

1 **Authors' Response to Reviewers' Comments:**
2 **Brief Communications: Observations of a Glacier Outburst Flood from Lhotse Glacier,**
3 **Everest Area, Nepal” by Rounce et al.**
4

5 We would like to thank both Duncan Quincey and the other anonymous reviewer for their
6 insightful and constructive comments. The following response seeks to address all of their
7 comments and detail the subsequent revisions made to the text.
8

9 **Response to Duncan Quincey's Comments**

10 **Major Comments**

11
12
13 The main deficiency of the submission is that no substantial conclusion relating to the source or
14 trigger mechanism of the flood can be reached based on the data that are presented. Three
15 additional analyses may provide some further illumination:
16

17 A detailed response to each of the three analyses is provided below. These additional
18 analyses added significant detail to the conclusions regarding the source and triggering
19 mechanism of the flood such that a new section was added to the results concerning satellite
20 imagery and the discussion was completely rewritten. Similarly, the abstract and conclusions
21 were rewritten to reflect these changes as well. Specific details for each of these sections is
22 provided in the comments below.
23

24 (1) Can you explore the satellite imagery archives (even just GoogleEarth) to see whether the
25 large supraglacial pond (at D in your Figure 1) has persisted over several years, or whether it was
26 a new feature in the build-up to the flood? If it was new, it lends support to your interpretation
27 that the flood was related to recent meltwater storage, possibly from a blockage in the englacial
28 system, with the pond representing the surface expression at the head of the stored water. If it is
29 not new, then this interpretation is less likely to be valid. Its disappearance would point more
30 towards more 'normal' drainage as the pond intercepts an englacial channel. If you integrate
31 these observations with the next suggestion, you might at least be able to say with more certainty
32 whether the water was supraglacially or englacially sourced.
33

34 Both GoogleEarth and DigitalGlobe imagery reveal that the large supraglacial pond (D in
35 Figure 1; herein referred to as supraglacial pond D) and the smaller supraglacial pond (E in
36 Figure 1; herein referred to as supraglacial pond E) appear to drain and fill over time.
37 WorldView-2 imagery from 14 May 2016 and 29 October 2016 show the areal extent of
38 supraglacial pond was greatly reduced from 4900 m² to 1500 m², respectively. Based on
39 Watson et al. (2016) who assessed the frequency of ponds using high resolution satellite
40 imagery from 2002, 2011, 2013, and 2015, supraglacial pond D appears to have originated in
41 2011 where it was 360 m² and proceeded to grow to 1500 m² in 2013 and to 6500 m² in 2015.
42 This analysis concerning the ponds surrounding the 2016 event has been added to the results
43 section:
44

45 **“3.3 Satellite imagery analysis:** Satellite imagery provides unique opportunities to
46 observe the contribution of supraglacial ponds to these glacier outburst flood events;

1 however, it is important that this imagery is acquired immediately before and after the
2 event as these supraglacial ponds experience large temporal and spatial changes (Figure 3).
3 In order to estimate the potential flood volume associated with the drainage of supraglacial
4 ponds, an area-to-volume relationship was used (Cook and Quincey, 2015). Based on the
5 change in areal extent between 14 May 2016 and 29 October 2016, the drained volume
6 from the furthest supraglacial pond upglacier (Figure 1c, Figure 2D) was $0.01 \times 10^6 \text{ m}^3$.
7 This volume is two orders of magnitude less than the estimated flood volume of 2.65×10^6
8 m^3 , which suggests that the drainage of a single supraglacial pond contributes very little to
9 the overall flood volume. In fact, if all of the 274 supraglacial ponds (0.21 km^2) that were
10 present on Lhotse Glacier on 14 May 2016 drained completely, the potential flood volume
11 would only be $0.52 \times 10^6 \text{ m}^3$. This provides strong evidence that a significant amount of
12 the flood water was stored in the glacier's subsurface.”

13
14 Satellite imagery surrounding the 2015 GLOF event also reveals supraglacial ponds filling
15 and draining. Specifically, a comparison of a WorldView-2 image from 25 May 2015 and a
16 WorldView-1 image from 07 June 2015 shows a 36000 m^2 supraglacial pond (27.910°N ,
17 86.907°E) that completely drained over this time period. Interestingly, a GeoEye-1 image
18 from 08 May 2015 shows that this pond did not exist at that time and the frequency analysis
19 done by Watson et al. (2016) also do not identify any large supraglacial ponds in this vicinity.
20 This analysis concerning the ponds surrounding the 2015 event has also been added to the
21 satellite imagery analysis results section:
22

23 “The glacier outburst flood on 25 May 2015 also originated from Lhotse Glacier and
24 occurred overnight (Sherpa, L., personal communication, 09 June 2015). Satellite imagery
25 from 08 May 2015, 25 May 2015, and 07 June 2015 reveals a large supraglacial pond
26 (0.036 km^2) filling between 08 – 25 May and draining completely between 25 May – 07
27 June (Figure 3c, d, e). The drainage of this supraglacial pond could have contributed up to
28 $0.17 \times 10^6 \text{ m}^3$ to the 2015 glacier outburst flood. Community members reported that the
29 2016 event was larger than the 2015 event. A similar outburst event was also reported to
30 have occurred in early May 2016 in the vicinity of the “crampon put-on point” (5600 m) of
31 Island Peak (6189 m) that damaged sections of the high and low basecamp regions (Sherpa,
32 P.T., personal communication, 18 June 2016).”

33
34 Unfortunately, the high resolution imagery that was available for the 25 May 2015 glacier
35 outburst flood is not available for the 12 June 2016. The best imagery surrounding the 2016

1 event is from 14 May 2016 and 29 October 2016 as previously mentioned. Watson et al.
2 (2016) and Miles et al. (2016) showed that supraglacial ponds frequently drain and fill over
3 the course of a melt season, which makes it difficult to confidently determine which ponds
4 may have drained during the 2016 event based on the available high resolution satellite
5 imagery. Fortunately, the field observations described in the discussion paper can
6 supplement the satellite images. These field observations indicated that supraglacial ponds D
7 & E likely drained on or around the 12 June 2016 glacier outburst flood as described in the
8 initial manuscript (P5, L19 – P6, L15).

9
10 The similarities between the size and the timing of the 2015 and 2016 events based on reports
11 from local residents indicate that these two glacier outburst floods were triggered by similar
12 mechanisms. In fact, the 2015 event showed the complete drainage of a supraglacial pond
13 that was an order of magnitude larger than those observed in 2016 (36000 m² vs. 3400 m²,
14 respectively), yet the 2016 event was larger according to local residents. This supports that
15 hypothesis that the flood was related to the accumulation of meltwater storage despite the
16 fact that supraglacial pond D was not necessarily a “new” pond. The reviewer suggests two
17 explanations: (1) the flood was related to a blockage in the englacial system or (2) the flood
18 is related to the normal drainage as the pond intercepts an englacial channel. We find it is
19 difficult to differentiate these two processes from one another as there is little information on
20 what normal discharge is or what constitutes a new pond and instead suggest that this flood is
21 likely a combination of both processes, i.e., the drainage network during the early melt
22 season may be distributed and inefficient, which causes the meltwater to accumulate until the
23 glacier outburst flood releases the water and opens up new efficient channels as previously
24 described in the paper. We have added the following explanation to the discussion regarding
25 triggering mechanisms discussing this:

26
27 “The rapid drainage of stored lake water through hydraulically efficient pathways is
28 another plausible triggering mechanism that commonly occurs for supraglacial ponds in the
29 Everest region (Benn et al., 2012). Field observations of supraglacial ponds (Figure 2D, E)
30 revealed that there were englacial conduits located at the end of both of these lakes that
31 likely helped facilitate their drainage. This link between the englacial conduits and
32 supraglacial ponds is not surprising as near-surface water storage on glaciers can result
33 from water accumulating in englacial conduits (Fountain and Walder, 1998). Once these
34 ponds come in contact with an englacial conduit or a highly permeable layer, the warm
35 pond water can cause significant internal ablation that helps facilitate the drainage of
36 additional stored water. The drainage of supraglacial ponds that was observed for the 2015
37 and 2016 events supports this theory; however, as previously discussed, the drainage of
38 supraglacial ponds alone likely accounts for a small fraction of the total flood volume.

39

1 This suggests that the most feasible triggering mechanism is likely some form of dam
2 failure resulting from the material blocking the englacial conduits being overburdened or
3 failure resulting from the progressive enlargement of englacial conduits. The timing of
4 these events, which occurred around the start of the monsoon season, further supports this
5 triggering mechanism as this provides ample time for these englacial conduits to fill with
6 meltwater or precipitation prior to dam failure. It should not come as a surprise that this
7 time of year is also when supraglacial pond cover is at its highest (Miles et al., 2016) as this
8 may be indicative of the amount of water stored englacial as well. In fact, it is possible that
9 the large supraglacial pond that filled immediately before the 2015 glacier outburst flood
10 (Figure 3c, d) was the surficial expression of the englacial conduits accumulating too much
11 water, which could explain the pond's short lifespan once the englacial conduits drained.
12 This may also explain how supraglacial pond E (Figure 1c) was not apparent in satellite
13 imagery on 24 May 2016, but appeared to have drained recently based on field
14 observations (Figure 3a, b), i.e., the pond likely filled between 24 May 2016 and the glacier
15 outburst flood. On the other hand, supraglacial pond D (Figure 1c) was present in the
16 imagery and had been growing since 2011 (Watson et al., 2016), which indicates that the
17 rapid drainage of supraglacial ponds through hydraulically efficient pathways may also be
18 contributing to these glacier outburst floods as well, albeit contributing a smaller volume
19 than the water stored englacial.”

20
21 (2) Can you use your rough estimates of discharge to back-calculate a conservative overall flood
22 volume? Clearly there will be large uncertainty associated with the calculation, but it may be
23 sufficient to rule out the simple drainage of one or two supraglacial ponds if, as I suspect is the
24 case, the overall flood discharge exceeds what you might reasonably expect the combined
25 supraglacial pond volume to be. Then you might be able to say with some certainty whether
26 water was being stored beneath the glacier surface.

27
28 Based on photos of the water level before it re-entered the englacial conduits as discussed in
29 the text (P4, L17-19) a best-estimate hydrograph was re-constructed (Figure R1). The peak
30 discharge from these photographs occurred at 12:26 p.m. and was estimated to be $210 \text{ m}^3 \text{ s}^{-1}$.
31 Figure R1 shows the flow steeply increased during the first 30 minutes of the flood event and
32 lasted for approximately 5 hours. The shape and timing of this hydrograph is consistent with
33 the constructed hydrograph for the Dig Tsho glacial lake outburst flood in 1985 (Vuichard
34 and Zimmerman, 1987), although the peak flow from Lhotse Glacier was significantly
35 smaller. Based on this hydrograph, the overall flood discharge was estimated to be $2.65 \times 10^6 \text{ m}^3$
36 ($1.88 - 3.45 \times 10^6 \text{ m}^3$ for the low and high estimates, respectively).
37

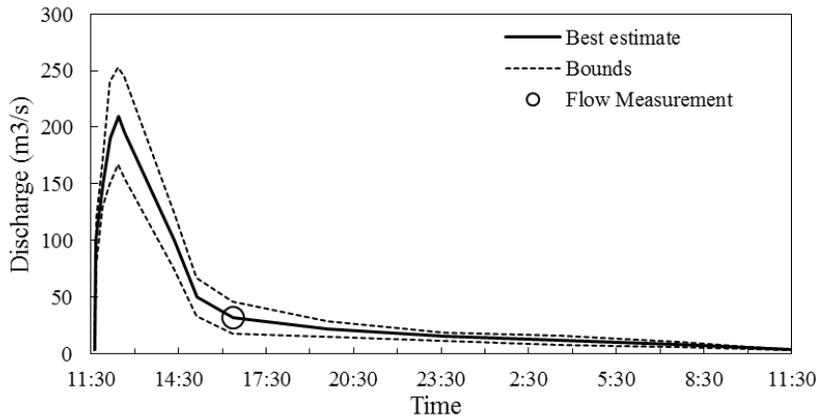


Figure R1. Estimate of the flood hydrograph from Lhotse Glacier 12 June 2016.

Fountain and Walder (1998) present an empirical equation for the magnitude of the peak flow from glacier outburst floods based on “glaciological experience” as follows:

$$Q_{MAX} = \frac{2Ad}{\tau}$$

where A is the glacier-bed area, d is the equivalent water layer over the entire glacier bed (~10 – 100 mm), and τ is the period of time over which the stored water is typically released (~15-60 min). The area of Lhotse Glacier according to GLIMS V5 is 6.825 km², which would estimate the magnitude of peak flow from Lhotse Glacier to range from 38 m³ s⁻¹ to 1500 m³ s⁻¹. While this is an empirical equation, it does lend confidence to our estimate of peak flow. Furthermore, the timing of the peak flow, which occurred ~45 minutes after the flood was initiated, agrees with the timing of the typical release.

In order to estimate the potential flood volume associated with the drainage of supraglacial ponds, an area-to-volume relationship was used based on Cook and Quincey (2015). Based on the change in areal extent between 14 May 2016 and 29 October 2016, the drained volume associated with supraglacial pond D was 0.0107 x 10⁶ m³. This volume is two orders of magnitude less than the estimated flood volume, which supports the hypothesis that accumulated water in Lhotse Glacier’s subsurface was an important source of flood water. In fact, in the 14 May 2016 image 274 supraglacial ponds were identified that covered an area of 0.21 km². If all of these ponds completely drained, which is very conservative, the total drained volume would only be 0.52 x 10⁶ m³. This total drained volume is still significantly smaller than the flood volume estimate of the glacier outburst flood (2.65 x 10⁶ m³), which provides strong evidence that subglacial discharge had a critical role in these glacier outburst flood events.

Figure R1 has been added to Figure 1 and part of the direct observations section of the results has been revised to the following to include the results of the hydrograph:

1 “The main channel continued to flow downstream until it re-entered englacial conduits
2 (Figure 1c), which created an “ice bridge” that allowed investigators to cross the secondary
3 and main channel after the peak flow started subsiding around 12:26 p.m. At 4:22 p.m.,
4 discharge below Chukhung was measured to be $32 \pm 14 \text{ m}^3 \text{ s}^{-1}$. Peak discharge was
5 estimated retroactively to be $210 \pm 43 \text{ m}^3 \text{ s}^{-1}$. This estimate is considered to be
6 conservative since it uses average velocity measurements taken four hours after peak
7 discharge. Interestingly, this estimate agrees well with an empirical approach for
8 predicting peak discharge based on glacier-bed area (Fountain and Walder, 1998), which
9 predicts the peak discharge to be $38 - 1500 \text{ m}^3 \text{ s}^{-1}$. A best-estimate hydrograph (Figure 1b)
10 was reconstructed based on the photos of the water level at the ice bridge showing a peak
11 flow of $210 \pm 43 \text{ m}^3 \text{ s}^{-1}$ at 12:26 p.m. followed by a gradual falling limb such that the
12 discharge returned to normal conditions within 24 hours. The shape and timing of the
13 hydrograph is consistent with the 1985 glacial lake outburst flood from Dig Tsho (Vuichard
14 and Zimmerman, 1987), although the peak flow from Lhotse Glacier was significantly
15 smaller. Based on this hydrograph, the overall flood volume was estimated to be 2.65×10^6
16 m^3 ($1.88 - 3.45 \times 10^6 \text{ m}^3$ for the estimated low and high bounds, respectively). Minimal
17 damage was caused to the community of Chukhung, which community members credited
18 to the recently constructed gabions (Figure 2C). The main damage was the loss of a
19 pedestrian bridge, an outbuilding, and small amounts of floodwater in the courtyard of one
20 lodge. Supplementary material provides footage of the observed events.”

21
22 (3) Are there any reports from locals about the shape of the hydrograph? Or are your own
23 observations sufficient to say anything about that? On page 7, line, 11, the text states that the
24 flood had sudden onset. If so, this implies there was a sudden failure of the dam rather than
25 something more gradual like surface water tapping into an inefficient hydrological system. If
26 even a crude hydrograph shape can be reconstructed it may help you at least narrow down the
27 flood trigger.

28
29 The shape of the hydrograph was estimated in response to the second comment based on
30 photos near the ice bridge and direct observations by the authors (P4, L17-19). The shape
31 clearly depicts that the flood was a sudden event, which, as the reviewer suggests, indicates
32 there was a sudden failure within the glacier’s subsurface as opposed to more gradual
33 processes of the surface water slowly finding more efficient channels. A discussion
34 concerning the timing and size of the flood and the information that it provides concerning
35 the triggering mechanisms has been added to the text in place of the previous discussion:
36

1 **“4.2 Triggering mechanisms:** Potential triggering mechanisms for these glacier outburst
2 floods include dam failure, the rapid drainage of stored lake water through hydraulically
3 efficient pathways, and/or catastrophic glacier buoyancy. The sudden discharge observed
4 during the 2016 event (Figure 1b) suggests that the trigger was most likely dam failure or
5 the rapid drainage of stored lake water, since catastrophic glacier buoyancy typically has a
6 hydrograph with a more gradual rising limb (Fountain and Walder, 1998).

7
8 Dam failure would require an englacial conduit to be temporarily blocked, which could
9 occur if meltwater refroze in the conduits over the winter (Gulley et al., 2009) or if passage
10 closure processes caused an englacial conduit to close (Benn et al., 2012). The former
11 blockage scenario seems more likely since these glacier outburst floods have occurred in
12 back-to-back years and the refreezing of meltwater is an annual process. During the early
13 melt season the subsurface drainage system is distributed and inefficient, which provides
14 opportunities for water to accumulate englacial (Fountain and Walder, 1998). Dam failure
15 may then occur if the hydrostatic pressures in the englacial conduits exceed the cryostatic
16 pressure that was previously constraining the stored water thereby causing the dam to
17 rupture (Richardson and Reynolds, 2000). Alternatively, as water accumulates in the
18 englacial conduits, the changes in water pressure can cause these conduits to grow in an
19 unstable manner thereby causing drainage to occur (Fountain and Walder, 1998). This
20 progressive enlargement is similar to piping failures and the failures of ice dammed lakes
21 (Richardson and Reynolds, 2000).”

22
23
24 Minor Comments

25
26 P1 Abstract: this needs some work. The abstract should summarize what was done and what was
27 found out.

28 The abstract has been completely redone:

29
30
31 “Glacier outburst floods with origins from Lhotse Glacier, located in the Everest region of
32 Nepal, occurred on 25 May 2015 and 12 June 2016. The most recent event was witnessed
33 by investigators, which provided unique insights into the magnitude, source, and triggering

1 mechanism of the flood. The field assessment and satellite imagery analysis following the
2 event revealed that most of the flood water was stored englacial and the flood was likely
3 triggered by dam failure. The flood's peak discharge was estimated to be $210 \text{ m}^3 \text{ s}^{-1}$."

4
5 P1 26-27: isn't the lack of attention simply because these floods are so unpredictable and thus
6 rarely observed?

7
8 Yes, this is likely true as well. The sentence has been changed to the following:

9
10 "In contrast, glacier outburst floods in the Himalaya, herein referring to outburst floods that
11 are not generated by a proglacial lake, have received relatively little attention likely due to
12 their seemingly unpredictable nature, which has resulted in these events rarely being
13 observed (Fountain and Walder, 1998)."

14
15 P2 3-6: these are a mixture of cause (triggers) and effect of drainage. Channels becoming
16 progressively enlarged, for example, are not a cause of floods. They are possibly a control on the
17 discharge, and are certainly more of an effect of the flood than a cause.

18
19 The authors agree that the channels becoming progressively enlarged that was observed
20 during the 2016 glacier outburst flood was an effect of the flood as opposed to a cause.
21 However, Richardson and Reynolds (2000) state that "there are three recorded mechanisms
22 by which glacier outburst floods occur: the rupture of an internal water pocket, the
23 progressive enlargement of internal drainage channels and catastrophic glacier buoyancy, or
24 'jacking', with sub-glacial discharge". Similarly, Fountain and Walder (1998) discuss the
25 enlargement of internal drainage channels as a means of rapidly draining stored glacier water.
26 As this section of the paper is meant to introduce the existing knowledge regarding these
27 glacier outburst floods, we have elected to keep the progressive enlargement of an englacial
28 conduit as a triggering mechanism; however, we have slightly altered the sentence to clarify
29 the enlargement of englacial conduits versus the drainage channel enlargement that we
30 observed during the event. The sentence now reads:

31
32 "Glacier outburst floods can occur sub-, en-, or supra-glacially when the hydrostatic
33 pressure of the stored water exceeds the structural capacity of the damming body, when
34 stored water is connected to an area of lower hydraulic potential, when englacial channels
35 are progressively enlarged in an unstable manner, and/or when catastrophic glacier
36 buoyancy occurs (Fountain and Walder, 1998; Richardson and Reynolds, 2000; Gulley and
37 Benn, 2007)."

38
39 We would also like to note that the observed channel enlargement from the 2016 event (P4,
40 L8-10) is clearly stated as a cause of the flood and not as a triggering mechanism.

41
42 P2 15: insert reference regarding mass loss

43
44 Reference to Bolch et al. (2011) has been inserted as an example. Benn et al. (2012) also
45 summarizes mass loss studies in the Everest region.

1
2 P2 20: are subsurface and englacial not the same thing?
3
4 Yes, this was a typo. The sentence was meant to refer to surficial, englacial, and subglacial
5 drainage. The text has been revised to read “the glacier’s surface and/or subsurface”.
6
7 P2 27: worth mentioning here that Lhotse is one of the few glaciers in the region without a steep
8 bounding terminal moraine (i.e. that might trap or at least modulate flood waters in other
9 locations).
10
11 The authors agree this would be good information to include. The sentence has been revised
12 to read as follows: “Lhotse Glacier is one of the few glaciers in the region that lacks a steep
13 bounding terminal moraine; instead, the terminus of the glacier is relatively steep ($> 6^\circ$)...”
14
15 P3 9 (and elsewhere) is it Chukung, or Chukhung? I’ve seen both, but I think the latter is more
16 common?
17
18 The spelling has been changed in all cases to “Chukhung”.
19
20 P3 11: replace ‘accounts for’ with ‘comprises’?
21
22 This change has been made.
23
24 P3 14: missing ‘the’
25
26 ‘the’ has been inserted.
27
28 P3 22: missing ‘the’
29
30 ‘the’ has been inserted.
31
32 P4 20: ‘retrospectively’?
33
34 This has been changed to ‘retroactively’.
35
36 P5 20: can you give an idea of the pond size? Just its rough diameter measured from the satellite
37 data would be helpful.
38
39 The area is 4900 m² based on satellite imagery from 14 May 2016. Its area has been added in
40 the satellite imagery analysis results.
41
42 P6 6-7: change to ‘was not possible due to...’?
43
44 This change has been made.
45

1 P7 3-4: I'm not convinced your observations reveal anything about the triggers in the current
2 version of the manuscript so you might choose to rephrase this sentence.

3
4 Based on the response to previous comments and changes made to the manuscript, this study
5 is able to discuss the triggers in more detail, which has been added to the paper as detailed in
6 the response to the major comments.

7
8 Figure 3: can you indicate the scale that is shown here?

9
10 Yes, the image has been revised to include an approximate scale.

11
12 P7 11-13: what does this sentence actually mean? That hydrofracture was the cause? Or that a
13 dam was breached? And what is the evidence? If you are suggesting that englacial hydrology
14 was blocked then you need to state this more clearly.

15
16 The sentence was meant to discuss that dam failure likely occurred in the englacial conduits
17 when the hydrostatic pressure exceeded the cryostatic pressure that was holding the water
18 back, i.e., that a dam was breached. The discussion of the triggering mechanisms has been
19 completely rewritten to reflect the response to the major comments above and we believe the
20 various scenarios are very clearly discussed.

21
22 P7 11: was the outburst definitely sudden? If so, you have evidence of dam failure and you may
23 be able to infer something more about the trigger than you already have.

24
25 Yes, this outburst sudden (Figure R1), which supports that there was some form of dam
26 failure as a triggering mechanism as the reviewer suggest. This is reflected in the new
27 discussion as previously discussed.

28
29 P7 18: do conduits 'rupture' in this way? I'm not familiar with this if so...

30
31 Based on the additional analysis into triggering mechanisms, we agree with the reviewer that
32 this situation likely did not occur and therefore have removed it from the text.

33
34 P7 19-20: wouldn't a simpler explanation be that the englacial system was overwhelmed so the
35 water found another (i.e. surface) route?

36
37 Yes, we agree with the reviewer's suggested explanation that the surface flow is caused when
38 the englacial system was overwhelmed thereby giving the water an alternative pathway;
39 however, this has been removed in the revised discussion.

40
41 P7 10-22: It might be helpful to separate out the discussion of the triggers vs subsequent
42 processes as they are very different.

43
44 The discussion has been separated into two subsections: source of the flood water and
45 triggering mechanisms.

46

1 P8 1-2: the increase in discharge is more likely to be related to the ability of the developing
2 channels to convey water, don't you think?

3
4 Yes, we agree with the reviewer that the enlargement of the channels and englacial conduits
5 would also help convey water more efficiently. The sentence has been changed to the
6 following:

7
8 "Once the flood was initiated, the melting of ice from both the channel banks and in the
9 englacial conduits caused these outlet pathways to grow, which likely contributed more
10 water to the total flood volume in addition to opening more efficient pathways for the
11 stored water to drain."

12
13 P8 3: what do you mean by meltwater storage in this context? Englacial specifically? Can you
14 clarify this?

15
16 This sentence was referring to flood water that was stored in the glacier's subsurface. Based
17 on the additional analyses conducted in response to previous comments, there is clear
18 evidence that this is important and the language used to describe the stored water has been
19 clarified.

20
21 P8 13-16: this process is not normally sudden. I think you have to invoke a slightly different
22 chain of processes.

23
24 The reviewer is correct that the evolution of the subglacial hydrological system in the Arctic
25 does not occur suddenly, but changes over the course of the melt season. The citation is
26 meant to show the similarity between an evolving subglacial hydrological system that
27 transforms from an inefficient to an efficient system over time. This citation has actually
28 been removed from the text and a better citation (Fountain and Walder, 1998) has been added,
29 which deals with alpine glaciers. Furthermore, the text has been clarified to simply state that
30 "During the early melt season the subsurface drainage system is distributed and inefficient,
31 which provides opportunities for water to accumulate englacial."

32
33 P8 22: I don't think this is likely to be true. Partly it depends on what you class as a scientist
34 (locals can also be 'scientists') and many 'scientists' have been working in the Himalaya for
35 many years. I suggest removing this statement as it is not necessary and it is unsubstantiated.

36
37 This sentence has been removed.

38
39 P8 23: as the manuscript is presented I don't think you shed any light on the triggers, so you
40 might want to modify this.

41
42 Based on the additional analyses included in response to both reviewers comments, we
43 believe that the manuscript now sheds greater light on the source and potential triggers. The
44 sentence now reads "... which provides unique insight into the magnitude, source, and
45 triggering mechanisms of these events."

46

1 P8 26-27: do you mean the difficulty of making interpretations on limited data highlights the
2 lack of knowledge? Can you clarify?

3
4 This sentence has been removed in the revised conclusions.

5
6 **Response to Anonymous Referee #1's Comments**

7
8 I am aware of few observations of englacial outburst flood, which is the primary reason why I
9 think this Brief Communication should be published. Please highlight this important facet of the
10 flood in both the title and abstract. One possible suggestion for a title would be: Observations of
11 the role of englacial conduits in a Glacier Outburst Flood from the Lhotse Glacier, Everest Area,
12 Nepal.

13
14 We appreciate the reviewers support and agree that the observations that we saw regarding
15 the englacial nature of this flood are important; however, both satellite and field observations
16 show that water stored in supraglacial ponds was likely a source of flood water as well.
17 Similarly, the reconstruction of the flood path shows both supraglacial and englacial paths.
18 Therefore, we believe that altering the title to focus solely on the role of englacial conduits is
19 too focused and prefer not to change the title. The import role that these englacial had in the
20 flood is detailed in both the abstract and the rest of the paper.

21
22 Abstracts should present the key findings of the research rather than tell the reader to read the
23 article. I suggest starting over from scratch.

24
25 The abstract has been re-written as follows:

26
27 “Glacier outburst floods with origins from Lhotse Glacier, located in the Everest region of
28 Nepal, occurred on 25 May 2015 and 12 June 2016. The most recent event was witnessed
29 by investigators, which provided unique insights into the magnitude, source, and triggering
30 mechanism of the flood. The field assessment and satellite imagery analysis following the
31 event revealed that most of the flood water was stored englacial and the flood was likely
32 triggered by dam failure. The flood’s peak discharge was estimated to be $210 \text{ m}^3 \text{ s}^{-1}$.”

33
34 Page 1, Line 7: Does the paper need to mention that the results of this paper are not the opinion
35 of the WV DEP?

36
37 The affiliation of Elizabeth Byers has been changed to Appalachian Ecology, which does not
38 require a similar statement.

39
40 Page 1, Line 18: the location of “unleashing” is not downstream.

41
42 The word ‘downstream’ has been removed.

43

1 Page 1, Line 19: change “mass movement” to landslide, ice falls and/or avalanches.

2

3 This change has been made.

4

5 Also, this will sound picky, but the cause of the flood is the resulting wave that overtops the dam,
6 leading to failure. The other triggers should probably also be described in the context of how
7 they contribute to dam failure.

8

9 The sentence has been revised to include the details of each triggering process as follows:

10

11 “Triggering mechanisms of these outburst floods include landslides, ice falls, and/or
12 avalanches entering a proglacial lake resulting in a wave that overtops the dam leading to
13 dam failure, dam failure due to settlement, piping, and/or the degradation of an ice-cored
14 moraine, and heavy rainfall that can alter the hydrostatic pressures placed on the moraine,
15 and many others (Richardson and Reynolds, 2000; Carrivick and Tweed, 2016).”

16

17 Page 2, Line 25: Not clear why supraglacial ponds are indicative of active ice dynamics.

18

19 The draining and filling of supraglacial ponds indicate that the subsurface of the glacier is
20 changing. The sentence has been changed to “The upper 4 km, located beneath the headwall
21 of Lhotse, is still quite active (Quincey et al., 2007), which can be seen by its highly
22 crevassed features and its transient supraglacial ponds indicating frequent changes in the
23 glacier’s subsurface (Watson et al., 2016).”

24

25 Page 3, Line 10: The rationale for assuming that the average velocity is 85% of the float velocity
26 is?

27

28 For natural channels the mean velocity is commonly estimated as 85% of the surface velocity
29 based on the assumption of a logarithmic profile (Rantz et al., 1982). This source has been
30 added.

31

32 Page 7, Line 13: Hydrostatic pressure exceeding cryostatic pressure seems an unlikely trigger for
33 an englacial/supraglacial lake drainage mechanism. More plausible is that two lake basins at
34 different elevations became connected by a permeable feature within the ice (such as a relict
35 supraglacial channel; Benn et al., 2012 or Gulley and Benn, 2007).

36

37 We agree that the connection of two lake basins at different elevations via a permeable
38 feature within the ice is a plausible and common scenario for the drainage of supraglacial
39 ponds; however, the analysis that was done in response to the other reviewers comment
40 indicates that the drainage volume from supraglacial ponds accounts for a small fraction of
41 the total flood volume. Furthermore, the sudden nature of the flood (Figure R1 above)
42 suggests that there was some form of dam failure. The satellite imagery suggests that both
43 dam failure and the connection of lake basins at different elevations may have occurred. The
44 discussion regarding triggering mechanisms has been edited to reflect this. Please see the
45 response to the other reviewer’s major comments for more detail.

46

1 Page 7, Line 15: It is not clear what is meant by “open up outlets of lower hydraulic potential”
2
3 This was meant to refer to the connection of two lake basins as the reviewer discusses in the
4 previous comment. The language in the discussion has been changed to “the rapid drainage
5 of stored lake water through hydraulically efficient pathways.”
6
7 Page 8, Lines 16-19: I don’t think that two events in two years can be called repetitive.
8
9 The use of repetitive has been removed from the text.
10
11 Page 8, Line 21: I think the authors need to clarify that this is possibly the first time that an
12 englacial outburst flood has been witnessed. I’m not aware of any similar observations on
13 debris-covered glaciers.
14
15 This sentence has been deleted entirely in response to a comment from the other reviewer.
16
17 Page 8, Line 26: The authors have not presented any direct evidence that the subglacial drainage
18 system played a role in this flood.
19
20 The satellite imagery analysis that was included in response to the other reviewer’s
21 comments clearly shows that the subglacial drainage system plays a role in this flood.
22
23 Figure 1: Is there no way to create a DEM of the glacier surface? It would go a long way
24 towards showing supraglacial flow paths.
25
26 Unfortunately, a high resolution DEM (< 5 m) of the glacier surface is not currently available
27 for Lhotse Glacier around the time of the flood event. However, the authors did walk the
28 flood path with a handheld GPS system, which helped determine the reconstruction efforts
29 along with the bio-indicators. The recommendation to have high resolution imagery over this
30 region (which could include repeat DEMs) has been included in a sentence concerning future
31 work in the conclusions as follows:
32
33 “Future work should seek to improve our understanding of the triggering mechanisms and
34 size of these events through detailed field surveys assessing both the glacier’s surface and
35 subsurface combined with methodically tasked high resolution satellite imagery.”
36
37 **References (new to the discussion paper)**
38 Bolch, T., Pieczonka, T., and Benn, D.I.: Multi-decadal mass loss of glaciers in the Everest area
39 (Nepal Himalaya) derived from stereo imagery, *The Cryosphere*, 5, 349-358, doi:10.5194/tc-
40 5-349-2011, 2011.
41 Cook, S.J. and Quincey, D.J.: Estimating the volume of Alpine glacial lakes, *Earth Surface*
42 *Dynamics*, 3:559-575, doi:10.5194/esurf-3-559-2015, 2015.
43 Miles, E.S., Willis, I.C., Arnold, N.S., Steiner, J., and Pellicciotti, F.: Spatial, seasonal and
44 interannual variability of supraglacial ponds in the Langtang Valley of Nepal, 1999-2013, *J.*
45 *Glaciol.*, 1-18, doi:10.1017/jog.2016.120, 2016.

- 1 Rantz, S.E.: Measurement and computation of streamflow: volume 1, measurement of stage and
- 2 discharge, No. 2175, USGPO, 1982.
- 3

1 **Brief Communications: Observations of a Glacier Outburst Flood**
2 **from Lhotse Glacier, Everest Area, Nepal**

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10 Keywords: Glacier outburst flood, Supraglacial lake, Englacial conduit, Everest, Nepal

11 **Abstract**

12 Glacier outburst floods with origins from Lhotse Glacier, located in the Everest region of Nepal,
13 ~~have occurred on 25 May 2015 and 12 June 2016. The most recent event was witnessed by~~
14 ~~investigators, which provided unique insights into the magnitude, source, and triggering~~
15 ~~mechanism of the flood. The field assessment and satellite imagery analysis following the event~~
16 ~~revealed that most of the flood water was stored englacial and the flood was likely triggered by~~
17 ~~dam failure. The flood's peak discharge was estimated to be $210 \text{ m}^3 \text{ s}^{-1}$.~~
18 ~~during the transitional early monsoon season in each of the last two years. The most recent~~
19 ~~event was witnessed by the investigators on 12 June 2016. Observations regarding the~~
20 ~~magnitude of the 2016 outburst flood and a reconstruction of the flood path immediately~~
21 ~~following the event are presented. These observations highlight the lack of existing knowledge~~
22 ~~regarding these glacier hazards and provide valuable insight to help spur future investigations.~~

23 **1 Introduction**

24 Glacier outburst floods occur when stored glacier water is suddenly unleashed ~~downstream~~.
25 Triggering mechanisms of these outburst floods include ~~landslides, ice falls, and/or~~
26 ~~avalanches~~~~mass movement~~ entering a proglacial lake ~~resulting in a wave that overtops the dam~~
27 ~~leading to dam failure~~, dam failure ~~due to settlement, piping, and/or the degradation of an ice-~~
28 ~~cored moraine, volcanic or geothermal activity, and~~ heavy rainfall ~~that can alter the hydrostatic~~

1 | ~~pressures placed on the dam, and many among~~ others (Richardson and Reynolds, 2000;
2 | Carrivick and Tweed, 2016). In the Himalaya, a specific subset of outburst floods called glacial
3 | lake outburst floods (GLOFs) has received the most attention with respect to hazards, likely
4 | because of their potentially large societal impact (e.g., Vuichard and Zimmermann, 1987). In
5 | contrast, glacier outburst floods in the Himalaya, herein referring to outburst floods that are not
6 | generated by a proglacial lake, have received relatively little attention likely due to their
7 | seemingly unpredictable nature, which has resulted in these events rarely being observed
8 | (Fountain and Walder, 1998). ~~This lack of attention is likely due to their apparent smaller~~
9 | ~~magnitudes and our current inability to model triggering mechanisms and their potential flood~~
10 | ~~extent.~~ While they are a known hazard and discussed in the literature (e.g., Richardson and
11 | Reynolds, 2000), few studies in Asia have investigated these hazards in detail (Richardson and
12 | Quincey, 2009).

13 | Glacier outburst floods can occur sub-~~, en-, en-~~, or supra-glacially when the hydrostatic pressure
14 | of the stored water exceeds the structural capacity of the damming body, when stored water is
15 | connected to an area of lower hydraulic potential, when drainage channels are progressively
16 | enlarged, and/or when catastrophic glacier buoyancy occurs (Fountain and Walder, 1998;
17 | Richardson and Reynolds, 2000; Gulley and Benn, 2007). For debris-covered glaciers, the
18 | drainage of supraglacial ponds commonly occurs through englacial conduits, which facilitate
19 | connections to areas of lower hydraulic potential (Gulley and Benn, 2007). These englacial
20 | conduits develop on debris-covered glaciers in the Himalaya through cut-and-closure
21 | mechanisms associated with meltwater streams, the exploitation of high permeability areas that
22 | provide alternative pathways to the impermeable glacier ice, and through hydrofracturing
23 | processes (Gulley and Benn, 2007; Benn et al., 2009; Gulley et al., 2009a; Gulley et al., 2009b).

24 | During the last half century, debris-covered glaciers in the Everest region have experienced
25 | significant mass loss (e.g., Bolch et al., 2011), which has led to the development of glacial lakes
26 | and supraglacial ponds (Benn et al., 2012). Proglacial lakes may develop if the surface gradient
27 | of the glacier is gentle ($< 2^\circ$), while steeper gradients ($> 2^\circ$) will help drain these ponds (Quincey
28 | et al., 2007). This causes supraglacial ponds to have large temporal and spatial variations as they
29 | frequently drain and fill (Horodyskyj, 2015; Miles et al., 2016; Watson et al., 2016). ~~This~~
30 | drainage can occur on the glacier's surface and/or; subsurface, ~~and/or englacially~~ (Benn et al.,
31 | 2012).

1 Lhotse Glacier (27°54'12" N, 86°52'40" E) is an avalanche-fed debris-covered glacier that
2 extends 8.5 km from the peak of Lhotse ~~at~~ (8501 m) to the glacier's terminus ~~at~~ 4800 m (Figure
3 1a). The lowest 3.5 km of the glacier is relatively stagnant ~~and contains~~with many supraglacial
4 ponds. The upper 4 km, located beneath the headwall of Lhotse, is still quite active (Quincey et
5 al., 2007), ~~which can be~~as seen by its highly crevassed features and ~~its~~ transient supraglacial
6 ponds indicating frequent changes in the glacier's subsurface (Quincey et al., 2007; Watson et al.,
7 2016). Lhotse Glacier is one of the few glaciers in the region that lacks a steep bounding
8 terminal moraine; instead, ~~T~~he terminus of the glacier is relatively steep ($> 6^\circ$), which facilitates
9 the drainage of supraglacial ponds and prevents the development of a large proglacial lake
10 (Quincey et al., 2007). As these supraglacial ponds drain and fill, they can cover up to 1.3-2.5%
11 of the debris-covered glacier's surface at any time (Watson et al., 2016). Speleological surveys
12 conducted at Lhotse Glacier found that cut-and-closure mechanisms and the exploitation of high
13 permeability areas were the main contributors to the development of englacial conduits and the
14 drainage of supraglacial ponds (Gulley and Benn, 2007).

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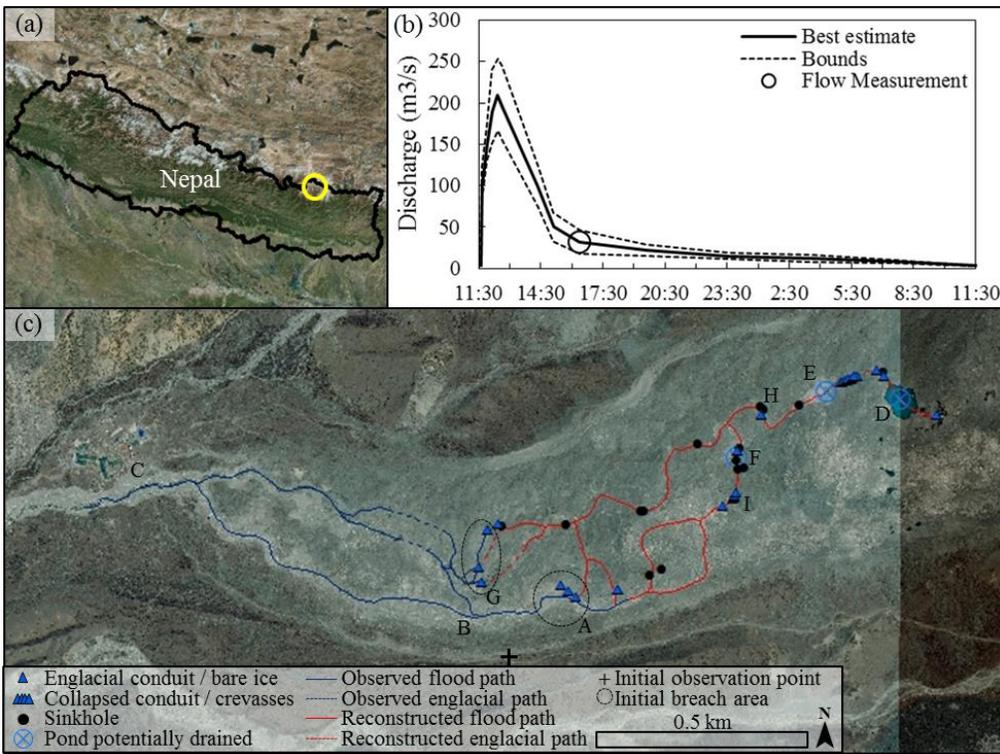


Figure 1. (a) location of Lhotse Glacier in Nepal, (b) hydrograph of the glacier outburst flood from Lhotse Glacier on 12 June 2016, and (c) map of observations and the reconstructed flood path down to the village of Chukhung with letters corresponding to key features in Figure 2.

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2 Methods

Glacier outburst floods with origins from Lhotse Glacier occurred on 12 June 2016 and 25 May 2015. The 2015 event was reported by local community members, while the 2016 event was observed by the investigators from the southern lateral moraine of Lhotse Glacier (Figure 1c). This provided a rare opportunity to photograph, record, and observe the outburst flood as it unfolded. The glacier outburst flood that occurred on 12 June 2016 was observed from the southern lateral moraine of Lhotse Glacier by the investigators (Figure 1), which provided opportunities to photograph, record, and observe the event as it unfolded. Flow measurements at 4:22:30 p.m., approximately 3–4 hours after the peak discharge, were estimated from cross sectional areas and float velocities using bundles of sticks in a relatively straight section of the channel below the village of ChukungChukhung (27°54'03" N, 86°51'46" E). Average velocity

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1 | for the flow measurements was ~~estimated~~~~assumed~~ to be 85% of the float velocity ([Rantz et al.,](#)
2 | [1982](#)). Uncertainty associated with the flow measurements ~~comprised~~~~accounts for~~ errors in river
3 | width (± 1 m), depths (± 0.3 m), float distance (± 1 m), and time (± 1 s). Peak flow was
4 | conservatively estimated using the same average velocity with ~~the~~ cross sectional areas derived
5 | from high water marks.

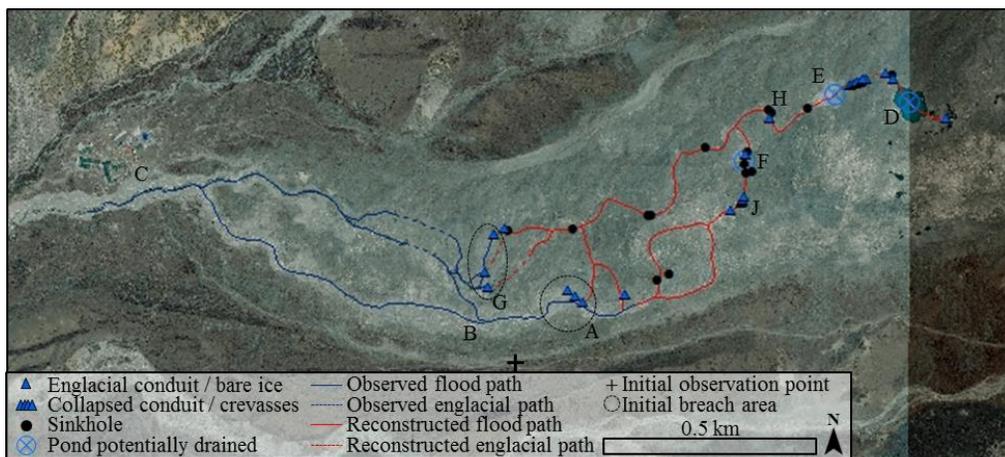
6 | During 14-21 June 2016, investigators conducted a field assessment on Lhotse Glacier to
7 | reconstruct the flood path. Key features, which included bare ice faces, entrances and exits of
8 | englacial conduits, sinkholes, collapsed tunnels, and ponds, were examined, photographed, and
9 | measured using a handheld GPS (Garmin Montana) and a laser range finder (Nikon Forestry Pro).
10 | Bio-indicators were also documented to assist reconstruction efforts. These indicators included
11 | visual observations of recently uprooted and displaced alpine shrubs providing insight into the
12 | surficial flood path. The presence of high water marks or wet, fine sediment that indicated
13 | potential sinkholes or drained ponds were also recorded.

14 | ~~High resolution (0.5 m) satellite imagery (DigitalGlobe, Inc.) was used to assess the draining and~~
15 | ~~filling of supraglacial ponds around the 2015 and 2016 events based on manual delineations.~~
16 | ~~Specifically, imagery from 14 May 2016 (WorldView-2) and 29 October 2016 (WorldView-2)~~
17 | ~~were used to assess the 2016 event, and imagery from 08 May 2015 (GeoEye-1), 25 May 2015~~
18 | ~~(WorldView-2), and 07 June 2015 (WorldView-1) were used to assess the 2015 event. The~~
19 | ~~image from 14 May 2016 was also used as a background image for the reconstruction of the~~
20 | ~~2016 glacier outburst flood. A WorldView 2 pan-sharpened satellite image (0.5 m) from 14 May~~
21 | ~~2016 was used as a background image to reconstruct flood path and assess the presence of ponds~~
22 | ~~prior to the flood when possible. High resolution satellite images were not available~~
23 | ~~to assess the drainage of ponds after the flood event. Given the large temporal changes~~
24 | ~~associated with the draining and filling of these melt ponds, pond drainage volumes were not~~
25 | ~~estimated.~~

26 | **3 Results**

27 | **3.1 Direct observations:** At 11:40 a.m. on 12 June 2016, three landslide-like features began
28 | flowing almost simultaneously down a south-facing slope of Lhotse Glacier, followed by large
29 | amounts of discharging water from three apparent englacial conduits and one supraglacial stream
30 | (Figure 1c, 2A). At the same time, ~~approximately 200 m northwest of these landslide-like~~

1 features, large amounts of sediment-laden water was observed to be discharging into the main
 2 channel from multiple englacial conduits and supraglacial channels, ~~located 200 m west of these~~
 3 ~~landslide like features, which was flowing into the main channel~~ (Figure 2B). Around 12:10
 4 p.m., an additional supraglacial torrent and two supraglacial streams, located upglacier and to the
 5 east of the initial observations, joined the floodwater discharging from this initial area. The
 6 discharging water immediately began ponding and quickly breached the pond allowing the
 7 floodwater to propagate downstream and join the pre-existing main channel in addition to
 8 creating a secondary channel down the southern lateral moraine (Figures 1c, 2B). During this
 9 time, channel banks composed of ice and debris were severely undercut as the floodwater melted
 10 the surrounding ice as well.



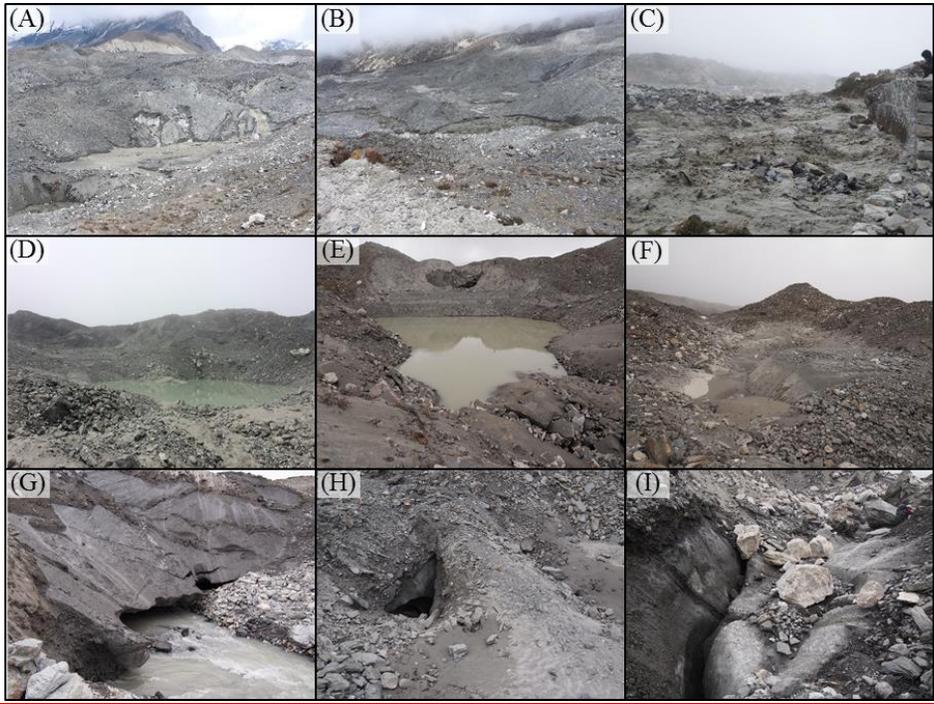
12 ~~Figure 1. Observations and reconstruction of the glacier outburst flood from Lhotse Glacier on~~
 13 ~~12 June 2016 showing the observed and reconstructed flood path down to the village of Chukung.~~
 14 ~~Letters correspond to key features in Figure 2.~~

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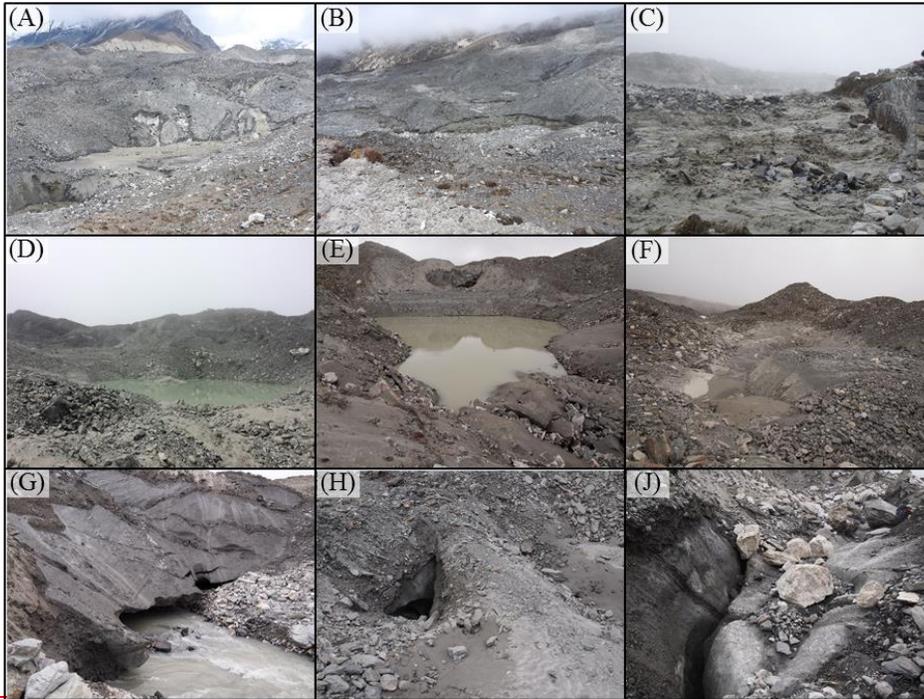
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17 The main channel continued to flow downstream until it re-entered englacial conduits (Figure
 18 1c), which created an “ice bridge” that allowed investigators to cross the secondary and main
 19 channel ~~after one~~ the peak flow started subsiding ~~around 12:26-1:30~~ p.m. At 4:225 p.m.,
 20 discharge below Chukung was measured to be $32 \pm 14 \text{ m}^3 \text{ s}^{-1}$ ~~at a point below Chukung~~. Peak
 21 discharge was estimated retroactively to be $210 \pm 43 \text{ m}^3 \text{ s}^{-1}$. ~~This estimate is considered to be~~
 22 conservative ~~since because~~ it uses average velocity measurements taken ~~four over 3~~ hours after
 23 peak discharge. Interestingly, this estimate agrees well with an empirical approach for

1 predicting peak discharge based on glacier-bed area (Fountain and Walder, 1998), which predicts
2 the peak discharge to be $38 - 1500 \text{ m}^3 \text{ s}^{-1}$. A best-estimate hydrograph (Figure 1b) was
3 reconstructed based on the photos of the water level at the ice bridge showing a peak flow of 210
4 $\pm 43 \text{ m}^3 \text{ s}^{-1}$ at 12:26 p.m. followed by a gradual falling limb such that the discharge returned to
5 normal conditions within 24 hours. The shape and timing of the hydrograph is consistent with
6 the 1985 glacial lake outburst flood from Dig Tsho (Vuichard and Zimmerman, 1987), although
7 the peak flow from Lhotse Glacier was significantly smaller. Based on this hydrograph, the
8 overall flood volume was estimated to be $2.65 \times 10^6 \text{ m}^3$ ($1.88 - 3.45 \times 10^6 \text{ m}^3$ for the estimated
9 low and high bounds, respectively). Minimal damage was caused to the community of
10 ~~Chukung~~Chukhung, which community members credited to the recently constructed gabions
11 (Figure 2C).- The main damage was the loss of a pedestrian bridge, an outbuilding, and small
12 amounts of floodwater in the courtyard of one lodge. Supplementary material provides footage
13 of the observed events.
14 ~~-The local community members credited recently constructed gabions (Figure 2C) for protecting~~
15 ~~their lodges from further damage (see supplementary material for footage of the observed events).~~
16 ~~Water levels appeared to return to normal stages within 24 hours.~~
17



1



1
 2 Figure 2. Key features of the glacier outburst flood from Lhotse Glacier: (A) subsurface englacial and
 3 and supraglacial flooding where the event was first observed, (B) main channels of flood path
 4 during the flood's peak, (C) flood undercutting the gabions at Chukung Chukhung, at 2:19 p.m.,
 5 shortly after estimated peak flow, (D) potentially drained pond with large bare ice faces behind it,
 6 (E) potentially drained pond with a collapsed englacial conduit behind it, (F) potentially drained
 7 pond with sinkholes, (G) meltwater exiting the glacier into the main channel via a large englacial
 8 conduit, (H) a vertical englacial conduit and sinkholes with wet, fine sediment indicating a
 9 drainage pathway, and (I) large vertical crevasses with clean ice likely from the supraglacial
 10 flood path.
 11

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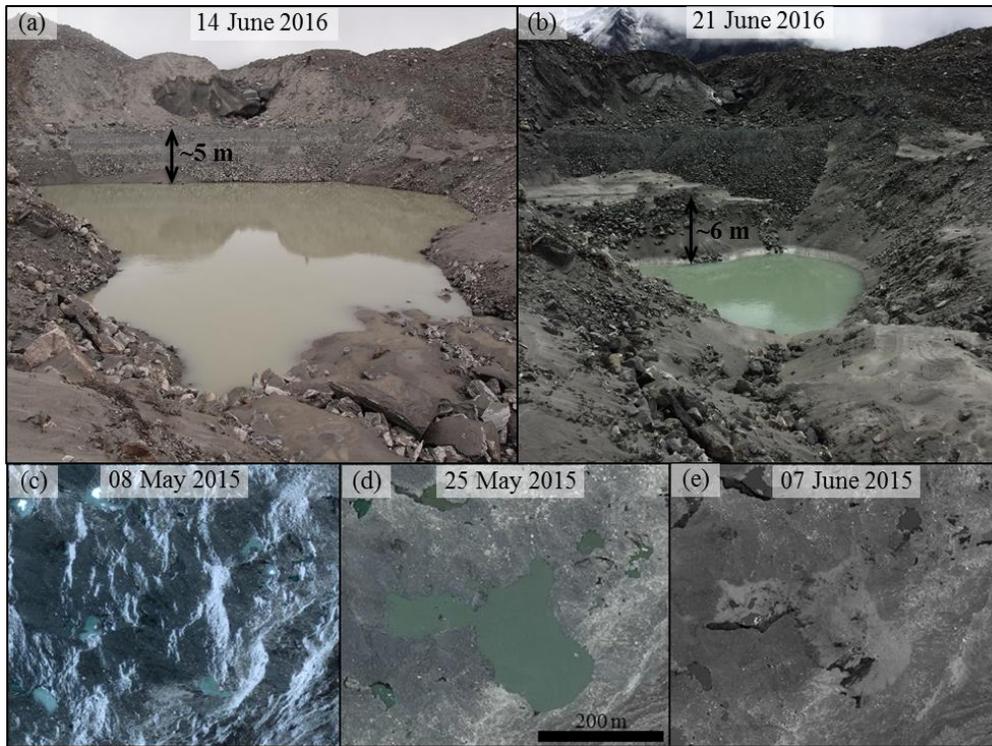
12 **3.2 Post-flood observations:** A detailed field assessment of Lhotse Glacier was conducted to
 13 reconstruct the glacier outburst flood by identifying potential flood pathways, englacial conduits,
 14 sinkholes, and drained ponds (Figure 1c). Satellite imagery from 14 May 2016 reveals a
 15 sizeable supraglacial pond (27°54'20" N, 86°53'27" E) with an area of 4900 m² located directly
 16 beneath a large bare ice face (~10-20 m) that was considerably smaller during our field
 17 assessment (Figure 2D). This pond also had fine, wet sediment along its slopes in addition to and
 18 had a series of bare ice, sinkholes, and englacial conduits located immediately downstream,
 19 which would have facilitated its drainage. This was the pond located the furthest upglacier that

1 appeared to have recently drained, although ~~it is possible that the flood originated further~~
2 ~~upstream via the drainage of other supra- or subglacial ponds. A~~ detailed assessment of all the
3 supraglacial ponds and terrain upglacier was ~~not possible~~~~unable to be conducted~~ due to time
4 limitations.

5 This ponded water likely entered a series of englacial conduits and potentially supraglacial
6 pathways before entering another supraglacial pond located ~200 m downglacier (Figure 1c).
7 This second supraglacial pond had similar indicators of having recently drained (Figure 2E),
8 although the satellite image does not show a large supraglacial pond. It is possible that
9 meltwater filled the pond between the glacier outburst flood and the time when the satellite
10 image was acquired. A collapsed englacial conduit was observed between these two ponds
11 (Figure 1c) in addition to a series of sinkholes ~~along with an and the~~ entrance to an englacial
12 conduit ~~located~~ immediately downstream of the pond (Figure 2H). Based on recently uprooted
13 and displaced alpine shrubs, the flood appeared to continue downstream where it branched into
14 multiple paths (Figure 1c). The southern branch appears to have entered a third supraglacial
15 pond (Figure 2F), which had similar indicators and large sinkholes. Downstream of this third
16 pond was a small valley that was littered with areas of clean ice and deep crevasses (Figure 2I).
17 It appears that this supraglacial pathway and englacial conduits fed into the flood torrent that
18 joined the initial discharge at 12:10 p.m (Figure 1c). The other branch showed signs of
19 supraglacial and englacial pathways in the form of bio-indicators, sinkholes, and englacial
20 conduits as well, which appear to have contributed to the heavy flow that was observed
21 ~~discharging into~~ the main channel as well (Figure 2G).

22 **3.3 Satellite imagery analysis:** ~~Satellite imagery provides unique opportunities to observe the~~
23 ~~contribution of supraglacial ponds to these glacier outburst flood events; however, it is important~~
24 ~~that this imagery is acquired immediately before and after the event as these supraglacial ponds~~
25 ~~experience large temporal and spatial changes (Figure 3). In order to estimate the potential flood~~
26 ~~volume associated with the drainage of supraglacial ponds, an area-to-volume relationship was~~
27 ~~used (Cook and Quincey, 2015). Based on the change in areal extent between 14 May 2016 and~~
28 ~~29 October 2016, the drained volume from the furthest supraglacial pond upglacier (Figure 1c,~~
29 ~~Figure 2D) was $0.01 \times 10^6 \text{ m}^3$. This volume is two orders of magnitude less than the estimated~~
30 ~~flood volume of $2.65 \times 10^6 \text{ m}^3$, which suggests that the drainage of a single supraglacial pond~~
31 ~~contributes very little to the overall flood volume. In fact, if all of the 274 supraglacial ponds~~

1 (0.21 km²) that were present on Lhotse Glacier on 14 May 2016 drained completely, the
2 potential flood volume would only be 0.52 x 10⁶ m³. This provides strong evidence that a
3 significant amount of the flood water was stored in the glacier's subsurface.
4



5
6 Figure 3. Images showing the temporal changes to supraglacial ponds (a, b) following the 2016
7 glacier outburst flood and (c, d, e) around the 2015 glacier outburst flood.

8
9 The glacier outburst flood on 25 May 2015 also originated from Lhotse Glacier and occurred
10 overnight (Sherpa, L., personal communication, 09 June 2015). Satellite imagery from 08 May
11 2015, 25 May 2015, and 07 June 2015 reveals a large supraglacial pond (0.036 km²) filling
12 between 08 – 25 May and draining completely between 25 May – 07 June (Figure 3c, d, e). The
13 drainage of this supraglacial pond could have contributed up to 0.17 x 10⁶ m³ to the 2015 glacier
14 outburst flood. Community members reported that the 2016 event was larger than the 2015
15 event. A similar outburst event was also reported to have occurred in early May 2016 in the

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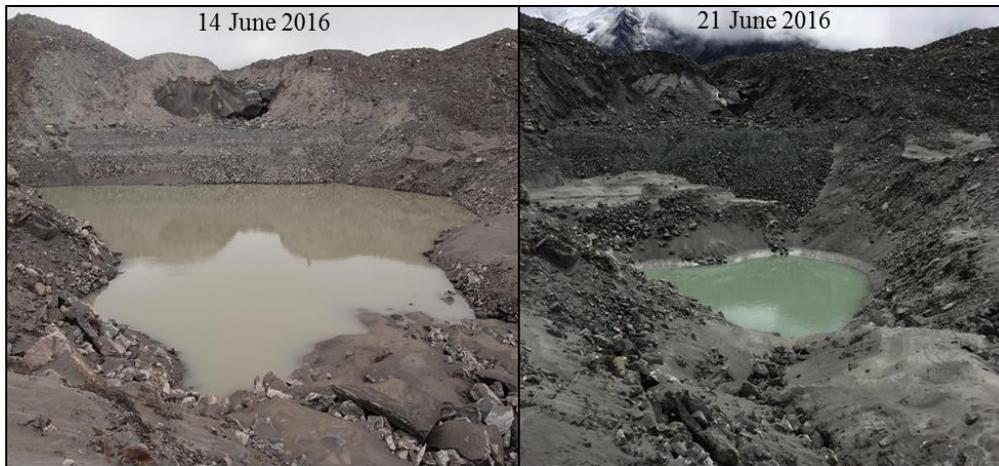
1 vicinity of the “crampon put-on point” (5600 m) of Island Peak (6189 m) that damaged sections
2 of the high and low basecamp regions (Sherpa, P.T., personal communication, 18 June 2016).

3 **4 Discussion**

4 **4.1 Source of the flood water:** The field observations immediately following the 2016 glacier
5 outburst flood suggest that some of the source water was from the drainage of supraglacial
6 ponds; however, the satellite imagery revealed that the drainage of supraglacial ponds alone
7 could not account for all of the flood volume. Therefore, the water that was unleashed during the
8 2016 glacier outburst flood was likely stored in both the glacier’s subsurface and supraglacial
9 ponds. Once the flood was initiated, the melting of ice from both the channel banks and in the
10 englacial conduits caused these outlet pathways to grow, which likely contributed more water to
11 the total flood volume in addition to opening more efficient pathways for the stored water to
12 drain. Due to the sub-, en-, and supraglacial nature of these events, glacier outburst floods are
13 difficult to study in detail, which provides challenges to understanding their frequency and
14 magnitude. One of the easiest ways to observe these outburst floods would be the use of repeat
15 high resolution satellite imagery such that the drainage of supraglacial lakes could be quantified.
16 However, the large temporal and spatial changes that these supraglacial ponds experience make
17 it challenging to obtain imagery that captures a flood event (Figure 3). Furthermore, remote
18 sensing does not provide any information regarding the sub- or englacial pathways of the flood.
19 Hence, the direct observations of the glacier outburst flood from Lhotse Glacier and the ensuing
20 field assessment immediately after the event provide unique insight into the triggering
21 mechanisms, flood path, and magnitude of these events that has rarely been captured before.

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1
2 ~~Figure 3. Repeat photography of a supraglacial pond on Lhotse Glacier showcasing the large~~
3 ~~temporal changes.~~

4
5 4.2 Triggering mechanisms: Potential triggering mechanisms for these glacier outburst floods
6 include dam failure, the rapid drainage of stored lake water through hydraulically efficient
7 pathways, and/or catastrophic glacier buoyancy. The sudden discharge observed during the 2016
8 event (Figure 1b) suggests that the trigger was most likely dam failure or the rapid drainage of
9 stored lake water, since catastrophic glacier buoyancy typically has a hydrograph with a more
10 gradual rising limb (Fountain and Walder, 1998).

11 Dam failure would require an englacial conduit to be temporarily blocked, which could occur if
12 meltwater refroze in the conduits over the winter (Gulley et al., 2009) or if passage closure
13 processes caused an englacial conduit to close (Benn et al., 2012). The former blockage scenario
14 seems more likely since these glacier outburst floods have occurred in back-to-back years and
15 the refreezing of meltwater is an annual process. During the early melt season the subsurface
16 drainage system is distributed and inefficient, which provides opportunities for water to
17 accumulate englacial (Fountain and Walder, 1998). Dam failure may then occur if the
18 hydrostatic pressures in the englacial conduits exceed the cryostatic pressure that was previously
19 constraining the stored water thereby causing the dam to rupture (Richardson and Reynolds,
20 2000). Alternatively, as water accumulates in the englacial conduits, the changes in water

1 pressure can cause these conduits to grow in an unstable manner thereby causing drainage to
2 occur (Fountain and Walder, 1998). This progressive enlargement is similar to piping failures
3 and the failures of ice dammed lakes (Richardson and Reynolds, 2000).

4 The rapid drainage of stored lake water through hydraulically efficient pathways is another
5 plausible triggering mechanism that commonly occurs for supraglacial ponds in the Everest
6 region (Benn et al., 2012). Field observations of supraglacial ponds (Figure 2D, E) revealed that
7 there were englacial conduits located at the ends of both of these lakes that likely helped
8 facilitate their drainage. This link between the englacial conduits and supraglacial ponds is not
9 surprising as near-surface water storage on glaciers can result from water accumulating in
10 englacial conduits (Fountain and Walder, 1998). Once these ponds come in contact with an
11 englacial conduit or a highly permeable layer, the warm pond water can cause significant internal
12 ablation that helps facilitate the drainage of additional stored water. The drainage of supraglacial
13 ponds that was observed for the 2015 and 2016 events supports this theory; however, as
14 previously discussed, the drainage of supraglacial ponds alone likely accounts for a small
15 fraction of the total flood volume.

16 This suggests that the most feasible triggering mechanism is likely some form of dam failure
17 resulting from the material blocking the englacial conduits being overburdened or failure
18 resulting from the progressive enlargement of englacial conduits. The timing of these events,
19 which occurred around the start of the monsoon season, further supports this triggering
20 mechanism as this provides ample time for these englacial conduits to fill with meltwater or
21 precipitation prior to dam failure. It should not come as a surprise that this time of year is also
22 when supraglacial pond cover is at its highest (Miles et al., 2016) as this may be indicative of the
23 amount of water stored englacial as well. In fact, it is possible that the large supraglacial pond
24 that filled immediately before the 2015 glacier outburst flood (Figure 3c, d) was the surficial
25 expression of the englacial conduits accumulating too much water, which could explain the
26 pond's short lifespan once the englacial conduits drained. This may also explain how
27 supraglacial pond E (Figure 1c) was not apparent in satellite imagery on 24 May 2016, but
28 appeared to have drained recently based on field observations (Figure 3a, b), i.e., the pond likely
29 filled between 24 May 2016 and the glacier outburst flood. On the other hand, supraglacial pond
30 D (Figure 1c) was present in the imagery and had been growing since 2011 (Watson et al., 2016),
31 which indicates that the rapid drainage of supraglacial ponds through hydraulically efficient

1 pathways may also be contributing to these glacier outburst floods as well, albeit contributing a
2 smaller volume than the water stored englacial.

3 ~~The first direct observations of the glacier outburst flood were three landslide-like features~~
4 ~~generated by water being discharged through englacial conduits. This sudden discharge was~~
5 ~~likely due to the hydrostatic pressures exceeding the cryostatic pressure that was previously~~
6 ~~constraining the water stored englacially (Richardson and Reynolds, 2000). As this flood~~
7 ~~occurred in mid-June, there was ample time for these englacial conduits to be filled with glacier~~
8 ~~meltwater. The discharge of this water would open outlets of lower hydraulic potential that~~
9 ~~would facilitate the drainage of englacial and supraglacial waters (Gulley and Benn, 2007).~~
10 ~~Another possibility is that the flood started further upglacier and as this floodwater propagated~~
11 ~~downglacier, the englacial conduits were overburdened, which eventually caused them to rupture.~~
12 ~~This would help explain the supraglacial flood paths that were observed during the field~~
13 ~~assessment. Conduits and sinkholes that were located along the supraglacial flood paths could~~
14 ~~have helped transport the floodwater into these englacial conduits causing the rupture and~~
15 ~~discharge that was first observed. The actual triggering mechanism is likely a combination of~~
16 ~~these various processes. Once the glacier outburst flood is initiated, a meltwater feedback is~~
17 ~~generated where the discharging water causes additional melt of ice thereby greatly increasing~~
18 ~~the magnitude of the flood, which was observed during this event.~~

19 ~~Based on the timing of the flood, meltwater storage likely had an important role in the cause of~~
20 ~~the outburst flood, which would also explain how drained ponds that were not apparent in the~~
21 ~~satellite image from 14 May 2016 were filled before the flood event. Additionally, the observed~~
22 ~~event from Lhotse Glacier was the second event in the last two years. On the night of 25 May~~
23 ~~2015, another glacier outburst flood originating from Lhotse Glacier occurred (Sherpa, L.,~~
24 ~~personal communication, 09 June 2015). A similar event reportedly occurred in early May 2016~~
25 ~~in the vicinity of the “crampon put on point” (5600 m) of Island Peak (6189 m) that damaged~~
26 ~~sections of the high and low basecamp regions (Sherpa, P.T., personal communication, 18 June~~
27 ~~2016). The timing of these events during the transitional pre-monsoon season suggests that the~~
28 ~~sub- and englacial hydrological system may play an important role. Specifically, during the~~
29 ~~early melt season the drainage network may be distributed and inefficient, which causes the~~
30 ~~buildup of stored water until the glacier outburst flood suddenly releases the water and opens~~
31 ~~new efficient channels similar to the evolution of subglacial hydrological systems in the Arctic~~

1 ~~(Carr et al., 2013). The repetitive nature of these events at Lhotse Glacier presents potential~~
2 ~~opportunities to more thoroughly investigate the triggering mechanisms, pathway, and size of~~
3 ~~these events through methodically tasked high-resolution imagery analysis and the deployment of~~
4 ~~specific field equipment, e.g., time-lapse cameras, pressure sensors, and flow measurements.~~

5 **5 Conclusions**

6 The direct observations of the glacier outburst flood on 12 June 2016 from Lhotse Glacier
7 provide unique insight into the magnitude, source, and trigger mechanisms associated with these
8 rarely observed events. The flood was observed to occur suddenly reaching a peak discharge of
9 210 m³ s⁻¹ only 45 minutes after the flood began. The detailed field assessment conducted in the
10 days immediately following the event in conjunction with the satellite imagery analysis was used
11 to determine that most of the flood water originated from the glacier's subsurface. Based on the
12 sudden discharge and magnitude of the event, the flood appeared to be triggered by dam failure
13 due to the englacial conduits being overburdened and rupturing or from the englacial conduits
14 progressively enlarging in an unstable manner until failure occurred. Community members
15 reported that another glacier outburst flood originating from Lhotse Glacier also occurred on 25
16 May 2015, which suggests that Lhotse Glacier may provide unique opportunities to study these
17 complex events in more detail in the future. Future work should seek to improve our
18 understanding of the triggering mechanisms and size of these events through detailed field
19 surveys assessing both the glacier's surface and subsurface combined with methodically tasked
20 high resolution satellite imagery. This will be important as improving our understanding of the
21 frequency and magnitude of these events has important economic and social implications for
22 downstream communities and hydropower companies.~~are the first time in the Himalaya that~~
23 ~~scientists have witnessed an event in real-time, to the authors' knowledge, which provides~~
24 ~~valuable information regarding the triggering mechanisms and the magnitude of these events.~~
25 ~~The detailed field assessment in the immediate days following the event assisted efforts to~~
26 ~~reconstruct the flood path and showed that in-situ observations are critical for understanding~~
27 ~~these hazards as the supraglacial hydrology changes rapidly. The sub-, en-, and supraglacial~~
28 ~~nature of these events also highlights our lack of knowledge; however, these events appear to be~~
29 ~~occurring repetitively at Lhotse Glacier, which provides a unique opportunity to conduct more~~
30 ~~thorough investigations in the future. This will be important as improving our understanding of~~

1 | ~~the frequency and magnitude of these events has important economic and social implications for~~
2 | ~~downstream communities and hydropower companies.~~

3 |

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9 | **References**

10 | Benn, D., Gulley, J., Luckman, A., Adamek, A., and Glowacki, P.S.: Englacial drainage systems
11 | formed by hydrologically driven crevasse propagation, *J Glaciol*, 55(191):513-523, 2009.

12 | Benn, D.I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L.I., Quincey, D.,
13 | Thompson, S., Toumi, R., Wiseman, S.: Response of debris-covered glaciers in the Mount
14 | Everest region to recent warming, and implications for outburst flood hazards, *Earth-Science*
15 | *Reviews* 114:156–174, doi:10.1016/j.earscirev.2012.03.008, 2012.

16 | [Bolch, T., Pieczonka, T., and Benn, D.I.: Multi-decadal mass loss of glaciers in the Everest area](#)
17 | [\(Nepal Himalaya\) derived from stereo imagery, *The Cryosphere*, 5, 349-358, doi:10.5194/tc-](#)
18 | [5-349-2011, 2011.](#)

19 | ~~Carr, J.R., Stokes, C.R., and Vieli, A.: Recent progress in understanding marine terminating~~
20 | ~~Arctic outlet glacier response to climatic and ocean forcing: Twenty years of rapid change,~~
21 | ~~*Prog Phys Geog*, 37(4):436-467, doi:10.1177/0309133313483163, 2013.~~

22 | Carrivick, J.L. and Tweed, F.S.: A global assessment of the societal impacts of glacier outburst
23 | floods, *Global Planet Change*, 144:1-16, <http://dx.doi.org/10.1016/j.gloplacha.2016.07.001>,
24 | 2016.

25 | [Cook, S.J. and Quincey, D.J.: Estimating the volume of Alpine glacial lakes, *Earth Surface*](#)
26 | [Dynamics](#), 3:559-575, doi:10.5194/esurf-3-559-2015, 2015.

1 [Fountain, A.G. and Walder, J.S.: Water flow through temperate glaciers, Rev Geophys,](#)
2 [36\(3\):299-328, 1998.](#)

3 Gulley, J. and Benn, D.I.: Structural control of englacial drainage systems in Himalayan debris-
4 covered glaciers, J Glaciol, 53(182):399-412, 2007.

5 Gulley, J.D., Benn, D.I., Müller, D., and Luckman, A.: A cut-and-closure origin for englacial
6 conduits in uncrevassed regions of polythermal glaciers, J Glaciol, 55(189):66-80, 2009a.

7 Gulley, J.D., Benn, D.I., Sreaton, E., and Martin, J.: Mechanisms of englacial conduit formation
8 and their implications for subglacial recharge, Quaternary Sci Rev, 28:1984-1999,
9 doi:10.1016/j.quascirev.2009.04.002, 2009b.

10 Horodyskyj, U.N.: Contributing factors to ice mass loss on Himalayan debris-covered glaciers,
11 PhD Thesis, University of Colorado, 2015.

12 [Miles, E.S., Willis, I.C., Arnold, N.S., Steiner, J., and Pellicciotti, F.: Spatial, seasonal and](#)
13 [interannual variability of supraglacial ponds in the Langtang Valley of Nepal, 1999-2013, J,](#)
14 [Glaciol., 1-18, doi:10.1017/jog.2016.120, 2016.](#)

15 Quincey, D.J., Richardson, S.D., Luckman, A., Lucas, R.M., Reynolds, J.M., Hambrey, M.J.,
16 and Glasser, N.F.: Early recognition of glacial lake hazards in the Himalaya using remote
17 sensing datasets, Global Planet Change, 56:137-152, doi:10.1016/j.gloplacha.2006.07.013,
18 2007.

19 [Rantz, S.E.: Measurement and computation of streamflow: volume 1, measurement of stage and](#)
20 [discharge, No. 2175, USGPO, 1982.](#)

21 Richardson, S.D. and Reynolds, J.M.: An overview of glacial hazards in the Himalayas, Quatern
22 Int, 65/66:31-47, 2000.

23 Richardson, S.D. and Quincey, D.J.: Glacier outburst floods from Ghulkin Glacier, upper Hunza
24 Valley, Pakistan, Geophysical Research Abstracts from EGU General Assembly 2009 held in
25 Vienna, Austria, 19-24 April 2009.

26 Vuichard, D. and Zimmermann, M.: The 1985 catastrophic drainage of a moraine-dammed lake,
27 Khumbu Himal, Nepal: cause and consequences, Mt Res Dev, 7:91-110, 1987.

1 Watson, C.S., Quincey, D.J., Carrivick, J.L., and Smith, M.W.: The dynamics of supraglacial
2 ponds in the Everest region, central Himalaya, *Global Planet Change*, 142:14-27,
3 <http://dx.doi.org/10.1016/j.gloplacha.2016.04.008> 2016\

4 **Supplementary Material**

5 Video footage of the glacier outburst flood from 12 June 2016 may be found at
6 http://www.crrwr.utexas.edu/video/Lhotse_Flood_Supplement_V3.mp4.