Author's Response

Dear Dr. Berthier,

I am hereby submitting a revised version of our manuscript:

> Cook, S. J., Kougkoulos, I., Edwards, L. A., Dortch, J., and Hoffmann, D.: Glacier change and glacial lake outburst flood risk in the Bolivian Andes, The Cryosphere Discuss., doi:10.5194/tc-2016-140.

Please find below responses to the two reviewers (Reviewer 1 Wilfried Haeberli; Reviewer 2 Anonymous) and the Interactive Comment by Mauri Pelto, as well as a marked-up version of the manuscript that illustrates all of the changes that we have made. Our general sense is that all three interactive comments are very positive about the manuscript, and see it as a valuable and publishable piece of research. Indeed, Mauri Pelto even wrote a blog piece for the AGU on our manuscript, indicating an enthusiasm for this work, as well as promoting *The Cryosphere*: http://blogs.agu.org/fromaglaciersperspective/2016/07/18/chaupi-orko-glaciers-bolivia-extensive-recession/

In general, we have accepted the comments of the reviewers and adjusted our manuscript accordingly. Indeed, we have found the review process to be very constructive – certainly, the manuscript has been improved.

If you have any further queries, need any additional changes or information from us, then please do not hesitate to contact me.

With best wishes,

Simon

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Reply to Mauri Pelto – Interactive Comment

We thank Mauri Pelto for his insightful comments and questions about our manuscript. This provides us with an opportunity to elaborate on some points in our study. Taking each point in turn:

2-27: It's hard to say with any certainty if the GLOF risk in the region is high or not. One of the points of our paper is to highlight that there is a risk, and that this risk has not been assessed before. Hoffmann & Wegenmann (2013) described the only documented GLOF in Bolivia, as far as we are aware, but that does not necessarily mean that it is the only GLOF that has occurred here. It is worth remembering that, for the most part, the people affected by such events live in rather remote communities. GLOF events may simply go undocumented. Last year, we travelled to Agua Blanca, in the Apolobamba Region (Northern part of our study area), where we spoke to the village leader about the work we were doing there and this led him to recount a story from his father who had witnessed a GLOF event some years ago in a neighbouring valley. There is no documentation of this event, and it is hard to verify, but the point is clear: there may be other undocumented GLOFs that have taken place in Bolivia.

4-1: OK

4-27: I think this is a reasonable point. I suppose the issue is whether a lake that occupies a basin that has been carved out by a glacier or dammed by glacial sediment constitutes a 'glacial lake', and hence if it were to burst can be considered a 'glacial lake outburst flood'. I agree that the term 'GLOF' would normally be used for outbursts from ice-contact lakes or lakes that had formed 'recently' following deglaciation (whatever you take 'recent' to mean). I hope that most readers would appreciate what is meant when we use the term 'GLOF' in the context of our work in Bolivia.

5-1: Not necessarily. In Bolch et al.'s (2008) paper, the whole study region is classified according to slope, with the slopes of 45 deg or steeper representing the greatest mass movement risk. They aren't necessarily recently deglaciated. We just wanted to make the extra point here that recently deglaciated slopes can be particularly susceptible to mass movements.

5-28: Good idea. We have reworded.

6-3: No, not that I am aware of. In compiling data for an earlier study (Cook and Quincey, 2015), we generated a list of studies that had employed the lake volume-area relationship of Huggel et al. (2002). At the time of doing that (c. 2014-15) there were some studies that borrowed the relationship to estimate lake volume for glacial lakes in the high mountains of Asia (Nepal, Tien Shan, etc), but none for the Andes. We have subsequently removed the equation from Huggel et al. (2002) in response to comments by Reviewer 1 (Wilfried Haeberli).

7-10: I suppose the extent to which a table vs. a figure best illustrates a trend in data is debateable. But I would like to emphasise a key issue here – we are not only making the point that ice-contact lakes have declined over time, but also that the pattern of change over time has been rather chaotic. I would argue that this is best illustrated with a figure because it is more immediately comprehensible.

7-17: As with the previous point, I would argue instead that the graph shows the complexities in lake change over time more effectively than a table of numbers, which would be harder to digest. I take the point that a Table would be useful in terms of information on lake type, but this is perhaps most relevant for potentially dangerous lakes – for these lakes, information on moraine-, rock-dammed lakes, etc, is provided in Table 2.

8-10: No, we did not determine the number of dangerous lakes for other years. Our reasoning for this is that, although understanding how the GLOF risk has evolved over time would certainly be interesting, the more important issue is to determine which of the lakes from the most recent dataset would be most likely to represent a GLOF risk. This seemed to us to be the more urgent question, and hence the one that should be given over to journal page space. This is something we could follow up on though – thanks for the thought.

9-26: Thanks very much. This is useful to know. Actually, we added some new material here in response to Reviewer 2. Soruco et al. (2015) found that reduced glacier area had been compensated by increased melt rates.

9-29: This is an important point, and I'm not sure that there is a clear answer in the literature about how important (or otherwise) glacial meltwater is for water supply in Bolivia (although see previous point and reference). One of the purposes of our paper is to stimulate further interest in this issue. Some studies have suggested that up to 40% of the water supply in La Paz is derived from glacial meltwater during the dry season (e.g. Vergara et al., 2007), whilst more recent estimates indicate a lower dependency of ~15% (Soruco et al., 2015). Likewise, some studies have indicated significant impacts of glacier decline on rural populations (e.g. Oxfam, 2009), whilst others have revealed that glacier change is not perhaps the most dominant force driving people away from rural locations (Kaenzig, 2015). Much of this information is already stated in the manuscript, and hopefully there is enough here to stimulate researchers to look more closely at this issue. We also made some changes relevant to this point in response to Reviewer 2.

10-26: This serves as a reason for keeping the information on ice-contact lake change as a figure (Fig 6) rather than a Table (as discussed above). Whilst the headline is that there has been a reduction in the number of ice-contact lakes, the trend is rather chaotic over time. If the glaciers continue to shrink, then their perimeter too shrinks, and the potential for there to be ice-contact lakes reduces. Hence, I would guess that there will continue to be an overall reduction in ice-contact lakes, but that there could be a lot of variability along the way. Much will depend on what is revealed by glacier recession – there could be large overdeepenings under these glaciers that will become sites of lake development in the future. Studies along the lines of Frey et al. (2010) and Linsbauer et al. (2016), which attempt to derive glacier bed topographies, would be very welcome in this regard.

11-7 to 14: The ultimate end point would be that all glaciers disappear and hence that all potential for GLOFs disappears too. The question of whether deglaciating landscapes are becoming more dangerous because of GLOF events and other hazards, or whether they become less hazardous over time because there is less area within which these hazards can take place is interesting. The record of GLOFs in Bolivia is also very poor, so it's hard to say what the longer term trend is. These issues vary on a site-by-site basis too. For example, if you take the example of Laguna Glaciar (Lake 23 in our inventory – see Supplementary material), this lake has got bigger and bigger through the course of the study period, and so arguably has become more dangerous as more of the overdeepening has been exposed. We also considered a similar point made by Reviewer 1 (Wilfried Haeberli).

12-5: Yes, interesting point, and one that we encountered when writing Cook and Quincey (2015). From that study, "As yet, there is no reliable technique available for measuring lake bathymetry or volume from satellite imagery where turbidity precludes the derivation of reflectance–depth relationships (e.g. Box and Ski, 2007)". Recent work by Pope et al. (2016) developed techniques for estimating supraglacial lake depths (http://www.the-cryosphere.net/10/15/2016/tc-10-15-2016.pdf), but obviously, these are not affected to the same degree by turbidity. Lake bathymetry is a crucial measure for GLOF hazard assessments, but remains a labour-intensive, field-based measurement.

12-25: We have re-worded this, but we maintain that the lack of reporting of GLOFs in Bolivia does not necessarily mean that they haven't occurred, nor that they won't be more frequent in the future. Reviewer 1 (Wilfried Haeberli) makes a comment on our paper that also suggests that deglaciating environments could become more hazardous.

Figure 3: Interesting – good spot. We traced our Peru-Bolivia border from the National Geographic basemap layer in ArcGIS. We double-checked our mapping, and it is correct. However, we have seen maps (e.g. GoogleEarth) where the border is drawn slightly to the east.

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Reply to Reviewer 1 – Wilfried Haeberli

We thank Wilfried Haeberli for his constructive comments on our manuscript, and are pleased that he views our work as welcome and interesting. We have made a number of changes to our manuscript in response to his comments, and respond to these below.

Hazard and risk aspects

A key criticism of our manuscript is that it employs a self-correlation between lake volumes and areas (Equations 2 and 3 in the original manuscript) to predict the volumes of Bolivian glacial lakes. These comments follow constructive interactive comments made by Wilfried Haeberli about Cook and Quincey (2015) (see http://www.earth-surf-dynam.net/3/559/2015/esurf-3-559-2015-discussion.html). In our original manuscript, we sought to avoid total reliance on the widely used empirical volume-area relationship of Huggel et al. (2002) by supplementing this with a new empirical volume-area relationship derived from a more targeted and appropriate selection of lakes from the collation of data undertaken by Cook and Quincey (2015), i.e. those of a similar area to the lakes encountered in Bolivia, and restricted to moraine-dammed lakes only. Nonetheless, this has not avoided the use of a volume-area self-relationship, and the reviewer has questioned the validity of its use here. These concerns are valid.

To address this issue in the revised manuscript, we have taken the reviewer's advice by instead using the depth-area data collated by Cook and Quincey (2015) to predict mean depth for Bolivian glacial lakes. Depth can be multiplied by measured lake area to derive lake volume. We now explain this in the text where we present Equation 2, and the updated values are shown in Table 2. We have removed the V-A relationship of Huggel et al. (2002), and we have removed values from Table 2 and in the text that were derived from that relationship. The majority of these changes can now be found on P6 L5-25.

On the subject of peak discharges calculated using Equation 4 (now equation 3), the reviewer raises the point that we should emphasise that these represent worst-case values. We have now highlighted that throughout the manuscript wherever we discuss these values, and where we describe the methods used (i.e. where Equation 3 appears). E.g. P6 L24 and P8 L22-3.

The reviewer also raises the interesting point that the potential for glacial hazards to occur may not reduce as glaciers disappear. This is pertinent to the interactive comment on our manuscript by Mauri Pelto (doi:10.5194/tc-2016-140-SC1), who queried whether GLOFs represent an "emerging" threat in Bolivia. Certainly, we agree that glacial hazards, including GLOFs, could become a worsening threat to communities in Bolivia, but there are no long-term data available (at least to our knowledge) to examine any such trends. See P5 L3-5 for example (plus other edits in response to minor corrections below).

Minor corrections

1-24: changed to “contain” P1 L24

2-04: changed to “increasing atmospheric temperature” P2 L4.

2-26: we now cite these references P2 L26-7

4-15 and 5-first paragraph: We have noted on p5 L11 that the selection of this distance threshold is somewhat subjective. We have followed the precedent here of Wang et al. (2011, 2015). We made the suggested addition about permafrost thaw, and cited a new study by Rangecroft et al. (2016) that indicates almost complete permafrost disappearance in the Bolivian Andes by the 2080s (P5 L3-5).

5-9: We have added a statement about the importance of other factors in determining flood magnitude. P5 L13-14.

5-13/14: We now acknowledge that smaller lakes could still generate damaging floods. P5 L18.

5-23: We now acknowledge that floods could propagate further than 20km. P5 L28.

7-33: removed “increase” P8 L7

8-10/14: We have added a statement to emphasise that these discharges are worst case / unlikely. P6 L24 and P8 L22-3.

11-01: We were unsure what the reviewer was suggesting. Perhaps a way of decreasing word count. We have left this for now.

11-23: We now cite Linsbauer et al 2016. P12 L25.

11-28: full stop removed P12 L12

12-28/29: We felt that the conclusion section was perhaps the wrong place to discuss rock dam stability since this appears to be an issue in its own right. Instead, we elaborated on this issue on P5 L34 to P6 L2, and removed mention of rock-dammed lakes in the conclusions. We have emphasised in the conclusions that these are worst-case scenario values of peak discharge.

Table 2: Yes. This was dealt with in an earlier point.

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Reply to Reviewer 2

We thank the reviewer for their thoughtful comments on our manuscript. We are pleased that they suggest our work be published, and that they praise the approach and merit of the work. We address the specific and minor comments below.

Specific comments

We agree that care should be taken when reporting statistics about water resources and vulnerability. It is easy to regurgitate these figures and lose a sense of the science upon which they are based, and the reviewer is right to check that we are using language and statistics appropriately. The reviewer first points to a specific example on p1-28 of the original manuscript. We should clarify that the values cited here are based on previous work, but we had failed to cite the accompanying reference (Soruco et al., 2015), which made the value look arbitrary. We have now added that reference (p1-28). We have also added further discussion of the results of Soruco et al (2015) into section 4.1 because they studied decadal changes (or lack of) in runoff to La Paz (P10 L2-5). We have added additional references (e.g. Painter, 2007) to the Introduction to back-up points that we had made (P1-29). I would argue that, overall, we have been careful and conservative in our writing – more so than in previous studies in some cases. For example, the reviewer suggests that some values are speculative without measured values, but we already state that further quantification is required (e.g. P2-2). We are also quite careful not to be alarmist – we use phrases like "La Paz… derives *some* of its electricity from hydropower generation, which depends to *some extent* on glacial meltwater generation". Compare that with the equivalent statement in Painter (2007): "La Paz is also dependent for *virtually all* of its energy supplies on hydroelectric power". One of us (Hoffmann) lives in La Paz, and knows that this latter statement is untrue, and hence we toned-down our writing of the importance of glaciers for hydropower in Bolivia. Elsewhere, we have toned-down our language. For example, in the abstract and introduction we had said that meltwater was "vital", but now we say it is "important"(P1-1 & 25).We hope that the addition of some missing references, along with further discussion of the few papers that have quantified glacier and runoff change (e.g. Soruco et al., 2015) will satisfy the reviewer here.

The reviewer comments on our process for identifying potentially dangerous lakes. We think that it is a good idea to include a flow diagram that summarises the process of identifying such lakes. We had considered this before submitting our manuscript, but decided against it on the basis of article length and page costs. We have, however, adopted this suggestion – see Figure 2. The reviewer's suggestion that we consider ranking the lakes in some way according to their level of danger is a good one, and this is something that we intend to work on as part of the second author's PhD project. However, there are, as yet, no universally accepted or adopted methods for determining how dangerous a lake is – should population exposure be a more important factor than lake size? Should the potential for rockfall into a lake be of greater concern than a degrading ice-cored moraine? Because this is such a complex issue, and because we simply wanted to identify lakes that are potentially dangerous (rather than measure their absolute level of danger/threat), we opted for a simpler approach – potential flood size – as the reviewer correctly identified. We have clarified in the text that we use peak discharge to order the lakes.

The reviewer comments on our error estimates. We adopted the technique outlined in Hanshaw and Bookhagen (2014), which calculates error as a function of glacier size (perimeter) and spatial resolution of the imagery. Hence, a relatively small total perimeter could yield a larger error estimate. For the most part, our glacier mapping was undertaken automatically. As reported in previous studies, automatic mapping yields errors typically between 2 to 6% (Paul et al., 2013). But again, we have been conservative here in our error estimate because we corrected some mapping manually. In reality, we expect the error to be lower than 10%. Hence, we cited Paul et al. (2013) with their error estimates for clean glaciers of ~5%.

We are glad the reviewer likes the kmz file – we hope this will prove to be a useful resource for anyone interested in the issues raised in our manuscript.

The reviewer suggests we look into reasons why patterns of lake development over time are not straightforward. Certainly, this is something that we are interested in, and intend to follow-up on in our continuing work. But we are keen to keep this manuscript focused on the three stated objectives outlined in the Introduction. The second objective was to evaluate lake development, which we have achieved. This is principally to allow us to move on to objective 3 to identify potentially dangerous lakes. Some interesting patterns emerge from our evaluation of lake development, but to explain these patterns could become a study in its own right. We are grateful for the suggestions and enthusiasm of the reviewer on how such a study could be approached. We will follow-up on this.

The reviewer asks us to clarify whether we consider moraine-dammed lakes to be more dangerous than bedrock-dammed lakes. As we state in section 2.3 (P5 L31), moraine-dammed lakes are generally considered to be more dangerous because there is the potential for breach incision through the moraine thickness, allowing for a greater volume of water to escape from the lake. But we also make the point that bedrock-dammed lakes can be sources of GLOFs, and cite some examples of this. So both are potentially dangerous, although there is a general consensus (as far as we are aware) that moraine-dammed lakes represent the greater threat. Hence, we categorised lakes by dam type in Table 2.

The reviewer questions our ordering or lakes in Table 2. Again, we have now clarified in the text that we have simply ranked the lakes by peak discharge (P6 L25). This is because there are no universally accepted methods of ranking lakes by threat – this is something we are working on, however.

The reviewer asks us to reconsider our use of the word “trend” in relation to ice-contact lake data, which show no strong tendency. This is a fair point, and we have adjusted our language accordingly (e.g. by using the word “change” instead). E.g. P11 L9.

Minor Comments

P3 L5: We have now changed this to “initial assessment”. P3 L6 & P4 L23.
P4L26: We have added a colon. P4L28
P5 L23: We weren’t sure what was being commented on here, so we have kept this the same.
P5 L27: We had to change this anyway in response to another comment – it now reads “lakes confined within”. P5 L34.
P8 L21: Changed as requested. P8 L29
P10 L27: Changed as requested. P11 L9
P11 L28: Changed as requested. P12 L12
P11, L32,33: Yes. Done. P12 L16-18
Map figures: We experimented with different map formats in preparing this manuscript – different ESRI backgrounds, Landsat imagery – natural and false colour. One of the issues is scale: our area of interest is very large, but the glaciers and lakes relatively small. If we were to plot up all of the locations of settlements from geobolivia for this region, it would somewhat dominate the map (essentially, a lot of dots). This is one of the reasons we produced the supplementary kmz file so that people could look at the detail for themselves, whilst leaving the map figures fairly simple in order to illustrate glacier change and lake locations.
Table 2: Please see our response to earlier comments. We prefer to keep this very simple and order by peak discharge. Thanks for the space-saving tip. We saved a lot of space anyway in dealing with Reviewer 1’s comments to remove the values derived from lake volume-area self-correlation. But we also changed the heading to “Dam type” to allow us to shorten the classifications to “moraine” and “bedrock”.

Glacier change and glacial lake outburst flood risk in the Bolivian Andes

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Abstract. Glaciers of the Bolivian Andes represent an ~~vital~~ important water resource for Andean cities and mountain communities, yet relatively little work has assessed changes in their extent over recent decades. In many mountain regions, glacier recession has been accompanied by the development of proglacial lakes, which can pose a glacial lake outburst flood (GLOF) hazard. However, no studies have assessed the development of such lakes in Bolivia despite recent GLOF incidents here. Our mapping from satellite imagery reveals an overall areal shrinkage of 228.1 ± 22.8 km^2 (43.1%) across the Bolivian Cordillera Oriental between 1986 and 2014. Shrinkage was greatest in the Tres Cruces region (47.3%), followed by the Cordillera Apolobamba (43.1%) and Cordillera Real (41.9%). A growing number of proglacial lakes have developed as glaciers have receded, in accordance with trends in most other deglaciating mountain ranges, although the number of ice-contact lakes has decreased. The reasons for this are unclear, but the pattern of lake change has varied significantly throughout the study period, suggesting that monitoring of future lake development is required as ice continues to recede. Ultimately, we use our 2014 database of proglacial lakes to assess GLOF risk across the Bolivian Andes. We identify 25 lakes that pose a potential GLOF threat to downstream communities and infrastructure. We suggest that further studies of potential GLOF impacts are urgently required.

1 Introduction

Tropical glaciers are sensitive indicators of climate change and provide important information on climatic trends in locations where meteorological observations are sparse (Kaser, 1999; Vuille et al., 2008; Soruco et al., 2009). In this study, we focus on glacier change in the Bolivian Andes, which contain~~s~~ ~20 % of the world's tropical glaciers (Jordan, 1991, 1998; Kaser, 1999). Here, glacial meltwater is an important ~~vital~~ water resource for major cities, such as La Paz and El Alto, as well as for mountain communities across the region (Vergara et al., 2007; Vuille et al., 2008; Oxfam, 2009; Rabatel et al., 2013; Rangecroft et al., 2013). La Paz and its neighbouring city of El Alto are home to ~2.3 million people, and it is estimated that glaciers supply ~15 % of the potable water supply to these areas (Soruco et al., 2015). La Paz, like many Andean cities, derives some of its electricity from hydropower generation, which depends to some extent on glacial meltwater generation (Painter, 2007). Some researchers have expressed concern that power generation during the dry season will become unreliable due to low water flows (Painter, 2007; Chevallier et al., 2011; Kaenzig, 2015), although this requires quantitative study.

There is also some evidence that more isolated mountain communities in Bolivia are suffering increasingly from the adverse effects of glacier recession and changing meltwater supply in response to increasing climatic atmospheric temperature warming (Oxfam, 2009), although it does not yet appear to be a direct driver of rural-to-urban migration (Kaenzig, 2015). Bolivia is the poorest country in South America and hence is very vulnerable to the impacts of climate change (Andersen and Verner, 2009; Winters, 2012). Indeed, it is estimated that only 56 % of Bolivia's rural population have access to safe water (Jeschke et al., 2012; Rangecroft et al., 2013), meaning that the sustainability of glaciers is a significant concern in the broader context of poverty and vulnerability to climate change.

Despite the regional importance of Bolivian glaciers, research to monitor their extent and response to climate change has been rather limited. Detailed mass balance and modelling studies have been performed for a few glaciers, such as the Zongo glacier (e.g. Sicart et al., 2011; Reveillet et al., 2015; Soruco et al., 2015). Other studies have documented the demise of Chacaltaya glacier, which disappeared in 2009 (Ramirez et al., 2001; Soruco et al., 2015). At a broader scale, Jordan et al. (1980) and Jordan (1991, 1998) developed the first inventory of glaciers in Bolivia. Soruco et al. (2009) calculated a volumetric reduction of 43 % for 21 glaciers of the Cordillera Real over the period 1963 to 2006 (location shown in Figure 1b), whilst Albert et al. (2014) demonstrated that glaciers of the small range of Tres Cruces had lost approximately half of their surface area between 1975 and 2009 (locations shown in Figure 1b). However, a comprehensive quantification of glacier change across the Bolivian Andes has hitherto not been undertaken, and little is known about broad-scale glacier change in the last decade since the 1963-2006 study period of Soruco et al. (2009).

A crucial further issue for consideration is the development of potentially dangerous glacial lakes. Glaciers tend to erode subglacial basins and deposit eroded materials around their margins as lateral-frontal terminal moraines (Cook and Swift, 2012). Recession into these basins and behind impounding moraines causes meltwater to pond as proglacial and supraglacial lakes (Carrivick and Tweed, 2013; Cook and Quincey, 2015). In many mountain ranges, these lakes represent a glacial lake outburst flood (GLOF) hazard, as moraine dam integrity reduces over time, leading to dam failure, and as mass movements of ice, snow and rock from surrounding valley slopes impact lakes, leading to wave-overtopping of moraine and bedrock dams (Clague and Evans, 2000; Richardson and Reynolds, 2000; Hubbard et al., 2005; Carey et al., 2012; Westoby et al., 2014; Haeberli et al., 2016). GLOF hazards have received almost no research attention in the Bolivian Andes, yet Hoffmann and Wegenmann (2013) documented a recent GLOF at Keara in the Apolobamba region in 2009, indicating that the potential impacts of such hazards have been overlooked. In this case, an ice-dammed lake burst, killing several farm animals, destroying cultivated fields, and washing away a road that left the village population cut off for several months. Fortunately, no human casualties occurred. In other locations, several studies have shown that glacier recession has been accompanied by an increase in the number and size of proglacial lakes (e.g. Carrivick and Tweed, 2013; Carrivick and Quincey, 2014; Komori, 2008; Loriaux and Casassa, 2013; Hanshaw and Bookhagen, 2014; López-Moreno et al., 2014; Wang et al., 2014), raising concerns that glaciated mountain regions are becoming more hazardous with respect to GLOFs. As yet, however, no study has quantified proglacial lake development in the Bolivian Andes to assess whether such a trend is prevalent here. Furthermore, no studies have assessed the extent to which these lakes represent a GLOF threat to downstream communities and infrastructure within Bolivia.

This study has three primary objectives to address these shortcomings: (1) to quantify glacier change in recent decades (from 1986 to 2014) across the Bolivian Andes; (2) to evaluate the development of proglacial lakes through this period; and (3) to provide an ~~first-pass~~initial assessment of whether any existing proglacial lakes represent a GLOF hazard that may require further monitoring. The time period is chosen based on the availability of satellite imagery, plus a desire to extend the period of observations from previous work on glacier change in the region – the observations of Soruco et al. (2009) extended to 2006 for the Cordillera Real, and those of Albert et al. (2014) extended to 2009 for the Tres Cruces region. The spatial extent of our study is chosen in order to provide a first integrated assessment of glacier change across the whole of the Bolivian Cordillera Oriental.

2 Study region and methodology

2.1 Study region

Figure 1 shows a map of Bolivia with the footprint of the satellite imagery used to map glacier change from 1986 to 2014. This study focuses on the glaciated areas of the Cordillera Oriental of Bolivia, which itself can be divided into a series of ranges. The most significant ice cover is in the Cordillera Real, in the middle part of our study region, and the Cordillera Apolobamba in the north, which straddles the Bolivia-Peru border. There are a series of smaller glaciated ranges further to the south of the main glaciated area of the Cordillera Real (including Huayna Potosí, Mururata, Illimani), and we consider all of these together as the Cordillera Real (after Jordan, 1991, 1998). The southernmost Tres Cruces region holds another small, glaciated range (Figure 1). We follow previous studies (Jordan, 1991, 1998; Soruco et al., 2009; Albert et al., 2014) in mapping across the three regions covered by the three satellite footprints: Cordillera Apolobamba, Cordillera Real, Tres Cruces.

Andean glaciers have experienced recent recession in response to increasing temperatures (e.g. Kaser, 1999; Vergara, 2007; Vuille et al., 2008; Rangecroft et al., 2013). Bolivian glaciers, unlike glaciers outside of the Tropics, accumulate mass during the summer wet season (November to April), and experience enhanced ablation during the winter dry season (May to October) and inter-seasonal periods when solar radiation is more intense (Jordan, 1998). Andean glaciers are particularly sensitive to the El Niño Southern Oscillation (ENSO) (e.g. Francou et al., 1995, 2000; Wagnon et al., 2001). El Niño years lead to enhanced mass loss, whereas La Niña years tend to lead to reduced mass loss or even mass gains (Vuille et al., 2008).

2.2 Mapping glacier and lake change

Landsat satellite imagery, with a spatial resolution of 30 m, was obtained from the United States Geological Survey (USGS) using the Earth Explorer interface (http://earthexplorer.usgs.gov/). Data were obtained for the three footprints outlined in Figure 1 for the years 1986, 1992, 1999, 2010 and 2014 (Table 1). Wherever possible, images were selected with minimal cloud cover, and all images were selected from the dry season when snow cover would have been at a minimum (which could be confused for glacier ice). Ice cover was identified automatically in the first instance by using the TM3/TM5 band ratio (i.e. the ratio of red to short wave infrared) (e.g. Bolch et al., 2010) on atmospherically corrected imagery (Burns and Nolin, 2014). Some manual editing of the TM3/TM5 output was also required. Firstly, lakes that had been misidentified as ice cover were removed. Secondly, all glacier polygons smaller than 0.05 km^2 were removed as they probably represented snow patches rather than glacier ice (Bolch et al., 2010). Thirdly, the areas identified as ice cover were checked against imagery in Google Earth, which has historic imagery stretching back to 2002 for much of the area considered in this study. Any other misidentified features (e.g. snow patches, areas of moraine or debris-covered ice, etc.) were then edited manually.

We estimated uncertainty in our mapping following the method outlined by Hanshaw and Bookhagen (2014). They assume that mapping errors are Gaussian, i.e. that ~68 % (1σ) of pixels will be subject to error. Uncertainty is calculated as:

$$Error\ (1\sigma) = (P/G) \cdot 0.6872 \cdot G^2/2 \qquad (1)$$

Where *P* is the measured glacier perimeter, and *G* is the grid cell size. Uncertainties calculated using ~~Equation~~Equation 1 are ~10 %. Paul et al. (2013) found that error for measuring clean-ice glaciers, such as in this study, are on the order of ~5 %.

Lake extents were digitised manually with reference to both Landsat false colour composites, and NDWI (Normalised Difference Water Index) rasters (Huggel et al., 2002; Bolch et al., 2010). All visible lakes were mapped where they occurred within approximately 2 km of the glacier margins. Ultimately, however, we focussed on those lakes located within 500 m of the glacier margins because these lakes are likely to be of most relevance in terms of GLOF risk (see below). As with glacier mapping, we estimate that our lake mapping uncertainty is ~5-10%.

2.3 Assessing glacial lake outburst flood risk

Several studies have proposed schemes or criteria by which to identify potentially dangerous glacial lakes, or to assess the consequences of GLOF events (e.g. Allen et al., 2009; Huggel et al., 2004; McKillop and Clague, 2007; Bolch et al., 2008). In this study, we first identified lakes from the 2014 imagery that have the potential to burst by using some of the criteria outlined by Bolch et al. (2008); we then undertook a~~ first pass ~~n initial assessment of the potential severity of the resultant flood event (i.e. by estimating flood peak discharge) following procedures outlined by Huggel et al. (2004) and McKillop and Clague (2007)~~ where possible~~. Some data identified in these studies (such as moraine height, glacier velocity, etc.) were not available to us and so could not be integrated into the risk assessment at this stage. Figure 2 summarises the process of GLOF risk assessment.

We considered potential GLOF sources to be: (1) lakes in direct contact with glaciers; and (2) lakes within 500 m of the glacier margin that were also within 500 m of a steep (45° or steeper) slope. Ice-contact lakes could be directly affected by glacier calving events that generate waves with the potential to overtop impounding moraine and rock basin slopes. Previous studies have considered lakes within 500 m of a glacier to be potential GLOF sources (e.g. Wang et al., 2011~~; Wang et al.~~, 2015). Both ice-contact lakes and lakes within 500 m of a glacier could be impacted by ice and snow avalanches, which could also generate overtopping waves. These immediate proglacial areas are also affected by slope debuttressing associated with recent deglaciation, and hence are more likely to experience paraglacial slope failures that could impact the lakes (e.g. Hubbard et al., 2005; Cook et al., 2013; Haeberli et al., 2016). The potential for mass movements is likely to increase as permafrost thaws (e.g. Haeberli et al., 2016); recent predictions by Rangecroft et al. (2016) suggest that permafrost in the Bolivian Andes will disappear almost entirely by the 2080s. Bolch et al. (2008) considered slopes steeper than 45° to be particularly hazardous in this regard. Hence, we generated a slope map from a 30 m resolution ASTER GDEM2 (downloaded from http://reverb.echo.nasa.gov/reverb/) to identify slopes of 45° or steeper that could shed material into proglacial lakes. Runout distances of ice and snow avalanches, rockfalls, rock avalanches, and debris flows vary widely, but appear to cluster on the order of 10^2 to 10^3 m (Alean, 1985; Rickenmann, 1999, 2005; Copons et al., 2009). In the absence of detailed modelling of mass movement runout distances, we considered any proglacial lake within 500 m of a 45° or steeper slope to be potentially dangerous, although we emphasise that the selection of these values is somewhat subjective.

Next, we removed lakes that were unlikely to yield large flood events if they were to burst. This assessment was based principally on lake area, assuming that the smaller the area, the less significant the potential flood volume, although clearly other factors, such as the triggering mechanism and downstream conditions, play crucial roles in determining flood magnitude. Unfortunately, there are no size criteria to determine the smallest lake size to include in any inventory of GLOF risk. We know that the damaging flood at Keara (Hoffmann and Wegenmann, 2013) resulted from the almost complete drainage of an ice-dammed lake that had a surface area of ~34,000 m^2. Hence, we set a lower lake size threshold of 30,000 m^2 to capture lakes of similar size to the one at Keara, although smaller lakes could generate damaging floods. This should be sufficient to capture ~~all~~ most potentially dangerous lakes because all of the mapped lakes are either moraine-dammed, or sit within glacially overdeepened rock basins, and hence are less likely to drain completely as was the case for the ice-dammed lake at Keara.

Having identified all of the lakes with a potential outburst risk, we then identified all such lakes within that population that posed a risk of damage to human interests (e.g. homes, roads or infrastructure, cultivated fields, etc.). For the most part, this was achieved using the GIS database of roads and settlements available freely from GeoBolivia (http://geo.gob.bo/). We also cross-referenced this with a visual assessment of human features in Google Earth and Bing Maps, plus our own observations of a few of the sites. As a first assessment, we judged lakes to be dangerous where they had a direct hydrological connection to downstream infrastructure and communities (e.g. where a road or village was in the direct path of a GLOF event), and in general, we searched for such infrastructure within ~20 km downstream of the proglacial lakes (the complete drainage of the ice-dammed lake at Keara affected the channel for ~10 km downstream). However, floods could propagate further than 20 km. Mapping of hydrological connectivity was achieved using the hydrological (i.e. flow routing) tools within ArcGIS 10.2.2, with the ASTER GDEM2 as input data.

We used Google Earth imagery to assess whether the lakes identified from previous steps were moraine- or rock-dammed. Moraine-dammed lakes are considered more dangerous because an initial trigger event, such as an avalanche-induced wave, could lead to breach incision in the moraine, and hence enhanced drainage of the lake (e.g. Westoby et al., 2015). Lakes ~~sat~~ confined within rock basins are less likely to experience breach incision~~.~~, but there are notable examples of bedrock-dammed lake outbursts (e.g. Dortch et al., 2011; Vilímek et al., 2015), and these lakes remain vulnerable to wave overtopping (e.g. Haeberli et al., 2016). However, catastrophic drainage of lakes with bedrock dams have been noted in other tectonically active orogens (e.g. Dortch et al., 2011). Thus, both moraine- and rock-dammed lakes represent potential sources of GLOFs.

To assess the severity of GLOF events from our inventory of potentially dangerous lakes, we first estimated lake volumes based on a measurement of their surface area. Cook and Quincey (2015) reviewed the empirical approaches that have been adopted in previous studies to model lake volume. Perhaps tThe most popular approachesformula (e.g. Huggel et al., 2002) , estimate lake volume based on a measurement of lake areawhich is based on a combination of data from ice-dammed, moraine-dammed, and thermokarst lakes, has been that of Huggel et al. (2002):

$$V = 0.104\,A^{1.42} \quad (2).$$

Where V is lake volume in m^3, and A is lake surface area in m^2. Cook and Quincey (2015) noted highlighted some issues in this approach. that the relationship of Huggel et al. (2002) performed well in estimating lake volumes in most cases, but that there were some situations where lakes could be especially shallow or deep, giving unusually small or large volumes for a given area. Hence, they advocated that geomorphological context be considered when deciding on which empirical approach to adopt. All of the lakes identified in our inventory are either moraine-dammed, or sit within rock basins. Specifically, volume-area relationships suffer from auto-correlation between volume and area, which gives an unrealistic impression of the strength of correlation between the two. Lake volume is typically calculated by multiplication between measured lake area and averaged or integrated lake depth. Consequently, it is more appropriate to use depth and area data, which can be measured independently, to estimate lake volume. Cook and Quincey (2015) also suggested that geomorphological context be considered when applying empirical techniques to estimate volume because different lake types (i.e. ice-dammed, moraine-dammed, thermokarst, etc.) can have different morphological characteristics. All of the lakes identified in our inventory are either moraine-dammed, or sit within rock basins. Given these suggestions, we used the dataset from Cook and Quincey (2015) to derive an empirical relationship between lake depth and area that is specific to moraine-dammed lakes of a similar area range to those found in this studyThe relationship of Huggel et al. (2002) was shown by Cook and Quincey (2015) to perform well for estimating the volume of moraine-dammed lakes because the data used to generate Equation 1 were derived largely from moraine-dammed lakes. For those cases, we adopt Equation 1, but also use the larger dataset from Cook and Quincey (2015) to derive an empirical relationship specific to moraine-dammed lakes of a similar area range to those found in this study. This takes the form:

$$VD = 0.097A^{10.4375} \quad (32)$$

Where D is mean lake depth in m, and A is lake surface area in m^2. Equation 2 can be used to predict mean lake depth, which can be multiplied by measured lake area to calculate lake volume. We are not aware of any empirical formula forthat can predict the volume estimation whereof lakes are situated within rock basins. We are not aware of any empirical formula for

Formatted: Space Before: 0 pt, After: 0 pt volume estimation where lakes are situated within rock basins. In the absence of any such formula, we use EquationEquations 1 and 22 to provide a first order estimation of their volumes as well as moraine-dammed lakes.

Lake volume can be used to estimate peak discharge (Q_{max}). Huggel et al. (2002) collated several empirical models for estimating GLOF peak discharge from lake volume, but ultimately adapted the relationship of Haeberli (1983) to give:

$$Q_{max} = \frac{2V}{t} \quad (43)$$

Where t, time, is equal to 1000 seconds. We used equation 3 to estimate peak discharge for the lakes identified as being potentially dangerous. It should be noted that peak discharges calculated using Equation 3 represent worst-case estimates. Lakes are ranked from lowest to highest peak discharges in Table 2.

3 Results

3.1 Glacier change 1986-2014

Our results reveal that total glacier areal cover across the Bolivian Cordillera Oriental in 1986 was 529.3 ± 52.9 km^2, and that by 2014 this area had reduced to 301.2 ± 30.1 km^2 (Figure 2Figure 3a). This represents a total areal reduction of 43.1 % over the 28-year study period. If the Peruvian Cordillera Apolobamba glaciers are included in the dataset, then the total glacier cover in 1986 was 626.5 ± 62.7 km^2 and in 2014 it was 351.7 ± 35.2 km^2, representing a 43.9 % reduction. Figure 2Figure 3a illustrates the reduction in overall glacier cover across this period. Rates of ice loss appear to vary across the study period, with an initially rapid shrinkage between 1986 and 1992 (14.5 km^2 a^{-1}), relatively modest losses between 1992 and 1999 (5.1 km^2 a^{-1}), strong ice shrinkage between 1999 and 2010 (8.1 km^2 a^{-1}), and modest losses between 2010 and 2014 (4.0 km^2 a^{-1}) (except for the Tres Cruces region).

For consistency with earlier studies, we present results in Figure 2Figure 3 of glacier areal change for separate glaciated mountain ranges, and Figures 3 4 to 5 6 illustrate glacier change as a series of maps for each region. All mountain ranges show decreases in overall glacier area across the study period with a total loss of 43.1 % glacier cover in the Bolivian Cordillera Apolobamba (172.3 ± 17.2 km^2 to 96.0 ± 9.6 km^2), 41.9% across the Cordillera Real (315.2 ± 31.5 km^2 to 183.1 ± 18.3 km^2), and 47.3 % in the Tres Cruces region (41.8 ± 4.2 km^2 to 22.0 ± 2.2 km^2). If Peruvian Cordillera Apolobamba glaciers are included, then the total loss for the Cordillera Apolobamba from 1986 to 2014 is 45.6 % (269.5 ± 27.0 km^2 to 146.3 ± 14.6 km^2).

3.2 Proglacial lake development 1986-2014

Figure 6Figure 7 illustrates how the number and areal cover of ice-contact and proglacial lakes has developed between 1986 and 2014 across the three regions of the Bolivian Andes. Data are presented for ice-contact lakes (Figure 6Figure 7a and b), and for lakes within 500m of the 1986 ice margin (Figure 6Figure 7c and d), which illustrates the cumulative change in proglacial lake number and area as the ice receded to its 2014 position. ~~Figure 7~~Figure 8 shows the total change in lake number and area across the Bolivian Andes.

Figure ~~6a~~ 7a indicates that that there is no clear pattern in the number of ice-contact lakes that developed from 1986 to 2014, although there has been an overall decline in the number of ice-contact lakes for all three regions. The Tres Cruces region shows the clearest trend of decline, although there were very few ice-contact lakes here throughout the study period (4 in 1986, and 0 in 2014). For the Cordillera Apolobamba, the number of lakes increased from 4 to 10 lakes between 1986 and 1999, before declining to 1 lake in 2014. The Cordillera Real region experienced the reverse situation to the Cordillera Apolobamba between 1986 and 2010, with a decline from 15 to 8 ice-contact lakes between 1986 to 1999, an increase to 12 lakes in 2010, before falling to 6 lakes in 2014. ~~Figure 7~~Figure 8a illustrates the overall decline in the number of ice-contact lakes across all regions, from 23 in 1986 to 7 in 2014.

~~Figure 6~~Figure 7b shows the change in area of ice-contact lakes for all three regions. The trend in ice-contact lake area for the Cordillera Apolobamba and Tres Cruces region follows the trend in the number of ice-contact lakes shown in ~~Figure 6~~Figure 7a. The Cordillera Real experienced an overall 22 % increase in ice-contact lake area from 0.9 ± 0.09 km^2 in 1986 to 1.1 ± 0.11 km^2 in 2014, although peaked at 1.2 ± 0.12 km^2 in 2010. This increase in lake area, even though lake number has fallen across the same period, is driven by the growth of a few large ice-contact lakes (e.g. Laguna Glaciar at the northern tip of the Cordillera Real, and the large lake, Laguna Arkhata, beneath the summit of Mururata – ~~Figure 4~~Figure 5). ~~Figure 7~~Figure 8b shows the overall trend in ice-contact lake area across the study period, indicating a very slight (10 %) overall increase from 1.0 ± 0.1 km^2 in 1986 to 1.1 ± 0.11 km^2 in 2014 (represented mostly by lakes in the Cordillera Real), with a peak at 1.6 ± 0.16 km^2 in 2010. The number of ice-contact lakes stayed relatively stable from 1992 to 2010 (~~Figure 7~~Figure 8a), yet the total area covered by these lakes increased (~~Figure 7~~Figure 8b). This is explained by growth of ice-contact lakes until 2010, followed by detachment, leading to an overall decrease in both lake number and area by 2014.

~~Figure 6~~Figure 7c shows that the number of proglacial lakes has increased from 1986 to 2014, for all regions, as the ice has drawn back from its 1986 position. These lakes fall within 500 m of the 1986 margin, and hence represent the cumulative total of lakes for the three regions as glaciers have receded. The greatest number of lakes exist in the Cordillera Real, which saw a 47 % increase from 92 lakes in 1986 to 135 lakes in 2014. The Tres Cruces region saw a 67 % increase from 24 lakes in 1986 to 40 lakes in 2014. The Cordillera Apolobamba has seen an overall increase of 72 % ~~increase~~ from 29 to 50 lakes across the study period, although there was a peak in 2010 at 53 lakes. ~~Figure 7~~Figure 8a reveals that there has been an overall total increase of 55 % in proglacial lakes from 145 to 225 lakes.

~~Figure 6~~Figure 7d shows that the area covered by lakes within 500 m of the 1986 ice margin has increased, and broadly reflects the pattern of lake number change illustrated in ~~Figure 6~~Figure 7c. In the Cordillera Real, there has been a 54 % increase in proglacial lake area from 2.7 ± 0.27 km^2 to 4.1 ± 0.41 km^2. The Tres Cruces region has seen a rather more modest increase of 15 % from 2.6 ± 0.26 km^2 to 2.9 ± 0.29 km^2, and the trend has levelled-off since 2010. Proglacial lakes in the Apolobamba region have seen a 51 % increase in area from 1.1 ± 0.11 km^2 to 1.7 ± 0.17 km^2, although the peak occurred in 2010 and lake area has since decreased. ~~Figure 7~~Figure 8b shows that total lake area has increased by 38 % from 6.33 ± 0.63 km^2 to 8.73 ± 0.87 km^2.

3.3 Identification of potentially dangerous lakes

In 2014, there were 137 lakes within 500 m of the 2014 ice margin, with a total area of 5.7 ± 0.57 km^2. From this ~~database~~database, we identified 25 lakes that have the potential to be the source of damaging GLOFs (Table 2). Table 2 shows that these lakes are either moraine-dammed or sit within rock basins, and have surface areas that range across three orders of magnitude from 32,800 to 1,355,700 m^2. Complete drainage of the smallest lake would yield a flood with an estimated peak discharge of ~~between 500 to 540~~~600 m^{3}s^{-1}. Complete drainage of the largest lake would yield an estimated peak discharge of ~~106,000 to 160~~126,~~000~~ 710 m^{3}s^{-1}, although the nine largest lakes are contained within rock basins and would be unlikely to drain completely. We emphasise that Equation 3, which is used to calculate peak discharges, yields worst-case estimates, and that such severe floods are probably unlikely. Many villages, farms and roads could be impacted by floods from the identified lakes. The lakes are also shown in Figures ~~3~~ 4 to ~~5~~6, although because of their size relative to the scale of the map, these are best viewed in the supplementary .kmz file.

4 Discussion

4.1 Bolivian glacier change

We make some comparisons with the limited previous research on Bolivian glacier change, although this is complicated to some extent because of inconsistent methodologies, different study periods, and inclusion or exclusion of ~~glaciated~~ glacierized areas in different inventories.

Glacier change in the Cordillera Apolobamba has not been investigated previously, which represents a significant gap in our understanding of Bolivian (and some Peruvian) glaciers. We have provided the first assessment of glacier change in this region. Jordan (1991, 1998) reported glacier areal coverage in this region for 1984 as 219.8 km^2. Our results from 1986 indicate ice coverage of 172.3 ± 17.2 km^2 for the Bolivian Cordillera Apolobamba, but this figure rises to 269.5 ± 27.0 km^2 when Peruvian glaciers are included (~~Figure 2~~Figure 3b and ~~3~~4). The discrepancy between our results and those of Jordan (1991, 1998) could be explained to some extent by further ice recession between 1984 and 1986. However, on closer inspection, it appears that Jordan (1991, 1998) included all ice across the Chaupi Orko range (see ~~Figure 3~~Figure 4 for location), both on the Bolivian and Peruvian sides of the border. When we include the same areas, the total for the Apolobamba Range is 221.3 ± 22.1 km^2, which is more consistent with Jordan's (1991, 1998) work. The slightly higher value is explained by our inclusion of some relatively small glaciers separate from the main glaciated ranges of the Cordillera Apolobamba, which were not included in Jordan's (1991, 1998) mapping. Since 1986, the trend of glacier loss has been sustained throughout the study period, similar to other glaciated mountain ranges in Bolivia (Figures ~~2~~ 3 to ~~5~~6), with an overall glacier ice shrinkage of 43.1 % for the Bolivian Apolobamba, and 45.6 % for the combined Bolivian-Peruvian Cordillera Apolobamba.

Whilst individual glaciers of the Cordillera Real have been the subject of intensive study over many years (e.g. Ramirez et al., 2001; Sicart et al., 2011; Reveillet et al., 2015; Soruco et al., 2015), only the study of Soruco et al. (2009) has examined broader changes in glacier ice cover across these mountains. Their study demonstrated a 48 % surface area loss from 1975–2006, which is broadly consistent with our results, albeit for a different time window. The 1984 inventory presented in Jordan (1991, 1998) gives glacier ice cover of 323.6 km^2 for the Cordillera Real, which is consistent with our 1986 value of 315.2 ± 32.4 km^2 (~~Figure 2~~Figure 3c and ~~4~~5).

Glacier change in the Tres Cruces region has been investigated by Albert et al. (2014) from 1975 to 2009. Their results indicated ~55 % areal loss over this study period, with a marked reduction in ice cover between 1975 and 1986, before the start of our monitoring period. Between 1986 and 2009, their results showed that ice cover had shrunk from ~36 km^2 to ~25 km^2, similar to our results (~~Figure 2~~Figure 3d). Since then, our results have shown a further reduction of 12.4 % to ~22 km^2 for 2014.

Overall, the glacier retreat rate across the Cordillera Oriental is 1.54 % a^{-1}, excluding Peruvian glaciers of the Cordillera Apolobamba, or 1.57 % a^{-1} if Peruvian glaciers are included. Regionally, the Tres Cruces experienced the highest retreat rates (1.69 % a^{-1}), followed by the Cordillera Apolobamba (1.54 % a^{-1} excluding Peruvian glaciers, and 1.63 % a^{-1} including Peruvian glaciers), with the Cordillera Real experiencing the lowest retreat rates (1.50 % a^{-1}). These values are comparable to retreat rates measured elsewhere in the Andes. For example, Rabatel et al. (2013) report retreat rates in Ecuador between 1962 to 1997 of 1.6 % a^{-1}, and 2 % a^{-1} for Columbian glaciers from the late 1970s to early 2000s; retreat rates of between 0.34 % a^{-1} and 2.05 % a^{-1} are reported by Vaughan et al (2013) for glaciers in Peru across similar time periods. Retreat rates further south in Patagonia are reported to be much lower at 0.14 to 0.66 % a^{-1} (Vaughan et al., 2013); in extra-tropical mountain ranges, such as the Alps, comparable rates of retreat of between 0.59 and 2.07 % a^{-1} are reported, although retreat is generally reported to be lower than in the present study (Vaughan et al., 2013).

The trend in glacier shrinkage across the Cordillera Oriental is of some concern in terms of water resources across the region, and particularly for the major cities of La Paz and El Alto. According to Soruco et al. (2015), the 50% loss of glacier cover between 1963 and 2006 had not led to a decrease in runoff at La Paz, indicating that the reduction in glacier area had, so far, been offset by increased melt rates. However, complete glacier disappearance would reduce runoff by ~12% annually, and by up to 24% during the dry season (Soruco et al., 2015)~~These trends are likely to continue into the future~~. Although glacier shrinkage is not yet known to have driven rural to urban migration (Kaenzig, 2015), this could be a further pressure in the future, and it is likely that the effects of glacier shrinkage will be felt both in large cities, which rely to some extent on glacial meltwater (Vuille et al., 2008; Rangecroft et al., 2013; Soruco et al., 2015), and in rural communities (Andersen and Verner, 2009; Oxfam, 2009; Winters, 2012). Even in the Cordillera Apolobamba, which is rather sparsely populated, there are still ~5,500 people who live within 10 km of the glaciers (according to GeoBolivia GIS data - http://geo.gob.bo/). Approximately 13,700 people live within 10 km of the Tres Cruces glaciers, and ~30,000 people for the Cordillera Real. Future changes to glacial water supply are likely to be felt keenly within these immediate rural areas, where communities may depend to some extent on meltwater during the dry season for drinking water, crop irrigation, and sustaining livestock. However, glacial meltwater also supplies populations in villages and cities beyond the immediate vicinity of the glaciated mountains. Another adverse impact would be toward the bofedales ecosystems (high altitude peat bogs and wetlands), which are also fed by glaciers, and which represent important water stores (Garcia et al., 2007; Squeo et al., 2009). Long-term glacier monitoring of the ice masses that supply water to La Paz and El Alto have been crucial in terms of understanding the sustainability of glacier meltwater in the region (e.g. Reveillet et al., 2015), yet similar studies have not been undertaken in other mountain ranges across Bolivia (e.g. in the Cordillera Apolobamba and Tres Cruces) where local populations could be very vulnerable to future glacier shrinkage (Andersen and Verner, 2009; Oxfam, 2009; Winters, 2012).

To provide a first-order estimate of future glacier evolution across Bolivia, we used the data presented in ~~Figure 2~~Figure 3a to derive an exponential function (because it provided the best fit with the data compared to linear and other best-fit lines) that could be used to model future glacier decay. This method indicates that glaciers across Bolivia will have shrunk to around 10 % of their 1986 area by ~2100. Extrapolation of glacier areal decline trends can only represent a first-order approximation, and masks the complex array of factors that determine glacier mass balance and volume, but our estimate suggests that further work is urgently required to accurately model glacier change, and to assess the consequences of that change on people and mountain ecosystems. There are few studies that model glacier demise in Bolivia, but Reveillet et al. (2015) modelled the future evolution of Zongo glacier, forcing the model with temperature changes predicted by the Coupled Model Intercomparison Project phase 5 (CMIP5). Their results indicated that the Zongo glacier would lose 69 +/- 7 % of its volume by 2100 with the intermediate CMIP5 scenario, and 40 +/- 7 % and 89 +/- 4 % with the extreme scenarios. Although we are comparing an individual glacier with glacier demise across the whole Bolivian Andes, our results are consistent with the ~~extreme~~ upper end of these predictions.

4.2 Proglacial lake development

We have made the first evaluation of proglacial lake development across Bolivia. In general, the number of proglacial lakes and their areas (i.e. those that formed within 500 m of the 1986 ice margin) increased as glaciers have receded from their 1986 positions (Figures ~~6c~~7c, ~~6d~~7d, ~~7a~~8a, ~~7b~~8b). This shows that ice recession has revealed further basins that have filled with meltwater. Several studies have described similar trends of increasing number and size of proglacial lakes from a range of locations, both from ice-sheet and valley glacier contexts (e.g. Carrivick and Tweed, 2013; Carrivick and Quincey, 2014; Komori, 2008; Loriaux and Casassa, 2013; Hanshaw and Bookhagen, 2014; Lopez-Moreno et al., 2014; Schomaker, 2010; Wang et al., 2014).

Conversely, there has been an overall decrease in the number of ice-contact lakes across the study period for all three regions (Figures ~~6a~~ 7a and ~~7a~~8a). However, this ~~trend~~ change has been ~~very~~ highly variable both spatially (across the three regions) and temporally. The ~~trends~~ changes in lake area have followed the changes in lake number for the Cordillera Apolobamba and Tres Cruces regions, but the Cordillera Real has experienced overall areal growth despite a reduction in lake number (~~Figure 6~~Figure 7b). This is because there are a few large ice-contact lakes in the Cordillera Real (e.g. Laguna Glaciar, Laguna Arkhata – ~~Figure 4~~Figure 5) that have been growing rapidly as ice has receded, in accordance with most findings in other deglaciating regions (e.g. Carrivick and Tweed, 2013; Komori, 2008; Loriaux and Casassa, 2013; Hanshaw and Bookhagen, 2014; Lopez-Moreno et al., 2014; Schomacker, 2010; Wang et al., 2014). Reductions in ice-contact lake number are explained by lakes becoming disconnected from the glacier. It is nonetheless intriguing that lake number has generally decreased across all regions (~~Figure 6~~Figure 7a and ~~7a~~8a), and lake area has decreased in the Cordillera Apolobamba and Tres Cruces regions (~~Figure 6~~Figure 7b and ~~7b~~8b).

A few studies have also found that ice-contact lakes have reduced in number and/or size over time. For example, Gardelle et al. (2011) found that proglacial lakes in the Karakoram had shrunk because glaciers had surged or experienced reduced mass loss. This cannot explain the trends observed in Bolivia where there are no surge-type glaciers, and all glaciers are shrinking. Emmer et al. (2015) found that some lakes in western Austria had shrunk as a consequence of sedimentation and changes in water supply from the glacier. This explains the loss of some of the lakes within 500 m of the 1986 ice margin, but is less important for the evolution of ice-contact lakes. Apart from the documented GLOF case for the Apolobamba (Hoffmann and Wegenmann, 2013), we did not observe any further evidence for significant lake drainage events. Perhaps the simplest explanation is that, as the ice has receded, there is now a lower contact area between the ice and ice-marginal zone, and hence much less space within which ice-contact lakes can exist (the ice-contact perimeter reduced by 32.6 % between 1986 and 2014). Another possibility is that glaciers have now receded far behind their Holocene erosional maxima, where basins were carved out under thicker, faster-flowing ice (cf. Cook and Swift, 2012). Hence, as glaciers continue to recede, there are fewer deep basins being revealed that could provide accommodation space for ice-contact lakes to develop. Likewise, unlike the debris-covered glaciers of the Himalaya, which develop large terminal moraine complexes that enclose lakes as ice recedes (e.g. Hambrey et al., 2009), Bolivian glaciers are mostly clean-ice glaciers that do not generally develop large terminal moraines. Indeed, most of the potentially dangerous lakes are found in rock basins (Table 2).

Despite the recent trend of reducing ice-contact lake development, it should be emphasised that the ~~trend~~ change in ice-contact lake number and area has been highly variable throughout the study period, indicating that future lake development could be unpredictable without further efforts to investigate proglacial lake appearance and evolution. New and large lakes could develop in the future. One promising avenue would be to measure or model glacier-bed topography in an effort to identify future lake locations ~~of lakes~~ (e.g. Frey et al., 2010; Linsbauer et al., 2016), some of which could ~~be dangerous with respect to~~represent a GLOF risk.

4.3 Glacial lake outburst flood risk

An emerging issue in the Bolivian Andes is the threat of possible GLOF events (Hoffmann and Wegenmann, 2013). From our 2014 dataset of proglacial lakes, we undertook a first-pass assessment of lakes that could represent the greatest outburst flood hazard (Table 2; supplementary .kmz file), and hence should be the subject of future monitoring and GLOF modelling studies. A total of 25 lakes were identified that were large enough, and sufficiently close to potential sources of ice or rock avalanches, to be considered a potential GLOF risk to downstream communities or infrastructure~~.~~. Nine of the potentially dangerous lakes are moraine-dammed. Our estimations of peak discharge indicate potentially very damaging floods from all of the lakes identified in Table 2, although these values represent worst-case scenarios. Indeed, even relatively small lakes can generate damaging floods. Specifically, the ~34,000 m^2 ice-dammed lake that drained at Keara in 2009~~, damaging the village of Keara~~ (Hoffmann and Wegenmann, 2013), produced a peak discharge of approximately 400 m^{3}s^{-1}. This discharge value is calculated using ~~(a value that we calculated~~ the ~~using~~ supplementary ice-dammed lake data in Cook and Quincey~~,~~ (2015)~~,~~ to derive an equation similar to Equation ~~3~~2, and ~~using~~ then using ~~Equation~~Equation ~~4~~ 3 to estimate peak discharge.~~),~~ ~~and~~ T~~t~~he ~~erosional and deposition~~geomorphological evidence for the Keara flood can be seen in GoogleEarth for ~10 km downstream. Hence, we recommend that future studies ~~be directed toward~~focus on more detailed modelling of potential floods from these lakes, more detailed hazard analysis taking into account the potential runout and inundation of the floods, as well as the vulnerability of the affected communities (e.g. Carey et al., ~~2014~~2012), and the monitoring of lake evolution and the development of new lakes. Bathymetric studies of the lakes would also be welcome in order to improve volume estimations (Cook and Quincey, 2015).

5 Conclusions

Glaciers of the Bolivian Andes represent an important ~~crucial~~ regional water source and hence there is significant concern with respect to the sustainability of that water supply in a changing climate. We have performed the first integrated study of glacier change across the Bolivian Andes. Our mapping from 1986 to 2014 revealed that there has been a reduction in glacier area from 529.3 ± 52.9 km^2 to 301.2 ± 30.1 km^2 across the study period, equivalent to a 43.1% shrinkage. Proportionally, ice loss was greatest in the southernmost part of our study area (Tres Cruces) where glaciers lost 47.3% of their area between 1986 and 2014. The Cordillera Real (middle part of our study area), represents the largest area of glaciation in Bolivia, and lost 41.9 % of its ice cover, while the Cordillera Apolobamba in the north lost 43.1% of its ice cover (or 45.6 % if the glaciers of the Peruvian Cordillera Apolobamba are also included). The trend in glacier recession has generally been rapid and continuous throughout the study period.

We undertook the first assessment of proglacial lake development in Bolivia. There has been a general increase in the number and size of proglacial lakes across the study period, in accordance with several studies of proglacial lake development elsewhere. However, the ~~trend~~ change in ice-contact lake number and area has been more complex throughout the study period. All regions show a net decrease in the number of ice-contact lakes through the study period, although this ~~trend~~ change has been highly variable. Whilst ice-contact lake area has experienced a net increase in the Cordillera Real, consistent with previous studies performed in other deglaciating mountain ranges, the area coverage in the Cordillera Apolobamba and Tres Cruces regions has decreased overall. It is unclear why these ~~trends~~ patterns have emerged, but the variability in lake number and area indicates that ongoing monitoring of proglacial lake development is required, especially in light of the potential for these lakes to burst and initiate glacial lake outburst flood (GLOF) events.

GLOFs represent ~~an emerging~~a potentially serious threat in Bolivia, with recent reports of GLOF events from the Apolobamba region (Hoffmann and Wegenmann, 2013). We used our 2014 (most recent) inventory of proglacial lakes to provide a first assessment of the potential for GLOFs in Bolivia. Overall, we identified 25 lakes that pose a potential GLOF risk to downstream communities or infrastructure. Estimated peak discharges from these lakes range from ~500 600 to ~160127,000 m^3s^{-1}, although the upper end of these values could be unlikely given that the nine largest lakes are situated within rock basins, which are arguably more stablethe values derived from modelling of peak discharges represent worst case scenarios. Nine of the lakes are moraine-dammed, and these could be susceptible to complete drainage. Sixteen lakes are rock-dammed, including the nine largest potentially dangerous lakes identified in this study. We recommend further monitoring of potentially dangerous lakes and modelling of GLOF hazards across Bolivia.

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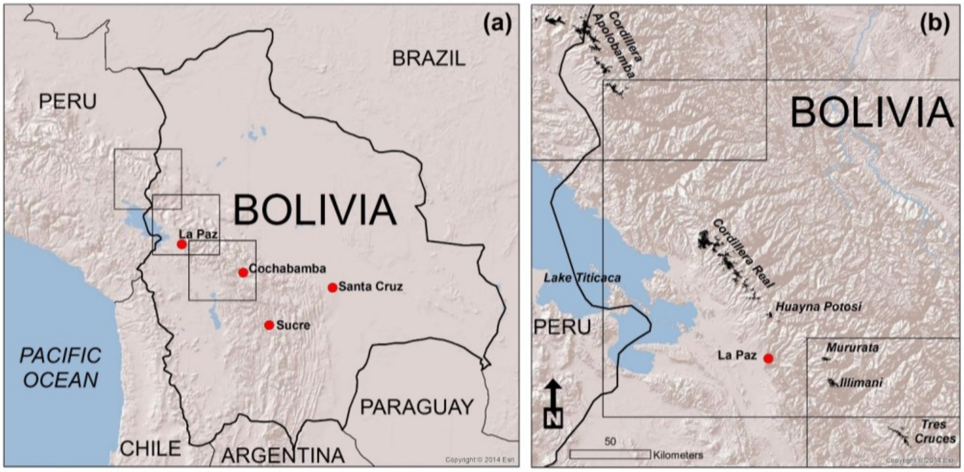

Figure 1: Location of the study area. (a) Topographic map of Bolivia indicating the footprint (grey squares) of Landsat imagery used in this study; (b) Extent of the glaciated regions (shown in black as of 2014) of the Cordillera Oriental within the footprint of the satellite imagery. Base map is the Esri World Shaded Relief map, 2014.

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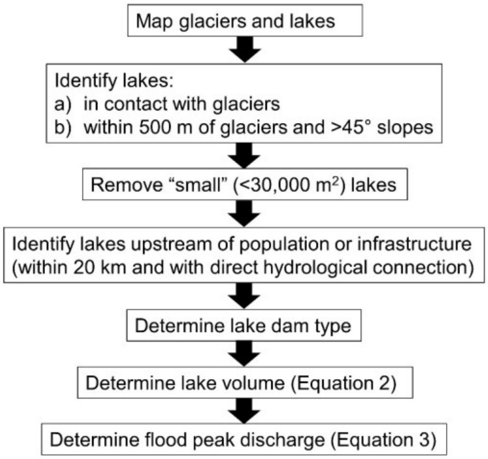

Figure 2: Flow diagram summarising the process of identification of dangerous glacial lakes.

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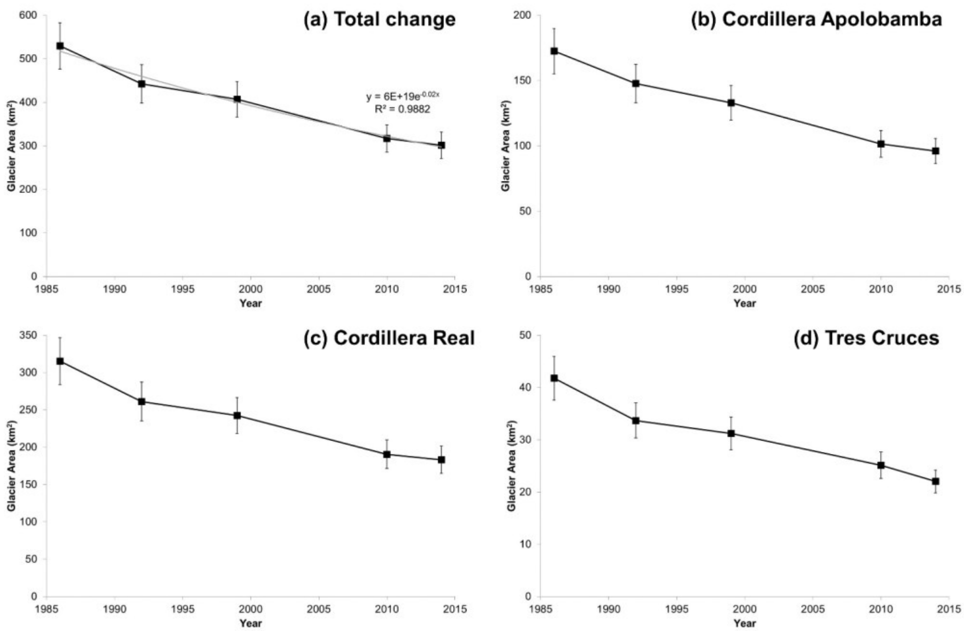
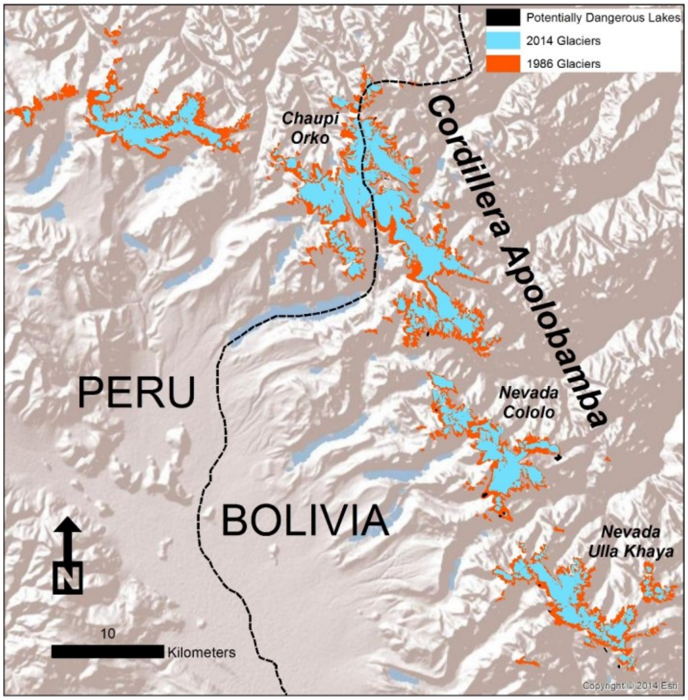
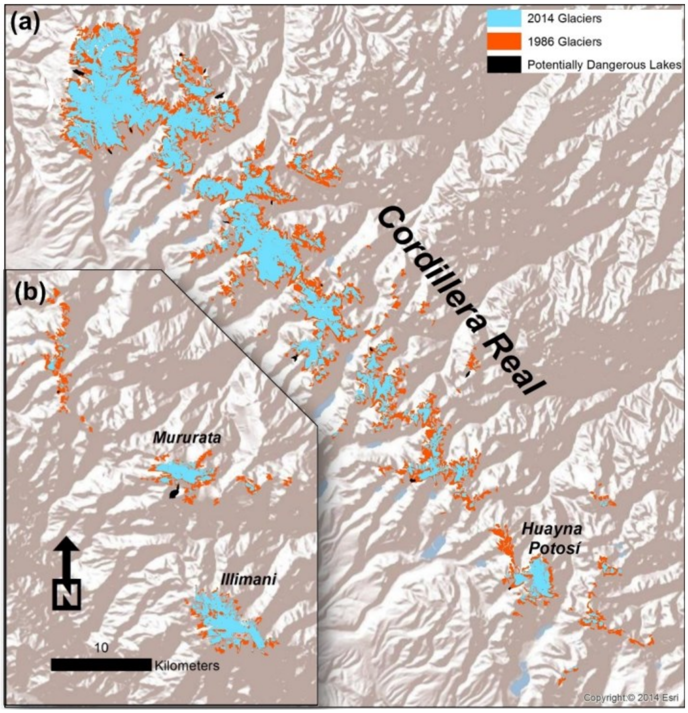


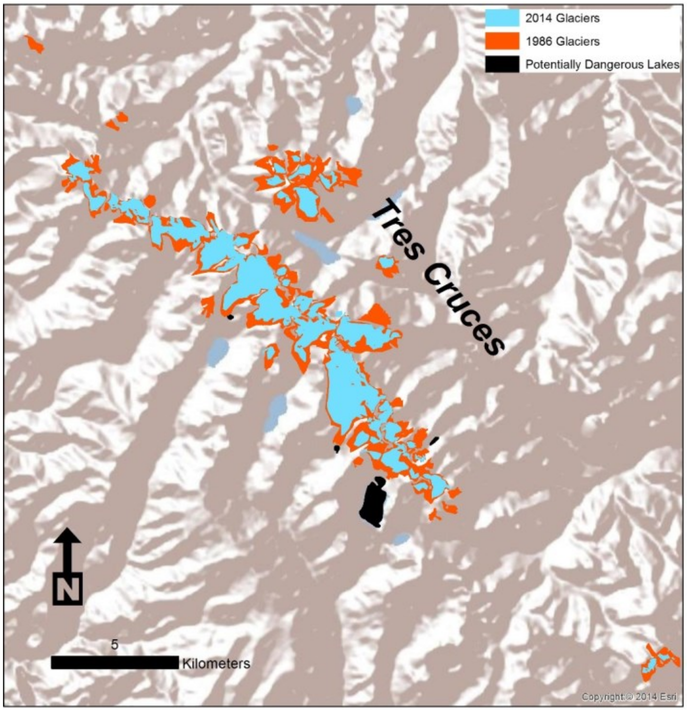
~~Figure 2~~Figure 3: Glacier areal change across the Bolivian Cordillera Oriental. (a) Total glacier area change (grey line is exponential best-fit relationship with associated equation and r^2 value); (b) Cordillera Apolobamba (excluding glaciers on the Peruvian side of the border); (c) Cordillera Real; (d) Tres Cruces region. Error bars are determined using Equation 1, and represent an uncertainty of ± 10 %.



~~Figure 3~~Figure 4: Glacier change 1986 to 2014 for the Cordillera Apolobamba. See Figure 1 for location of region. Base map is the Esri World Shaded Relief map, 2014.



~~Figure 4~~Figure 5: Glacier change 1986 to 2014 for the Cordillera Real. Map (a) shows the main (northern) part of the Cordillera Real, and map (b) shows an inset of the southern Cordillera Real. See Figure 1 for location of region. Base map is the Esri World Shaded Relief map, 2014.



~~Figure 5~~Figure 6: **Glacier change 1986 to 2014 for the Tres Cruces region. See Figure 1 for location of region. Base map is the Esri World Shaded Relief map, 2014.**

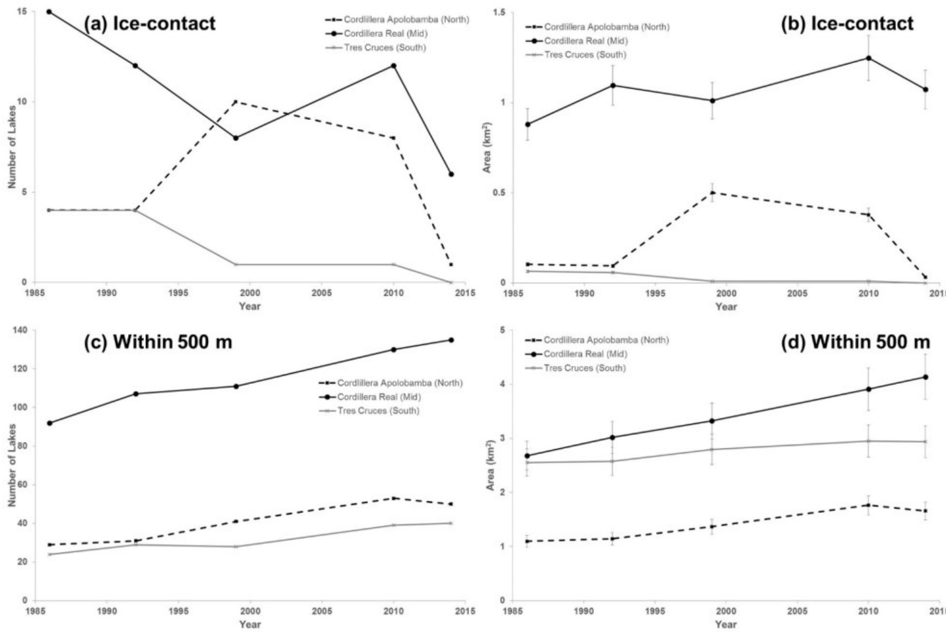
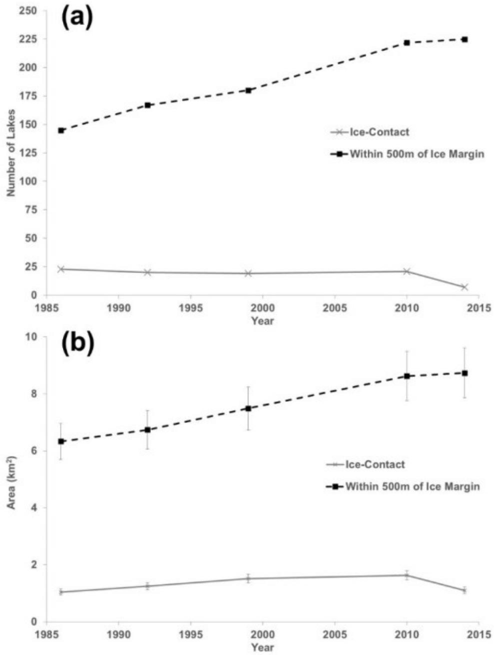


Figure 6Figure 7: Proglacial lake evolution from 1986 to 2014 across the Cordillera Apolobamba (North), Cordillera Real (Middle), and Tres Cruces (South) regions. The number and area of ice-contact lakes are shown in (a) and (b) respectively. The number and area of lakes within 500 m of the 1986 ice margin are shown in (c) and (d) respectively. Error bars are determined using Equation 1, and represent an uncertainty of ± 10 %.



~~Figure 7~~Figure 8: **Total change in proglacial lake number (a) and areal cover (b) according to distance from ice margin (i.e. ice-contact, and within 500m of the 1986 ice margin). Error bars are determined using Equation 1, and represent an uncertainty of ± 10 %.**

Scene ID Number	Path/Row	Date	Sensor	Satellite	Cloud Cover (%)
LC80020702014215LGN00	002/070	03/08/2014	OLI & TIRS	8	8.81
LC80010712014128LGN00	001/071	08/05/2014	OLI & TIRS	8	19.78
LC82330722014153LGN00	233/072	02/06/2014	OLI & TIRS	8	8.62
LT50020702010220CUB00	002/070	08/08/2010	TM	5	0
LT50010712010261CUB00	001/071	18/09/2010	TM	5	7
LT52330722010126CUB00	233/072	06/05/2010	TM	5	0
LT50020701999222COA03	002/070	10/08/1999	TM	5	7
LE70010711999255COA01	001/071	12/09/1999	ETM+	7	18
LT52330721999224COA03	233/072	12/08/1999	TM	5	0.14
LT50020701992203CUB00	002/070	21/07/1992	TM	5	10
LT50010711992212CUB00	001/071	30/07/1992	TM	5	21.91
LT52330721992173CUB00	233/072	21/06/1992	TM	5	7
LT50020701986298XXX03	002/070	25/10/1986	TM	5	10
LT50010711986227XXX04	001/071	15/08/1986	TM	5	30
LT52330721986220CUB03	233/072	08/08/1986	TM	5	10

Table 1: Summary of Landsat scenes used in this study.

Location	Coordinates	~~Lake~~ Dam Type	Area (m^2)	Volume (m^3) ~~Equation~~Equation 2 ~~Cook & Quincey (2015)~~	Q_{max} (m^3 s^{-1}) ~~Equation~~Equation 3 ~~Cook & Quincey (2015)~~	Potential Effect
Apolobamba – Puina (1)	476504, 8384832	Moraine~~-dammed~~	32800	301000~~248000~~	600~~500~~	Isolated farms; Village in Puina district; damage to road
Apolobamba - Taypi Cayuma (2)	491182, 8343142	Rock basin	34900	329000~~273000~~	660~~550~~	Village of Taypi Cayuma; damage to road
Apolobamba - Taypi Cayuma (3)	492072, 8340807	Moraine~~-dammed~~	35500	337000~~280000~~	670~~560~~	Village of Taypi Cayuma; damage to road
Tres Cruces (4)	670245, 8126070	Moraine~~-dammed~~	40500	408000~~344000~~	820~~690~~	Damage to road
Apolobamba - Hilo Hilo (5)	487996, 8349572	~~Rock basin~~Bedrock	45600	483000~~413000~~	970~~830~~	Villages of Hilo Hilo; damage to road
Cordillera Real - Comunidad Pantini (6)	612872, 8182149	Bedrock~~Rock basin~~	48400	526000~~453000~~	1050~~910~~	Isolated farms; bridges and road
Apolobamba - Hilo Hilo (7)	487666, 8349316	Bedrock~~Rock basin~~	48500	528000~~455000~~	1060~~910~~	Villages of Hilo Hilo; damage to road
Tres Cruces (8)	674446, 8120893	Moraine~~Moraine-dammed~~	53600	610000~~532000~~	1220~~1060~~	Mining camp; damage to road
Apolobamba - Cholina Cholina (9)	498284, 8335884	Moraine~~Moraine-dammed~~	54300	621000~~542000~~	1240~~1080~~	Damage to road; flooding of agricultural fields
Tres Cruces (10)	678278, 8121207	Bedrock~~Rock basin~~	62400	758000~~673000~~	1520~~1350~~	Isolated homesteads; damage to road
Cordillera Real – Cocoyo (11)	556846, 8251418	Bedrock~~Rock basin~~	66700	835000~~747000~~	1670~~1490~~	Village of Cocoyo; damage to road
Cordillera Real – Cocoyo (12)	559120, 8249880	Bedrock~~Rock basin~~	68300	863000~~774000~~	1730~~1550~~	Village of Cocoyo; damage to road
Apolobamba - Cholina Cholina (13)	497085, 8337363	Moraine~~Moraine-dammed~~	70900	911000~~820000~~	1820~~1640~~	Damage to road and isolated farms
Cordillera Real – Rinconada (14)	552071, 8244232	Moraine~~Moraine-dammed~~	76000	1008000~~915000~~	2020~~1830~~	Damage to road
Apolobamba – Pelechuco (15)	481205, 8365591	Moraine~~Moraine-dammed~~	80000	1084000~~990000~~	2170~~1980~~	Direct damage in Agua Blanca and Pelechuco; damage to road

Cordillera Real – Rinconada (16)	550069, 8242190	Moraine~~Moraine-dammed~~	102700	1552000~~1460000~~	3100~~2920~~	Damage to road
Cordillera Real – Umapalca (17)	584186, 8220965	Bedrock~~Rock basin~~	130500	2190000~~2120000~~	4380~~4230~~	Village of Umapalca; damage to road
Cordillera Real – Condoriri (18)	578927, 8210860	Bedrock~~Rock basin~~	146800	2594000~~2540000~~	5190~~5080~~	Isolated homesteads; damage to road
Apolobamba - Puyo Puyo (19)	486275, 8351196	Bedrock~~Rock basin~~	154800	2800000~~2760000~~	5600~~5520~~	Damage to road
Cordillera Real - Laguna Wara Warani (20)	567694, 8222503	Bedrock~~Rock basin~~	201800	4100000~~4165000~~	8200~~8330~~	Village of Halluaya; damage to road
Apolobamba - Hilo Hilo (21)	492850, 8354529	Bedrock~~Rock basin~~	254500	5720000~~5969000~~	11440~~11900~~	Isolated farmsteads and dwellings of Chiata community damage to road
Cordillera Real – Cocoyo (22)	560553, 8247486	Bedrock~~Rock basin~~	289400	6881000~~7288000~~	13760~~14600~~	Village of Cocoyo; damage to road
Cordillera Real - Laguna Glaciar (23)	547085, 8249728	Bedrock~~Rock basin~~	328600	8259000~~8877000~~	16520~~17800~~	Damage to roads, agricultural land, several villages; popular tourist destination
Laguna Arkhata, Mururata (24)	624521, 8172040	Bedrock~~Rock basin~~	699200	24457000~~28676000~~	48910~~57400~~	Village of Totorapampa and Tres Rios; damage to road
Tres Cruces - Laguna Huallatani (25)	675910, 8118767	Bedrock~~Rock basin~~	1355700	63355000~~80180000~~	126710~~160000~~	Isolated homesteads; damage to road and agricultural land

Table 2: Compilation of potentially dangerous lakes across the Bolivian Andes. Area, volume and discharge values given to 3 significant figures. Number in brackets in 'Location' column refers to lake identification number in Supplementary .kmz file.

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