GLOFs of Laguna de los Témanos, glacier-dammed side lake of Glaciar Steffen, Hielo Patagónico Norte, Chile, since 1974

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Abstract

Glacier lake outburst floods (GLOF) at Laguna de los Témanos, a glacier-dammed side lake of Glaciar Steffen, Hielo Patagónico Norte, were documented for a period between December 1974 and February 2020. With manual interpretation of 150 remote sensing images of aerial surveys, vertical aerial photographs, Landsat MSS, TM, ETM and OLI, ALOS, and ASTER images, 19 GLOFs were captured/inferred by focusing on icebergs and water levels, except two periods in the 1980s and the 1990s for which no image was available. This translates to the occurrence of the GLOF on average once ca. every 14 months. Many GLOFs occurred in late summer to early fall, with a few in late spring: but one GLOF was inferred to have occurred in wintertime. The causes of GLOFs were supposed to be heavy rainfalls, probably accompanied with rapid snow/ice melting by warm air temperatures, judging from the general weather condition over the laguna area. The latest two GLOFs (2016 & 2017) were very large, enough to have completely exposed the lake floor in the middle section. The GLOF of 2017 (Mar. 31) was registered in a hydrograph set up at Lower Río Huemules. After this GLOF, the water level has become stable with a more or less continuous outlet stream along the glacier sidewall and there has been no GLOF to date. So probably the prospect of another GLOF has considerably diminished by now. As Glaciar Steffen receded about 6 km during this study period, the glacier has thinned accordingly, to which the water level adjusted with three distinctive relatively stable states while fluctuating frequently.

Key words: GLOF, Glaciar Steffen, Hielo Patagónico Norte, Patagonia

1. Introduction

In light of recent climate change, i.e. global warming, monitoring/studying glacier lake outburst flood (GLOF) has become important and the serious concern to local inhabitants who are potentially at risk as well as those engaged in glacier research. GLOFs in the Himalayas, those in Nepal and Bhutan in particular have been paid much attention from the 1990s, because many locals are living in the downstream of glacier-/moraine-dammed lakes (e.g., Yamada, 1998; Ageta and Iwata, 1999; Nagai et al., 2017). Due to accelerated glacier melting caused by global warming, many glacier lakes all over the world have been enlarging, thereby having increased the risk of GLOFs.

The Hielo Patagónico (HP or Patagonia Icefield), South America, is one of the largest temperate icebodies in the world, comprising two separate icefields (Norte and Sur) with a combined area of ca. 16,300 km² (Casassa et al., 2012; Barcaza et al., 2017) and more than 70 major outlet glaciers (Aniya, 1999). Although the HP is supposed to be no exception for GLOFs, reports/analyses on GLOFs are few (e.g., Tanaka, 1980; Aniya, 2009, 2014, 2017; Dussaillant et al., 2010; Dirección General de Aguas, hereafter, DGA, 2014, 2018, 2019; DGA and Dirección de Vialidad, 2018), probably not because GLOFs have not occurred, but because there are not many inhabitants in the risky area who could observe/report GLOFs and/or be affected. Also there were not many scientists working there who would have reported/analyzed them until recent times. Loriaux and Casassa (2013) reported and analyzed the increase and enlargement of glacial lakes of Hielo Patagónico Norte (HPN) between 1945 and 2011.
using satellite images, and discussed about the increasing risk of GLOFs.

Quite recently, three GLOFs were reported in HPN (Fig. 1). A GLOF occurred on Apr. 19, 2018 from a side lake of Glaciar Exploradores, which was caused by the rapture of damming lateral moraine (Fig. 1A) due to heavy rainfall and excessive snow melting by warm air temperature (per. comm., Aniya with Wündlich, Apr. 2018; DGA, 2018). Another occurred at a small lake on the slope above the road (Fig. 1B) in the valley of Río Norte and Río Exploradores on Oct. 27, 2018 (DGA and Dirección de Vialidad, 2018). The consequent debris flow impounded Río Norte, thereby blocking traffic for more than a month. On Jan. 15, 2019, local residents reported a flood of Upper Río Huemules that is located at the southernmost of HPN (Fig. 1C). With satellite images it was recognized that a GLOF occurred at a glacier-dammed side lake of Glaciar HPN4 (DGA, 2019). The first report of GLOFs at HPN4 was Feb. 15, 2014 (DGA, 2014), after which such flooding had occurred about once a year.

As illustrated in Fig. 1, we can classify GLOF lakes with the criterion of either its relative location to the glacier (front or side) or damming material (moraine debris or glacier ice). If one is located in front of a glacier, it is usually dammed by a terminal moraine such as Fig. 1B: if located on the side, damming material would be either a lateral moraine (Fig. 1A) or glacier ice (HPN4). Among these, a glacier-dammed side lake tends to cause the GLOF repeatedly as with the case of HPN4.

It was Tanaka (1980) who pioneered a GLOF study in Patagonia when he accompanied the Japan—Chile Climbing Expedition in 1956 to Cerro (Co.) Arenales (3365 m), the second highest mountain of HPN. He recognized a GLOF at Laguna Arco, a glacier-dammed side lake of Glaciar Colonia that drained ice from Co. Arenales, from stranded icebergs on the lake floor. He supposed the drainage was subglacial.

Aniya (2009) documented a GLOF at Laguna del Co. Largo of the Río Soler valley area of HPN that occurred either in 1987 or 1989 (two different years given by two local families living about 40 km downstream). Visiting the lake in 1998, he estimated the drop of the water level at 97 m; the volume of water lost at 0.176 km$^3$; and the volume of eroded damming moraine debris at 325 x 10$^4$ m$^3$. The failure of the damming moraine (Little Ice Age, Aniya and Shibata, 2001) was probably caused by water jumping, which in turn was induced by an ice avalanche from the north face of Co. Largo.

Dussaillant et al. (2010) reported and closely analyzed in detail GLOFs from Lago Cachet Dos, a glacier-dammed side lake of Glaciar Colonia, which were initiated by thinning of the damming glacier in 2008 and repeated several times thereafter. In their paper, some major GLOFs of the southern Andes including Patagonia were listed. To date, 20 GLOFs were recorded at this lake; but now it is dry, with a stream channel.

2. First Clear Recognition of GLOF with Direct Evidence at Laguna de los Témapanos

It was 2013 when Aniya obtained a clear, direct evidence of and became aware of a GLOF (Aniya, 2014). During the aerial survey of HPN in Feb. 2013, he noticed many stranded icebergs in a glacier-dammed side lake of Glaciar Steffen, Laguna de los Témapanos (Fig. 2A). Then, during another aerial survey in the next austral summer, Dec. 2013, this lake was full of water with many icebergs floating (Fig. 2B).

Photographs from these two aerial surveys clearly indicated that a GLOF had occurred before Feb. 19, 2013, thereby draining the lake water beneath Glaciar Steffen, as there was no visible surface stream along the glacier margin from the air. With this finding, Aniya checked his old aerial survey photographs of HPN outlet glaciers since 1986 (Aniya, 2017), and found several dates of photographs of this lake with many stranded icebergs floating without water, indicating that GLOFs had repeatedly occurred.

Glaciar Steffen is located at the southern end of HPN (Fig. 3) and is ca. 41 km long. It is the third largest glacier
of HPN with an area of ca. 443 km$^2$ (Aniya, 1988, 2017). Accumulation area ratio is 0.71. On the 1:50,000 topographic map published by the Chilean Instituto Geográfico Militar (IGM) in 1981, names were given to two glacier-dammed side lakes (Fig. 3A): Laguna de los Témpanos (our concern, hereafter LdlT) and Laguna El Bolsón. The uppermost lake (visible in Fig. 3C) was still covered with ice then and no name was given. The valleys of these side lakes used to be filled with glacier ice. As Glaciar Steffen started receding and thinning, these valleys started being filled with water, thereby having become glacier-dammed lakes.

At Glaciar Steffen, there is not any kind of ground-measured data such as glacier flow speed and thickness change, hydrology or meteorology, with which to accurately identify and/or verify inferred occurrences of GLOFs in the past and to discuss in detail causes of GLOFs. As for hydrology, however, Univ. of Bristol (UK) started in 2016 monitoring flow of Lower Río Huemules that drains out from Lago Steffen (not official name), a proglacial lake of Glaciar Steffen. Glacier variations since 1945 are the only long-term data available for this area (Aniya, 2017).

Therefore, the purpose of this paper is primarily, utilizing remote sensing data, to report detected GLOFs since 1974, with which to arouse and further professional and public interests in GLOFs in HP and provide information for future investigations.
3. Data

The total number of images utilized for this study is 150, comprising 14 periods of oblique aerial survey photographs taken by Aniya, two periods of vertical aerial photographs (1974 and 1998) taken by Chilean agencies, and 132 Landsat (MSS, TM, ETM and OLI—mostly Natural color, with some panchromatic Band 8), one ALOS and one ASTER satellite images.

The 150 images cover a period of about 45 years from Dec. 1974 to Feb. 2020 (Fig. 4). Naturally time intervals of image dates are not evenly spaced, because usable images were dictated by local weather conditions and image acquisitions (particularly early period). In these data, there are two large gaps in 1980-84 and 1991-96, when Landsat data did not exist for this area and a few aerial surveys failed due to bad weathers. Understandably, summer (Dec., Jan. & Feb., no. of data, 44) and fall (Mar., Apr. & May, 39) have most usable images (Fig. 5). Spring (Sept., Oct. & Nov.) has 35 images. Even for wintertime (June, July & Aug., 32) surprisingly, a quite few number of usable images were available, confirming local observations “winter weather is not so bad as many people suppose” of more than 40 years by a pilot of a regular commercial flight over HPN (per. comm., Aniya with Roberto León in Coyhaique, 2004).

4. Method

Basically the occurrence of a GLOF was captured/inferred from manual interpretation of the state of the lake as follows. Step 1: whether or not water was present. Step 2: whether or not icebergs were present. If there were, stranded or floating? If icebergs were stranded, the occurrence of a GLOF is certain (captured). Although we have no concrete data about exactly how long it will take the Laguna to recover full water, it seems rather rapid in most cases, which will be discussed in the following section. So when we recognize stranded icebergs on the lake floor, it is probably safe to judge that a GLOF had occurred shortly before the image date.

If icebergs are floating, check their sizes and distribution (fairly evenly or rather concentrated, and loose or packed) and the water level against the shoreline mark on the side slope. If the water level is lower than the shoreline mark and icebergs are concentrated at the glacier edge, it may indicate that the water level had been in the process of recovering after a GLOF, because rapid water draining causes the concentration of icebergs at the glacier edge. However, if the water level was at/near the shoreline mark, the concentration may have resulted from recent calving of the glacier. If no or very few icebergs are present, check the water level in relation to the shoreline mark. The exposure of the lake floor is also important. The final judgment is carried out by the holistic interpretation of successive images as will be demonstrated in the following section.

5. Results

Table 1 is a list of selected data with the sequential data number, date of acquisition, source, lake conditions and occurrence of GLOF, which also includes GLOFs at Laguna El Bolsón and no-name lake as ancillary data. We listed only those, with which we could capture/infer a GLOF along with some important events in the lake environment such as water level fluctuations/changes. A GLOF in bold indicates the certainty of occurrence with stranded icebergs on the lake floor, while a GLOF in plain letter denotes those whose occurrence was inferred from water level fluctuations and/or iceberg conditions. Altogether, 19 GLOFs were captured/inferred between 1985 and 2017, with 16 for certain (captured) and three inferred. Some descriptions of lake conditions and capture/inference of a GLOF are given below.

As for the water level (surface area), we recognized that lake water fluctuated often, with three distinctive, relatively stable stages. So the surface area (5.63 km²) of Fig. 1A (1980) was taken as the initial state for this study and denoted L1. Subsequent stable states were denoted L2 and L3 (Fig. 6), which will be discussed later. For the initial state (Fig. 6A), Landsat image of 1976 was used, as there was no 1980 image.
5.1 Descriptions and Discussion of GLOFs

GLOF (1): Captured in Mar. 7, 1985 image. With images on our hand this is the first image on which we could recognize some stranded icebergs on the upper lake floor (far end in Table 1), with the low water level (L2). Also there was the concentration of icebergs at the glacier edge.

GLOF (2): Inferred in Sept. 18, 1986 image. The recovery of the water level (L1) could be recognized on the next available image of Aug. 17, 1986. However, on the image

Table 1. List of selected data and state of Laguna de los Témanos in relation to icebergs and water level, and GLOF, and Laguna El Bolsón and Unnamed Lake GLOFs

| Data No. | Date    | Source | Iceberg condition | Water state | Comments (GLOF) | El Bolsón | No name |
|----------|---------|--------|-------------------|-------------|-----------------|-----------|---------|
| 1        | 1974.12.10 | VAP    | Full of icebergs  | (Full water = L1) | GLOF (1) | GLOF | Lake S1 |
| 2        | 1976.02.15 | LM02   | Several large scattered icebergs | Full water at L1 | Lake size 1 | GLOF |
| 3        | 1979.02.01 | LM02   | One large iceberg  | Full open water at L1 | GLOF |
| 4        | 1979.03.08 | LM02   | Few large icebergs | Full open water at L1 | GLOF |
| 5        | 1980.05.07 | LT05   | Stranded icebergs (far end) | Low water (L2) | GLOF (1) | GLOF | Lake S1 |
| 6        | 1986.08.17 | LT04   | Icebergs in front of Gl edge | From Topographic Map | GLOF (1) | GLOF | Lake S1 |
| 7        | 1986.09.18 | LT05   | Icebergs concentrated in E-half of lake near Gl Edge (off higher than 08, 17) | Western half open water with some lake ice | GLOF (2, small) | GLOF |
| 8        | 1987.02.09 | LM05   | Full of icebergs with small open water | Full open water at L1 | GLOF |
| 9        | 1989.06.30 | LT05   | Iceberg cover 4/5 of lake (with snow cover) | Small open water at far end. | GLOF (2) | GLOF |
| 10       | 1990.02.25 | AS     | Many icebergs - newly calved | Full water at lower level*L2 | GLOF (4) | No data |

| Data No. | Date    | Source | Iceberg condition | Water state | Comments (GLOF) | El Bolsón | No name |
|----------|---------|--------|-------------------|-------------|-----------------|-----------|---------|
| 14       | 1997.11.03 | LT05   | 2/3 of lake = full of icebergs | 1/3 of lake open water at Gl front. | GLOF (5) | GLOF | Lake S1 |
| 15       | 1998.02.19 | VAP    | Stranded icebergs and floating icebergs concentration at Gl front | Very low water | GLOF (5) | GLOF | Lake S2 |
| 20       | 1999.01.29 | LT05   | Full of icebergs (complete cover) | Wl slight decrease since 01, 03 | GLOF (6) | GLOF | No data |
| 22       | 1999.03.03 | AS     | Stranded icebergs all over | Low water | GLOF (6) | No data |
| 23       | 1999.10.02 | LE07   | Except far end area, complete iceberg cover | Low water | GLOF (7) | GLOF |
| 24       | 2000.03.08 | LE07   | Some stranded & full of floating icebergs in main body | Low water | GLOF (8) | No data |
| 27       | 2000.10.02 | LE07   | Some stranded & full of floating icebergs in main body | Low water | GLOF (8) | No data |
| 28       | 2001.03.01 | LE07   | Some stranded & full of floating icebergs in main body | Low water | GLOF (8) | No data |
| 29       | 2001.05.14 | LE07   | Full of icebergs except far end | Low water | GLOF (8) | No data |
| 30       | 2001.09.03 | AS     | Full of icebergs except far end | Low water | GLOF (8) | No data |
| 34       | 2001.11.29 | AS     | About 1/2 of lake with icebergs | Far end & 1/3 of main body open water | GLOF (9) | No data |
| 36       | 2004.03.04 | LE07   | 3/5 of lake with icebergs (Open water in center) | Full water at L2 | GLOF (9) | No data |
| 40       | 2003.05.20 | LE07   | About full cover by icebergs (but water can be seen among icebergs) | Full water at L2 | GLOF (9) | No data |
| 42       | 2004.05.22 | LE07   | About full cover by icebergs | Full water at L2 | GLOF (9) | No data |
| 43       | 2004.08.18 | LT05   | Full of icebergs | Full water at L2 | GLOF (9) | No data |
| 45       | 2004.11.22 | LT05   | Full of icebergs except far end | Far end became almost empty with GL0F (9, small) | No data |
| 47       | 2004.12.25 | AS     | Far end stranded icebergs | Lake slightly > S2 | flooded | Small GLOF |
| 48       | 2005.02.10 | LT05   | Almost full of icebergs | Far end became almost dry, WL at L3 | No data |
| 50       | 2005.04.23 | LE07   | Only lake with icebergs | WL at L3 | No data |
| 51       | 2005.06.18 | LT05   | 4/5 covered with icebergs incl. some in far end | Full water at L3 | No data |
| 54       | 2005.08.29 | LE07   | 3/5 of main body with icebergs | Far end became dry, WL at L3 | No data |
| 55       | 2005.09.30 | LE07   | Main body full of icebergs but open water along Gl edge | Full water at L3 | No data |
| 57       | 2006.02.01 | LE07   | Main body full of icebergs with some open water along Gl edge | Full water at L3 | No data |
| 60       | 2006.08.03 | AS     | Stranded icebergs all over | Very low water (nearby empty) | GLOF (10) | No data |
| 63       | 2007.03.05 | AS     | Stranded icebergs all over | Very low water | GLOF (10) | GLOF |
| 64       | 2007.04.01 | ALP    | Stilled stranded icebergs all over | Very low water | GLOF (10) | GLOF |
| 69       | 2007.09.28 | LT05   | Full of icebergs (packed) | Full water at L2 | GLOF (10) | No data |
| 70       | 2007.11.23 | LE07   | Full of icebergs in main body | Full water at L2 | GLOF (10) | No data |
| 71       | 2007.12.25 | LE07   | Far end with some stranded icebergs | Far end empty of water, stream channel incised | GLOF (10) | No data |
| 72       | 2008.02.27 | LE07   | Mostly covered with icebergs | Far from inside water, stream channel incised | GLOF (10) | No data |
| 73       | 2008.03.17 | AS     | Stranded icebergs all over | Very low water (nearby Empty) | GLOF (10) | No data |
| 74       | 2008.05.01 | LE07   | Far end & W-half of main body open water | Far end & W-half of main body open water | GLOF (10) | No data |
| 78       | 2008.10.24 | LE07   | Full of icebergs except far end | Open water in far end. | GLOF (10) | No data |
| 80       | 2008.12.11 | LE07   | Full of icebergs (almost complete cover) | Two spots of open water at gl edge & far end | GLOF (10) | No data |
of one month later (Sept. 18, 1986) icebergs were concentrated at the front of the glacier with low open water in the western part at L2. This stage of low water (L2) can be recognized on the next three images and it was on 1987 (Feb.) image that the water level was recovered to L1. So this series of images implies that a GLOF had occurred sometime between Aug. 17 and Sept. 18, 1986, although probably small. It is noteworthy to point out that this is austral wintertime.

GLOF (3): Inferred in June 30, 1989 image. This image shows low water in far end with its area about a half of the L1 level, implying that a GLOF (small?) had occurred some time before.

GLOF (4): Inferred sometime between July 1989 and Dec. 1990. The aerial survey image of 1990 (Dec.) showed that the lake was full of floating icebergs with the water level lower than the previous image (1989) and a dense pack of icebergs concentrated at the glacier edge, thereby implying a strong water flow, i.e., a GLOF. For this interpretation, we cannot preclude the possibility of gradual lowering of the water level over this period without a GLOF, by either a decrease in the water supply or an increase in the subglacial drainage, or both. We have no concrete data to examine these alternatives, but they seem unlikely from other data.

Subsequently, this water level of 1990 was taken as a new stable water level and denoted L2, because the next available image (Nov. 1997) showed that the laguna was full of water at this new water level mark on the side slope (see Fig. 6C).

GLOF (5): Captured in Feb. 19, 1998 image (Fig. 7). The IGM vertical photographs show lots of stranded icebergs

Data No. Date Source Iceberg condition Water state Comments (GLOF) El Bolsón
81 2009.01.11 AS Full of icebergs incl. far end WL at L2
83 2009.04.18 LE07 Main body full of icebergs Far end empty. New WL at L3 GLOF (13, small) Lake S3
91 2011.02.10 AS Full of icebergs (with small open waters) Full water at L3
97 2012.01.21 LE07 W-half of main with icebergs (loose) Far end with small open water
E-half open water with some icebergs WL increased since 10.25 to between L3 & L2
100 2012.03.25 LE07 W-half of main with icebergs (very loose) Far end WL increased since 02.22, small icebergs
E-half open water with few icebergs WL slightly < L2
101 2012.04.26 LE07 Scattered icebergs in main body Mostly open water with some icebergs in W-half
Far end open water, with WL slightly < L2
102 2012.06.13 LE07 W-half of main with stranded icebers W-half of main body & far end no water GLOF (14, large)
Only E-half of main covered with icebergs Stream channel from far end to middle of main
103 2012.07.15 LE07 Almost full of icebergs in main body Far end drained of water. WL about at L3
104 2012.09.01 LE07 About full of icebers with patch of open water in middle Far and completely dry. WL about at L3
106 2013.02.08 LE07 Full of icebers (even coverage) WL at L3, slightly increased since 09.17 Lake S3, but water too little for GLOF?
107 2013.02.19 LE07 Main body stranded icebers Far end no water (but must have been filled before GLOF). Low water GLOF (15)
108 2013.02.13 LE07 Full of icebers uniformly No open water at all. WL slightly > L3 Lake S3
112 2013.12.07 AS Full of icebers uniformly Full water at L3
113 2014.01.18 LC08 Main body full of icebers WL increased since 12.07 to near L2 No data
114 2014.02.19 LC08 Full body about full of icebers WL at L3 GLOF (16, small)
115 2014.05.18 LE07 Full of icebers in main body Far end drained of water & W-L near L3
116 2014.06.19 LE07 Full of icebers in main body WL probably near L3
117 2014.11.02 LC08 W-1/3 of main body, full of icebers Far end no water at all. W-L much < L3 GLOF (17, large)
118 2014.12.02 AS Main with some stranded icebers About half of main with water? Confirm GLOF1?
Far end with some stranded icebers Water level close to L3?
119 2015.01.21 LC08 Full of icebers in E-half of main body Far end completely empty of water or icebergs Stream among stranded icebers in W-half Water drain, well lower than 11.02
120 2015.03.29 LC08 Stranded icebers in W-part (melting) Patch of open water in middle of main body
Pack of icebers in E-part with water W-half of main body, lake floor exposed
122 2015.11.05 LC08 4/5 covered with icebers with open water at GJ edge WL restored to L3
125 2016.03.12 LC08 W-half of main body with stranded icebers No open water. WL well < L2, lake floor exposed in middle section GLOF (18, large)
127 2016.05.15 LC08 Some icebers in E-half of main body Remaining E-half with icebers
W-half still with some stranded icebers Small open water at head & along shore
130 2016.09.04 LC08 Eastern 2/3 with icebers Western 1/3 open water. WL well below L3 Lake 1/5 of S2
131 2016.10.22 LC08 W-half dense pack of icebers, E-half Wide open water along GJ edge
loose pack of icebers WL increased & restored close to L3
133 2017.03.15 LC08 4/5 of main body with loose icebers Wide open water along GJ edge. WL almost at L3
134 2017.03.31 LC08 Stranded icebers in W-part No open water. WL well below L3, lake floor exposed in middle section GLOF (19, large)
regist. in hydrograph
150 2020.02.28 LC08 3 icebers & bergy bits in W-part Open water with WL slightly < L3 Lake S3

Table 1. (continued)

Data No. sequential from the earliest on hand that were used for interpretation. In this table only those that were used to capture/infer GLOFs and associated phenomena were listed.

Type of Images: AS (Aerial Survey) 14; VAP (Vertical Aerial Photographs), 2; Landsat { LM02 (MSS), LT05 (TM), LE07 (ETM), LC08 (OLI), 132; AL-P (ALOS-PRISM), 1; Aster, 1

GLOFs of Laguna de los Tempanos, glacier-dammed side lake of Glaciar Steffen, Hielo Patagónico Norte, Chile, since 1974
on the bottom of far end of the lake along with many floating icebergs choking the main body in low water. GLOF (6 & 7): Captured in Nov. 30, 1999 (AS) image (6) and in Mar. 8, 2000 image (7), respectively. Aerial survey photographs show many stranded icebergs all over the main body in low water while no water in far end (about L3): hence a GLOF. The next available image of Mar. 8, 2000 indicates a similar condition of the lake with many stranded icebergs in low water (also no water in far end). The image interval is only little more than three months without intermediate data. Aided with other data from GLOF’s 11 and 12 that will be discussed later, we interpreted these as separate GLOF’s rather than the continued state of Nov. 1999.

GLOF (8): Captured in Mar. 11, 2001 image. On this image far end was completely empty of water or iceberg. The water level was just enough to fill up the main body only, where many scattered icebergs were floating (L3). The water level restored to L2 by late Nov. 2001.

GLOF (9): Captured in Nov. 22, 2004 image. Three and a half years after GLOF (8) saw the stable condition at L2 until this date, when far end had become almost empty with just a trace of water, implying a recent GLOF. Since this state of low water could be recognized in subsequent images of several years after, this water level was denoted L3. The aerial survey photographs taken on Dec. 25, 2004 show some stranded icebergs in far end, thereby confirming the GLOF inferred in Nov. 22 image.

As for the water level, an interesting change was observed in June 18, 2005 image, when an increase from L3 was recognized by water spilling into far end. This increasing trend continued until Jan. 20, 2006 when the water level was restored to L2. What would have had caused this increase in the water level during winter-spring time, when melting was minimum? Sustained rainfall?

GLOF (10): Captured in Mar. 5, 2007 (AS) image (Fig. 8A). The water level stayed more or less at L2 until Mar. 5, 2007, when an aerial survey captured the lake with stranded icebergs almost uniformly scattered all over including far end. The water level was lower than L3. The next image of ALOS (PRISM), Apr. 1, shows almost the same condition of the lake as Mar. 5 image. The appearance of the lake had changed very little in a month. The water level recovered to L2 by Sept. 2007 (Fig. 8B).

GLOF (11): Captured in Nov. 23, 2007 image, in which far end was littered with few stranded icebergs and a channel incised on the lake floor (Fig. 8C). The main body was totally covered with floating icebergs along with the concentration at the glacier edge. Surprisingly, the next
image, a month later, of Dec. 25, 2007 shows the water level at about L2 (Fig. 8D). It was very quick recovery.

GLOF (12): Captured in Mar. 17, 2008 (AS) image (Fig. 8E). The lake was totally covered with icebergs in very low water (<L3) with the concentration at the glacier edge. The water level changes after GLOF 11 were interesting. In Feb. 27, 2008 image, three months later, it was considerably higher than L2 (but still lower than L1). It was summer time; but what promoted a considerable increase in the water level when the normal water level had been stable for more than one year at L2 except when a GLOF occurred? Had the subglacial water channel underneath Glaciar Steffen changed? Or heavy, but not enough to trigger a GLOF, precipitation caused this temporary rise? Incidentally only 20 days later of this Feb. 27, image, a GLOF was captured with an aerial survey.

GLOF (13): Captured in Apr. 18, 2009 image. Between Jan. 12 and Apr. 18, 2009 the water level dropped from L2 to L3, leaving far end completely free of water or icebergs. The state of L3 continued until around Jan. 21, 2012 when the water level had increased to somewhere between L3 and L2 and by Mar. 25, 2012 it recovered almost to L2.

GLOF (14): Captured in June 13, 2012 image. While the water level was L2 in Apr. 26, 2012 image, Landsat Band 8 (panchromatic with 15-m resolution) of June 13 image revealed that the western part of the main body was scattered with many stranded icebergs without water where stream channel (s) could be recognized, thereby suggesting that the lake floor was exposed. It was probably a large GLOF.

A comparison of Apr. 26 and June 13 images revealed that the glacier edge at the lakeside was greatly eroded, particularly at the southern edge of the glacier between the sidewall. A trough runs from this point along the glacier sidewall to Laguna El Bolsón, which appears without water, though. The trace of this trough started appearing in 2005–2006.

GLOF (15): Captured in Feb. 19, 2013 (AS) image (see Fig. 2A). The subsequent images showed that far end had been dry (no water, no iceberg) until aerial survey data of Feb 19, 2013, indicating a GLOF. On this image some stranded icebergs can be recognized even in far end, implying that the water level was once high enough to fill in this part so that icebergs could drift that far, before the GLOF. The satellite image of Feb. 8, only 11 days before the GLOF shows a little water in far end, an increase from L3. This water level fluctuation was very similar to that before GLOF 12. Was this increase in the water level indicative of an imminent GLOF?

GLOF (16): Captured in Feb. 19, 2014 image. The water level was little higher than L3 until Sept. 2013 when it settled down to L3. Then it had increased in Jan. 18, 2014 image so that far end was filled with water (near L2). In Landsat B8 image of Feb. 19, 2014, far end was found drained of water with many stranded icebergs, indicating a GLOF. The recovery of water was fairly quick so that
its level was about L3 in the image of May 18, 2014.

GLOF (17): Captured in Nov. 2, 2014 image. The image of June 19, 2014 shows the water level at about L3. The next available image of Nov. 2, 2014 (Band 8) shows stranded icebergs in far end where there was no water in June 19 image, and a stream channel cutting through far end to the westernmost part of the main body. So sometime between June and Nov., water had increased to near L2, thereby covering far end as well so that icebergs could drift into them. Again the water level change pattern was the same as those before GLOFs 12 and 15. The aerial survey of Dec. 2 confirms this GLOF with stranded icebergs, with the water level near L3.

Subsequent images of Jan. 21 and Mar. 26, 2015 show gradual melting of stranded icebergs and the extension of the stream channel on the lake floor toward the middle section of the main body, suggesting (renewed?) draining of water through the subglacial channel. In Mar. 26, 2015 image, the lake floor of the western half of the main body appears exposed with a patch of open-water in the middle section, while some stranded icebergs still remained there. It was only Apr. 11 image when increasing water was recognized (ca. 2/3 of main body) and the full recovery to L3 was recognized on the next available image of Nov. 5, 2015 image.

GLOF (18): Captured in Mar. 12, 2016 image. The color of the western half of the lake on Mar. 12, 2016 image is brown, totally different from the previous images (Fig. 9A1). Upon a close examination of Landsat B8 image, it was found that the brown area was completely drained of water, with some stranded icebergs on the westernmost side, and the exposed lake floor in the middle section that had become terraces of two or more levels by stream erosions (Fig. 9A2). Since the lake floor was terraced, the drain of water was not one rush, but probably intermittent with a pause or two. So the occurrence of a very large GLOF is supposed.

The recovery of water was slow and it was Sept. 4 image when open water was recognized in the middle section while the rest (eastern part) was covered with icebergs in very low water, well below L3. The recovery to about L3 was recognized on the image of Oct. 22, 2016. GLOF (19): Captured in Mar. 31, 2017 image. A similar lake state can be recognized in this image of one year later. In Fig. 9B1 image, the brown area appears as though dividing the lake into two parts; however, Landsat B8 (Fig. 9B2) revealed that the western side is covered with stranded icebergs without water. It appears this GLOF was also large.

A hydrological station set up at the beginning of Lower Río Huemules (see Fig. 3C) by Univ. of Bristol registered a peak flow of 2,600 m$^3$s$^{-1}$ on Mar. 28 from the base flow of ca. 100 m$^3$s$^{-1}$, thereby catching this GLOF (O’Kuinghttons, 2019). On the next image of Apr. 16, the lake condition was similar to Mar. 12, and it was May 18 image when the lake floor was covered in water at slightly less than L3, along with the extensive iceberg cover. It was Dec. 12, 2017 image when the water level was recovered to near L3.

5.2 Summary of GLOFs

Table 2 summarizes the 19 GLOFs along with water levels that were captured/inferred between 1985 and 2017 (33 years). This number may be sort of a minimum, be-

![Fig. 9. Two large GLOFs, which had completely exposed the lake floor. With color images (A1 & B1, pixel size, 30 m), it was difficult to interpret lake conditions properly; only with the aid of Band 8 (A2 & B2, pixel size, 15 m), it was possible to interpret the detail of topography and lake conditions.](image-url)
cause we could have missed a few GLOFs in certain years for which available data were scarce or none. Even with this limitation, the occurrence interval was less than one to a little more than three years; the shortest being four months. If we exclude two periods for which no data was available, the frequency is about once every 14 months on average. Incidentally, five out of the 19 GLOFs were captured with aerial survey photographs. In addition, they confirmed two GLOFs of satellite image interpretation. An increase in the water level before a GLOF was recognized for GLOFs 12, 15 and 17.

As for the occurrence month of the GLOFs, it could be up to about three months before the detected month, because of image intervals between the normal and the drained lake conditions. Figure 10 shows the detected month of the GLOFs, indicating that these GLOFs occurred mostly during late summer to early fall, with some at late spring. Since, as shown in Fig. 5, the number of data in each month used for this study is not so biased, we can conclude that since 1974, the GLOFs at LdlT have occurred mainly in late summer to early fall, followed by late spring.

5.3 Notable changes in Laguna after the latest GLOF

It is noteworthy that from Feb. 14, 2018 image through Feb. 28, 2020 image for two years, there has been almost no iceberg in the lake with water levels at slightly less than L3. Only on some images, few icebergs could be recognized, indicating that calving activity of the glacier at the lakeside has diminished greatly. Glaciar Steffen used to flow into LdlT with a snout at which calving was very active as shown in Fig. 6. However, due to glacier thinning this snout receded and the glacier ceased to flow into the lake by 2008–2010; thereby the lakeside of the glacier had become a cliff rather than a calving snout.

Starting around the beginning of 2018, several spots of water pools in the trough along the sidewall of the glacier can be recognized on the way down to Laguna El Bolsón, which from its water color appears subglacially connected with proglacial lake, Lago Steffen, since about 2013 or so, due to glacier retreat. In Oct. 15, 2019 image, we can recognize the stream inlet at the southeastern end of the lake, and down below it the trough that has become broader and more conspicuous, suggesting more or less continuous water in it. This change probably accounts for the stable water level since 2018, and thereby the prospect of further GLOF has probably diminished considerably.

5.4 GLOFs at Laguna El Bolsón and No-name Lake – ancillary data

In the course of interpretation, it was found on some satellite images that Laguna El Bolsón also had eight GLOFs between 1985 and 2008 (see Table 1). Aerial survey photographs did not cover this lake. Of these, six are certain, one probable, and one uncertain because the immediate previous image was clouded. Incidentally, five GLOFs of Laguna El Bolsón coincided with GLOFs of LdlT, while remaining three independently occurred.

GLOFs at no-name lake were also checked and nine were inferred between 1979 and 2008 (see Table 1). Of these only one GLOF coincided with that of LdlT (and Laguna El Bolsón as well). This lake consists of three basins of different levels and after GLOFs the water level dropped distinctively, similar to LdlT, with the upper two basins now dry (see Fig. 3C). In Table 1, S (size) 1 means all three basins were filled with water; S2 indicates that the upper basin was dry (see Fig. 3A; only the middle basin was with water); and S3 means the upper and the middle basins were dry, and only the lowest (main) basin was filled with water.

6. GLOFs in relation to glacier conditions and lake changes

Glaciar Steffen retreated roughly 6 km during this
study period. So the glacier had become thinner as well. Consequently, the glacier side protruding into the laguna as a wasting snout had receded. The water level has also lowered, making the lake surface area smaller. We checked water levels at the full stage by comparing successive images, and recognized three distinctive relatively stable stages. The initial stage (1980) was denoted L1 (see Fig. 6A). On the 1990 aerial survey image, an elongated arm-like hump (peninsula in Fig. 6C, also Fig. 2A) was visible above water even at the full water stage, which almost separated the lake into two bodies. Subsequently, this water level was taken as L2. On Dec. 2009 image, the upper 1/3 (far end) of the lake was dried up (Fig. 6D) and water was only in the lower basin (main body), which was denoted L3. Figure 11 shows these distinctive stages. The water levels naturally fluctuated between these stages.

LdIT has one steady, principal source for lake water: a stream that originates from a small upper lake that is fed with snow/ice melting as well as rainfall (see Fig. 3A). In addition, there are eight small (ephemeral?) streams coming down from lakeside slopes. Adding to these obvious sources, sub/englacial streams from Glaciar Steffen and snow/glacier-ice melting contribute as well. These sources control how fast the lake would be filled up after a GLOF. The shortest interval of recovery was just one month, while longer ones took as long as nearly nine months.

There was no recognizable surface water drainage from LdIT until recently; yet, between GLOFs the water level was more or less stable, indicating that the drainage was through subglacial channel(s). Then, the water level was probably determined by the balance between the water head of the lake and the size of the subglacial channel that was primarily controlled by the thickness of the overburden glacier. When the glacier was thick, subglacial channels were smaller, thereby draining a smaller amount of lake water and maintaining a higher water level. Therefore, these successive lowering of the water level at a full stage can be interpreted as adjusting to glacier thinning.

7. Likely Cause of GLOFs

The relatively stable water level between successive GLOFs indicates the equilibrium between the water supply and the drainage. Then what caused the disruption of the equilibrium; heavy rainfall, rapid snow/ice melting from lakeside slopes by unusually warm air temperatures, or sudden supply of glacier-melt water from Glacier Steffen, or a combination of these? Aniya has flown 21 times over HPN between 1986 and 2014 for glacier variation studies (Aniya, 2017). Of these he succeeded to take photographs of LdIT only 13 times: even those were very often under overcast and/or turbulent clouds. Other eight times, heavy clouds (often with rain) blocked the view completely, even though the weather in the northern part of HPN was good enough for aerial surveys. Therefore, it appears reasonable to suppose that heavy rainfalls are the most likely cause of GLOFs, which were probably often combined with rapid snow/ice melting by warm air temperatures, especially if they occurred in late summer/early fall. The aerial survey pilot, Roberto León, always told about the bad weather in the Glaciar Steffen area whenever we encountered dark clouds, from his experience of commercial flights over HPN for more than 40 years since the late 1970s.

8. Summary and Concluding Remarks

Utilizing various remote sensing images of 150 dates between 1974 and 2020, the occurrence of GLOFs at Laguna de los Témpanos, a glacier-dammed side lake of Glaciar Steffen, Hielo Patagónico Norte, were captured/inferred. In the period of about 45 years, 19 GLOFs were identified from manual interpretation of these images: 16 for certain (captured) and three inferred. Excluding two periods (1980‐84 and 1991‐996) when no image was available, a GLOF occurred on average at ca. every 14 months. Many occurred in late summer to early fall, with a few in late spring; however, one GLOF was inferred in winter. Most GLOFs were probably caused by heavy rainfalls, which may have been often accompanied with excessive snow/ice melting due to unusually warm air temperatures.

Collaborating with Univ. of Bristol, DGA started monitoring the flow of Lower Río Huemules in Nov. 2019 that drains Lago Steffen, with which to capture GLOFs that may affect the downstream area. The monitoring
station has three possible sources of GLOFs: (1) Laguna de los Témpanos; (2) no name lake; and (3) side lake of Glaciar HPN4. Laguna El Bolsón had GLOFs in the past, but it is no longer a threat because it has become part of Lago Steffen by now. A GLOF from Glaciar HPN4 directly affects local ranchers before reaching the monitoring station. As for LdlT, it appears that the prospect of another GLOF has greatly diminished by now because a continuous surface (or shallow subsurface) stream channel has opened along the sidewall. As Glaciar Steffen continues to retreat with thinning, the no-name lake may start causing GLOFs more frequently, which will be the likely origin of a GLOF from Glaciar Steffen.

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