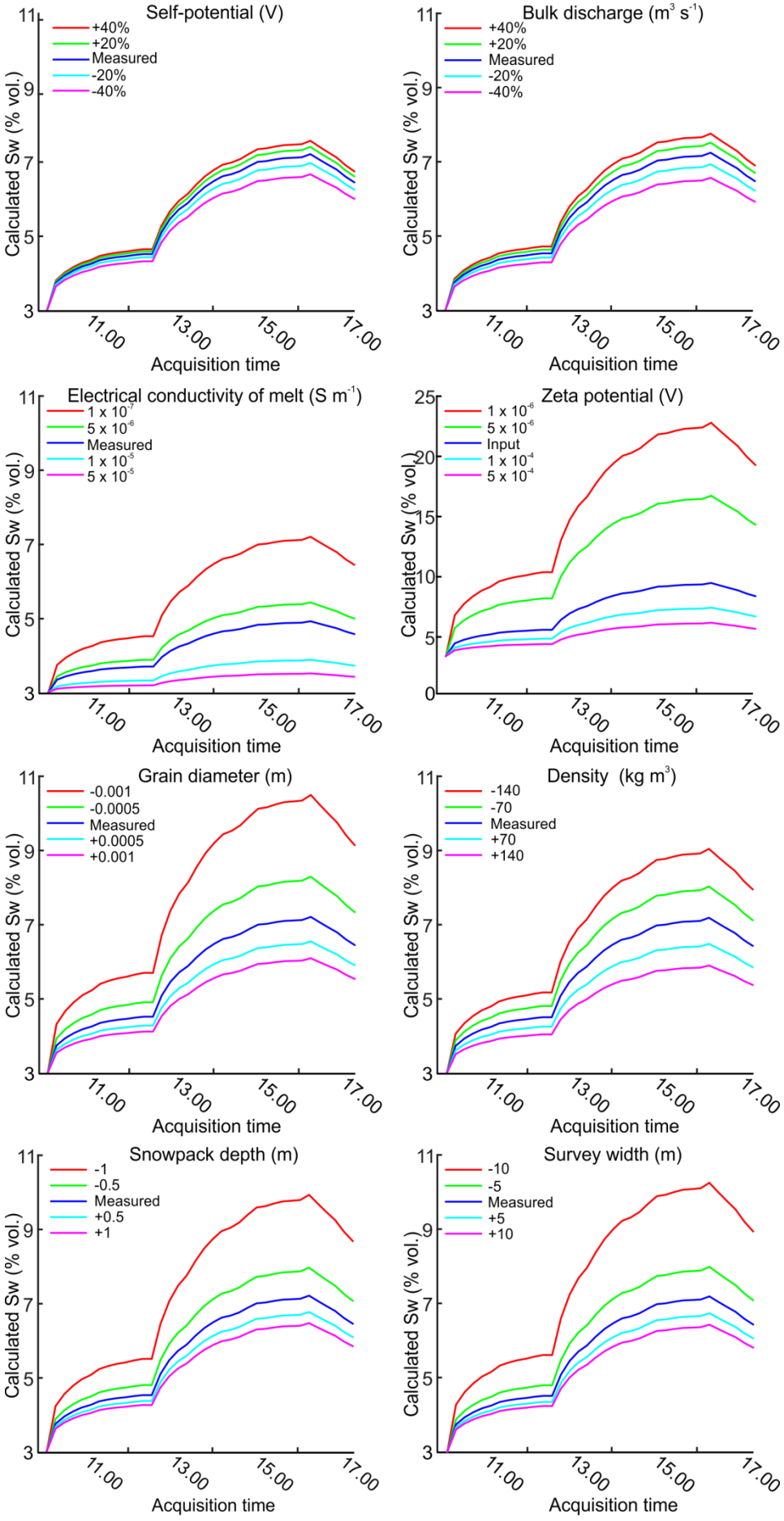
Self-potential (V)
+40%
+20%
Measured
-20%
-40%
Bulk discharge (m3 s-1)
+40%
+20%
Measured
-20%
-40%
Electrical conductivity of melt (S m-1)
1 x 10-7
5 x 10-6
Measured
1 x 10-5
5 x 10-5
Zeta potential (V)
1 x 10-6
5 x 10-6
Input
1 x 10-4
5 x 10-4
Grain diameter (m)
-0.001
-0.0005
Measured
+0.0005
+0.001
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 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.*

Review 2

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.

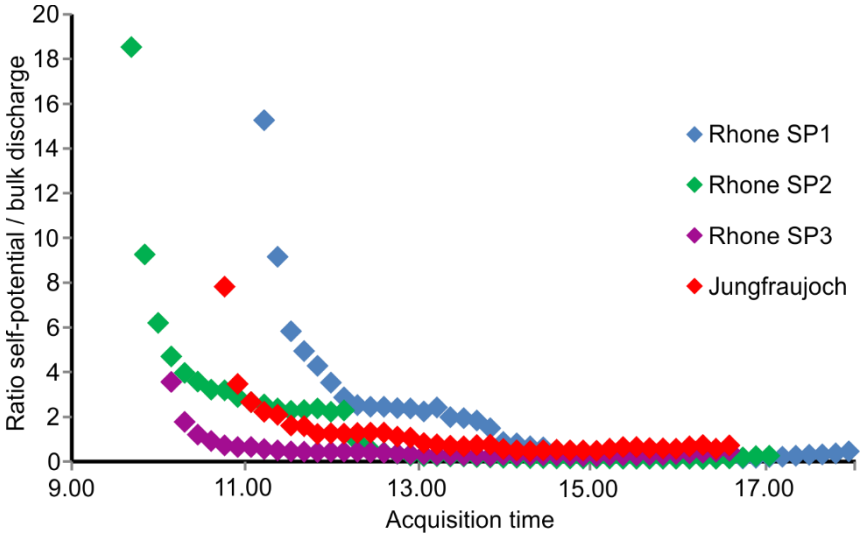

Figure 3: *Ratio between self-potential (V) and bulk discharge (m^3 s^{-1}) for each of the four surveys through time, illustrating the ratio changes consistently over time.*

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 the conclusion 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 er 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 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. (3)'.