Anonymous Referee #1

General comments

Understanding the links between climate, glaciers and hydrology in high mountain area is a growing and very important topic. This paper builds on other work by this group. There is potentially an interesting paper in here, which is novel and might lead the way to demonstrating how the changing size of ponds in mountainous regions that are not in immediate contact with ice but which contain glaciers in their catchments might be used to infer spatial and temporal trends in climate (precipitation, temperature, evaporation, glacier melt). The paper uses a statistical approach to the problem and the authors are to be commended for such a detailed analysis. Eventually one might imagine being able to use perhaps a more robust physically based approach, similar to that used by, e.g., Leclercq & Oerlemans, to reconstruct climate from glacier length fluctuations. This paper could be a useful stepping stone in that direction. [P.W. Leclercq, J. Oerlemans 2012. Global and hemispheric temperature reconstruction from glacier length fluctuations Climate Dynamics 38 1065-1079, doi: 10.1007/s00382-011-1145-7]

Comment: we thanks the reviewer for the detailed revision of the paper. Generally, we hope that the readability is now improved and the key messages are emerged.

I see 4 key problems with the paper as it currently stands although I hope the authors might be able to deal with these, re-orientate, focus, correct things and rewrite the paper so that it provides a better contribution to the cryospheric sciences.

1. The aim, objectives and overall general methodology of the paper are not articulated towards the beginning of the paper, so that the reader [or this one at least] remains generally confused about what is being done and, more importantly, why things are being done and has to gradually piece things together while reading the paper.

Comment: more specific objectives have been inserted. The overall general methodology has been described in a specific new paragraph.

2. The paper is very involved and dense with lots of different levels of analyses, and lacks a clear focus of what it is trying to achieve. I'd encourage the authors to work out what the key take home messages of the paper are and to present only the material that leads to those conclusions.

Comment: we hope that after having described the overall methodology the reasons behind the analyses could be emerged.

3. The paper is hard to follow, with sufficient ambiguities, inconsistencies, apparent contradictions and small lapses in grammar and syntax, to justify rewriting quite large sections, especially the Abstract and Conclusions. It would benefit from running through a spell checker and from proof reading by a native English speaker if at all possible.

Comment: the abstract and conclusion have been largely rewritten. Considering we are not native English speaker, before submitting the last version of the paper, we provided to submit the paper to the

American Journal Expert for the proof reading. An expensive certificate was released. We hope the kind help of the three reviewers could have deleted the grammar and syntax errors.

4. I query some of the scientific assumptions / results

Comment: please read the answers reported below.

I elaborate on these points below.

Specific comments

1. The paper needs to articulate what the overall aims, objectives and methodology are. Currently, all we have on lines 83-86 is this: “This contribution examines the surface area changes of unconnected glacial ponds on the south side of Mt. Everest (an example is shown in Figure 1) during the last fifty years to evaluate whether they act as potential indicators of changes in the main components of the hydrological cycle (precipitation, glacier melting, and evapotranspiration) at high elevations in the Himalayan range.” Even as a general aim, this is rather vague. This needs tightening up, we need to be given some more specific objectives and told an overall methodology of how these objectives will be achieved. Currently, after these 5 lines, we have an introduction to the field area (Section 2) followed by a detailed section on Data and Methods (Section 3). But when reading Section 3, we don’t know why we’re being told about the climate data, digitization of ponds, calculation of glacier surface area and melt, derivation of morphological parameters , etc. For example, on line 203 you refer to “degree of correlation among the data” But we have no idea what precise data you’re talking about, nor why you want to correlate them.

Comment: More specific objectives have been inserted. The overall general methodology has been described.

2. The paper is very detailed, convoluted and involved, with a lot of separate components:

i) looking at correlations between reanalysis climate data and ground climate data after 1994 to see which reanalysis products may most reliably be used to infer climate in the region prior to 1994;

ii) generating other proxy data ultimately from the climate data, notably evapotranspiration and glacier melt (using a simple temperature index model);

iii) calculating glacier shrinkage and “unconnected pond” area shrinkage (where “unconnected ponds” refer to those not physically in contact with glacier ice) for 6 time periods since 1963 from a map (1963) and satellite imagery (1992, 2000, 2008, 2011,2013);

iv) performing a suite of non-parametric statistical tests to investigate whether trends in pond area, glacier area, climate & climate derivatives (evapotranspiration and glacier melt) are statistically significant in different time periods (e.g. the whole period 1963-2013 or sub-periods 1963-1992, 1992-2013); between different types of unconnected pond (those whose upstream catchment is > 10% or < 10% glacierised) or for different “morphological boundary conditions” (e.g. elevation, aspect);

v) performing a Principal Components Analysis on the variables to investigate climate drivers of pond area change.

Furthermore, some of the analysis is done on the full set of 64 ponds, and some is done on a sub-set of 10 ponds. Similarly, some of the analysis splits the time period into two (1963-1992 and 1992-2013) and some splits the time period into three (1963-1992, 1992-2000 and 2000-2013). All in all, the reader gets rather bogged down in the detailed analysis and loses a sense of the big picture.

Comment: we thanks the reviewer for this tentative of summary. We used this scheme for generating a paragraph related to the overall methodology.

3. Because the paper has many different strands, it is particularly important to have a very clear abstract and conclusion. Reading the abstract, it is not at all clear what the key take home messages of the work are. Unfortunately, having ploughed my way through the paper and emerged somewhat exhausted from the final sentence of the conclusions, I was still rather unsure what the key conclusions were.

Lines 369-371 tell us that during the monsoon period the “unconnected ponds” declined in area (by 10%). Fine, this is clear.

Lines 371-372 tell us that this is due to a drop in precipitation and a decrease in maximum temperature (and therefore glacier melt). Also quite clear.

Then it gets confusing. Lines 372-373 tell us that “the continued shrinkage of glaciers likely due to the effects of less precipitation than an increase in temperature”. This is not a grammatically correct sentence but I assume the authors mean that “the continued shrinkage of glaciers [is] likely due to the effects of less precipitation [rather] than an increase in temperature.” I don’t recall where in the paper this was discussed. The paper involved a statistical analysis explaining variation in pond area not glacier area. By “continued shrinkage” I assume the authors are referring to the actual shrinkage that occurred in the past, and are not speculating about shrinkage that may or may not occur in the near future? Note how we’re told that pond area shrinkage is due to a “decrease in maximum temperatures” but that glacier shrinkage is likely not due to an “increase in temperature”. It’s a little ambiguous whether temperatures have, in fact, increased or decreased over the time period. On line 280 we’re told that the mean temperature decreased, although not significantly. On line 281 we’re told that maximum temperatures decreased. On line 282 we’re told that minimum temperatures increased. Actually we’re told that the increase in the minimum temperature “balanced” the decrease in the maximum temperature, although this isn’t strictly correct as then, I assume, the mean would stay exactly the same. Is it really the case that mean temperature decreased? Figure 4a, shows that the mean temperature increased over the time period!

Comment: we provided to underline the key messages; the main conclusions have been rewritten and clarified; Figure 4a shows the trend of the mean annual temperature (which is increasing). Lines from 280 to 282, as specified in the text, report the trends during the monsoon period (the mean temp is slightly decreasing). However, in general, we accept the general suggestion that the discussion is too much convoluted. Therefore our efforts were devoted to simply the discussion.

Section 4.3 is virtually impossible to follow. It spans just a side of A4 during which we’re asked to study Table 4, then Table 2, then Fig SI3, Table 3 and Figure 4. That’s just the first short paragraph. We then need to look at Fig 5, SI4 and SI5, Fig 6a and SI4, back to 6b, back to SI4, then again, and again, then flip back to 2b. We then have to jump forward again to 6b, move to Table SI5, Figure 5, and Fig 5 again, Table 4, Figure 6 and finally back to Table 4.

I was concerned throughout this section that I was moving the pages back and forth so much that I’d accidentally end up making some sort of 3D origami animal. I’d encourage the authors to cut down on the Figures and Tables and discuss things in a way that doesn’t involve so much movement.

Comment: we tried to simply this section.

4-1. Can you explain better how melt is being derived for the glaciers? In lines 171-176, is it necessary to refer to the work of Salerno et al (2015) regarding the calculation of temperature at the mean elevation of each glacier? Is it not the case that the pyramid data are used together with a lapse rate (tell us what the lapse rate is) and the melt factor to calculate the melt across each elevation band (tell us what the band width is and what DEM is used) and that these are then summed for each glacier to calculate the melt to each glacier?

Correction: the text has been corrected according to the suggestion.

4-2. Given the way that you're calculating glacier melt, there will be huge autocorrelation between Tmax and Glacier melt. So it's not surprising that your correlation coefficients involving Tmax and Glacier melt are so similar. I'm therefore surprised by Fig 5 where you seem to show that glacier melt and Tmax are two strong independent variables contributing to the principle components. Have I understood this correctly?

Comment: The PCA shown in Figure 5 attempts to provide an overall overview of the relationships among the trends related to the potential drivers of change and the pond surface areas: glacier melt and precipitation, while evaporation is excluded. Following the suggestion Tmax probably needs to be removed to avoid that the reader could think that our aim is to show similarities between Tmax and melt (Tmax).

Correction: Tmax has been removed from the PCA.

4-3. Table SI5. Do I understand this analysis correctly? For each pond, are you only working with 14 data points? Is this sufficient to demonstrate every variable is normally distributed so that you can use the parametric correlation test (as you state you do lines 203-5)

Answer: Yes the interpretation is correct. We used the annual ponds surface area for the 2000-2013 period and we compared the area with the correspondent driver of change (14 comparisons). The number of years considered in the analysis is given by the availability of satellite imagery. Given a not so much elevated number of comparisons, however, we need considered that the same analysis is repeated for (corroborated by) 10 lakes which present very similar relationships with the selected variables. No other data is available for the past.

Moreover, to test the normality of the comparisons there is not a minimum number of data. Razali and Waph, 2011 demonstrate that the Shapiro-Wilk test (used in this paper) presents the highest power for small sample size (analyzing sample size ranging from 10 to 2000).

Correction: we wrote in the text that Razali and Waph, 2011 demonstrate that the Shapiro-Wilk test presents the highest power for small sample size.

4-4.k On line 100 you tell us that the precipitation has a specific gradient. Given that you go to all the trouble of calculating glacier melt using a lapse rate, and given the importance of precipitation for your analysis, why do you not use this lapse rate in the calculation of precipitation from the pyramid station when analysing the precipitation relevant to the different ponds? The ponds are at different elevations, and the catchments above them have different elevation ranges (and hypsometries). The pptn gradient above 2500m is non-linear. All these things will mean the precipitation falling above the lakes in your analysis will be very different for the different lakes.

Comment: In this analysis we are not interested in the absolute (annual cumulate) value of precipitation on each specific ponds. If it was this case, as suggested by the reviewer, applying the precipitation gradient analyzed by Salerno et al., 2015**,** we could be able to estimate it. In order to analyze the possible relationships between pond surface area changes and precipitation variations we need to compare the just the trends of these variables. Therefore, 10 ponds were selected and their surface areas tracked yearly. For each pond, the series of annual surface areas has been compared vs annual precipitation series. We carried out the same procedure for the glacier melt. The assumption behind this analysis is that the precipitation trend along the gradient and along the valleys is the same. This is a reasonable assumption/limitation due to the fact that land precipitation series at this elevation are so rare. However, the last paragraph aims to investigate this assumption: the result is that there is not an altitudinal or spatial pattern.

Correction: the assumption has been specified in the text, as well as, its analysis in the last paragraph.

4-5. Section 3.5. I'd like to see a better articulation of the sources of error and how they were calculated for this study. First you imply error is a function of linear error and perimeter. Then you refer to a linear resolution error and a co-registration error. This all needs explaining more carefully and precisely.

Answer: we applied this procedures in other papers, probably here was too much hermetic.

Correction: the paragraph has been rewritten.

Technical corrections; typing errors, etc.

There are a lot and I don't have time to give them all. Below I give some of the key ones. Numbers refer to line numbers.

14. "unconnected ponds" This is defined in the paper but the abstract should be intelligible on its own. Explain what is meant here.

Answer: done

15. "We infer an: : :"

Answer: done

17-19. Rewrite. I think this should be at least 2 sentences. Meaning not at all clear.

Answer: done

31. glacier

Answer: done

44. ": : :increases in the evaporation / precipitation ratio: : :" [refer to evaporation / precipitation ratio also above on line 41 to be consistent]

Answer: done

51-53. Vague. Rewrite.

Answer: done

61. What do you mean by "these lakes"? Just proglacial lakes or all 3 categories?

Answer: done

64. "decidedly similar". To what?

Answer: done

67 opening

Answer: done

67. Ref to englacial conduits is relevant to supraglacial lakes but not proglacial.

Answer: done

54-72. Para could be shorter with tighter articulation of key relevant points.

Answer: done

73 A valuable

Answer: done

75 glacierized not glaciated.

Answer: done

75-6. “: : :region has the largest number of lakes in: : :”

Answer: done

78. reduced dimensions. Do you mean “relatively small size”?

Answer: done

80 “: : :make them especially: : :”

Answer: done

78-82. This sentence is confusing. Is it their small size that’s relevant or the low water volumes and high surface area to depth ratios. You start the sentence implying it’s the first, and end saying it’s the 2nd & 3rd attribute that’s important. Rewrite.

79. Can you check the entire document? Here you define lakes and ponds according to size. But earlier and later you use the terms interchangeably and (according to this definition) sometimes incorrectly. You need consistency. Define at the very start of the paper. You could use “water bodies” if you want a generic term.

Answer: done

89. Do you need the abbreviation “CH”? Do you use this term again?

Answer: done

93-4. “: : :of the territory contains temperate glaciers and less than 10% is forested.”

Answer: done

97. “For the last 20 years” Avoid phrases like this. Later you refer to “the last decade” I think too. These phrases are ambiguous. The last 20 years means 1996-2016 to me, but actually pyramid station has been operating since 1994. Always state the precise dates to avoid confusion.

Answer: done

99 “: : :precipitation falls between June and Sept: : :”

Answer: done

102. “: : :large glaciers in the SNP are: : :”

Answer: done

103. Delete “In the SNP”

Answer: done

109. “realised the complete cadaster” What does this mean?

Answer: done

110. “univocal” suggest change to “unique”

Answer: done

113 “: : :Everest after the: : :”

Answer: done

118. check grammer here.

Answer: done

122 “: : :and the monthly cumulated: : :”

Answer: done

123 delete “recently”

Answer: done

125. Why evapotranspiration not also calculated for 1994-2002?

Answer: done

126. “recorded continuously” Is this a monthly time-series too? Or calculated more frequently and averaged?

Answer: done

130. You casually say “before the 1990s” but you should say before 1994. See other instances of this throughout the paper,

Answer: done

143. “intermediate periods” is confusing. Why not just say “scenes”?

Answer: done

146. “environments” is completely the wrong word. Do you mean “biases?

Answer: done

147-8 “For the 2000 – 2013 period, due to the wider availability of satellite imagery, ten ponds were: : :”

Answer: done

155. Semester is the wrong word

Answer: done

158. “these characteristics” What characteristics are you talking about here?

Answer: done

161. “The acceleration disappears” This is wrong. No acceleration has been discussed

Answer: done

previously. Do you mean that there is a decrease in area?

Answer: done

167. “pond basins” This is a bit unclear. You’re referring to the basins (or catchments) containing? Or Upsteam of? The ponds.

Answer: done

178. remove the phrase “such”. Just list all the parameters you use.

Answer: done

180-181. Vertical accuracy greater than horizontal? Are you sure?

Answer: yes we have checked, please refer to Tachikawa et al., 2011.

185. Is this EM also used for defining the elevation bands for the calculation of melt? Should have been referred to earlier.

Answer: done

187. Map not maps.

Answer: done

194. morphological? Or best to use morphometric for consistency.

Answer: done

217 pond size

Answer: done

221 before 1994

Answer: done

223. Why are seasonal data shown for temperature but not precipitation in Table 1?

Answer: during the monsoon, as described in the text, the precipitation are the 90% of the annual cumulated amount. Therefore outside the summer, during the pre and post monsoon season, the seasonal cumulated amounts are often equal to zero. Thus the parametric statistic does not make sense. We decided to present the data aggregated at annual level, as compromise.

235. Are the 170 ponds all from the SNP region?

Answer: done

237. delete "prefer to"

Answer: done

238. "environments"? Do you mean ponds? Water bodies?

Answer: done

235-242. You don't refer to columns 1 & 2 in Table 2. Are these redundant? Remove them?

Answer: we think that the two columns are important and cannot be removed because they point out the different features of the two groups of data.

248. "glacier surface differences" ? Do you mean glacier surface area changes?

Answer: done

250. Further loss of area (-18%) is ambiguous. It's not an extra 18% loss since 2011.

Answer: done

251. Poor grammer

Answer: done

255 "Having analysed: : :"

Answer: done

257. delete "Usually and"

Answer: done

258. "this inbound component" Do you mean glacier melt input?

Answer: done

259-264. Vague, confusing and poor English here.

Answer: done

302. don't need the word "monsoon" at the end of this line with reference to temperature here do you? All these variables are for the monsoon right?

Answer: done

303 "relevant" is the wrong word

Answer: done

307 "sensible factor" is incorrect.

Answer: done

322 ": : :ponds were in catchments with a glacier: : :"

Answer: done

323-3. Needs writing.

Answer: done

324-5. Why are you calling ponds in catchments that are <10% glacierised "ponds without glaciers"? Why not just call them "ponds in catchments that are <10% glacierised"?

Answer: because we need to identify this group of data a lot of times, using “ponds-with-glaciers” this need is simplified.

336. “during the intermediate periods” is confusing. Do you mean in the 1st, 2nd and 3rd part of the 1963-2013 period?

Answer: done

344 “: : :glaciers had significantly: : :”

Answer: done

344-5. Rewrite.

Answer: done

359. “: : :tracing of pond surface area”. The word “tracing is not quite correct” Check entire document as this has been used a few places. The word “measuring” would be better.

Answer: done

370 and 374. First you talk about “over the last 50 years” and then “over the last decade”. Why not first discuss the full conclusions of the long term 1963-2013 analysis and then talk about the full conclusions associated with the 2003-2013 work. As stated earlier, I suggest you avoid these phrases.

Answer: done

394-405. This part of the conclusions seems rather weak and not a good place to end.

Answer: done

Table 2. Lakes & Ponds seem to be used interchangeably here. In the Table heading, explain the 3 columns. And is this the sample of 64 or 10 ponds shown here? Median is written twice in the column 3 heading. And in the final column the maximum area for pond area should read 56.3 not 56.2.

Answer: done

Figure 2a. I may be wrong but I think it’s only once we look at this Figure that we learn that some ponds do not have glaciers in them. There are 10 selected ponds on this Figure but in the text referring to it I think you said you selected 64 ponds.

Answer: Probably there is misunderstanding. To avoid further problems, we avoided in the new text to use the verb “selection” for the entire population of ponds considered in this work (64 ponds). From this population 10 ponds were selected…. Moreover in the caption the number of ponds is added.

Fig 4c and d. Y axis label should read “fraction” not “%” or the numbers should be multiplied by 100. First data point needs to be plotted against 1963 not 1962!

Answer: done

Fig 7. Blue dots depicting the mean in the box plots are barely legible, esp. in the blue 2000-13 Figure c. Is there some distortion as the circles look like ovals?

Answer: done

Fig 8. Heading is wrong.

Answer: done

Fig 9. Change colour scheme as blue dots are invisible.

Answer: done

Banerjee (Referee)

This paper reports on the surface area changes of unconnected glacial ponds in the south of Mt Everest during the period 1962 to 2013 using maps and satellite images. This time-series data is analysed to identify the drivers of the change using statistical analysis of the correlations with available meteorological data. However, the present draft may greatly benefit from a more careful analysis of this very interesting data set, and also a slightly more systematic description of the methodological details.

Comment: we thanks the reviewer for the revision. Generally, we hope to have suitably followed the suggestion received in particular in relation to the new analysis and the more detailed methodology.

My major concerns are as follows:

1) While it has been argued at the outset rather briefly that lakes and ponds are sensitive indicators of climate change, this point demands more serious consideration. The cited references of Beniston et al, 2006 do not seem to discuss lake/pond, while the other referred article by Burasachi et al, 2005 does not include a relevant discussion of climate sensitivity of the lake/pond area and particularly of the response time scales.

Answer: Thanks for the suggestion. The references are wrong as suggested by the reviewer.

Correction: the right reference is Smol and Douglas, 2007. PNAS

The temporal variation of the surface area of a given pond must be controlled by 1) the balance between water in and out - therefore by the climate, and 2) the bathymetry. But, any attempt to infer climate signal from sparse point measurements of such a time series has to take into account the relevant time-scales associated with response to the fluctuating climate variables.

Answer: we hope having followed all revision provided by reviewers, the suggestion provided by the reviewed could be suitably addressed.

For example in figure 3, some of the biggest ponds/lakes (eg LCN77, LCN24) show large (_5n%) increase/decrease in their area in a month's time, indicating a strong control of high frequency changes of the climate variables. For the rest of the ponds which are even smaller in size, these high frequency noise would presumably be even larger. How can this sparse time series with high frequency 'noise' that is of similar magnitude as the low frequency signal (_10n% change over 50 years), possibly be used to infer low frequency changes of the climate? In this context it may be noted that glacier length fluctuations can be inverted for temperature change as their slow response makes them immune to high frequency noise.

Answer: Figure 3 shows that some single pond presents singularly an Oct-Dec dispersion of around 5%. However, the same figure points out that just averaging this information on a population only a little bit larger, the dispersion between October and December becomes almost zero (1%). Climatic inferences from the behavior of ponds population surely needs to consider the widest number of ponds as possible in order to reduce the dispersion due to the local conditions of each lake. The same approach is used also in dendrochronology where a lot of cores are sampled and analysed.

Correction: the suggestion of the reviewer has been considered carefully inserting these concepts in the new text.

Similar large fluctuations are also seen in the annual rates reported in Table 3: During 1992 to 2011, rates are very small or insignificant and then there is a very large (1 to 2 order of magnitude larger than the background) spike during 2011-2013. In fact this spike dominates the mean. Is this a signal from a particular short-lived event picked up due to sparse sampling or a real climate change signal? Surprisingly, no such sharp changes are seen in the precipitation or glacier melt data during 2011-2013 as presented here. This needs to be considered very very carefully before accepting the interpretation offered by the authors here.
Further, this issue of high frequency noise can not be overcome simply by averaging over a large set of ponds from the same region, as they are all seeing a strongly correlated noise due to their spatial proximity. And of course, practical limitations like unavailability of suitable images etc would prevent a higher temporal resolution.

Answer: In relation to the abrupt change observed by the reviewer (-7% vs -25%,i.e., -18%), we can start observing Table SI2. The resolution of the two images is the same. Moreover giving a look at fig. 8 Fig. 8. Probably here it looks much less strange. From 1992 to 2011 the decreasing is 20% (the computation can be done also from the table 3 from +13% to -7%). Surely -18% in two years is a lot, but in in line with the decreasing of precipitation observed since the early '90s (Fig. 8). Furthermore the behavior of surface are change has been observed significantly correlated with precipitation.

Correction: this concept has been discussed in the text.

2) While the authors have employed a careful statistical methods to derive their conclusion regarding the climate signal, some simple physical considerations might strengthen their analysis. For example, the climate data (reanalysis/gridded) used is from the grid point that is closest to the Pyramid station. Would not be better to use the grid point closest to a given pond for analysing the area change data for that particular pond? This choice might have led to serious biases in the results as pointed out below.

Answer: Unfortunately, the grid resolution for Era Interim and GPCC does not allow to use the grid point closest to a given pond, because this point is common to all points and at same time it is the same grid node used in the comparison with the land wheatear station. We agree with the reviewer. In fact in the introduction we wrote: "their use for climate change impact studies at the synoptic scale must be performed with caution due to the absence of weather stations across the overall region, which limits the ability to perform land-based evaluations of these products". The added value of this work to have carried out a land-based evaluation of these products. Probably, the comparison presented in this work in the unique case where this comparison has been done for a so long period of time in the overall Himalayan range due to other long time climatic series do not exist in the region at so high elevation.

Moreover the comparison between ponds surface area and climatic variables is done with Pyramid data. To avoid further misunderstanding we tried to clarified these concept as specified below.

Correction: the method section has been rewritten to clarify the methodological approach followed in the paper: Moreover a map of Nepal showing the location of all 64 considered ponds and the grid/reanalysis nodes has been inserted in the Supplementary Material. In this way it is clear the comparison between the resolution of grid/reanalysis products and the distribution of the 64 considered lakes.

All the 'ponds with glaciers' (LCN 24,9,3,68) that show significant correlation with glacier-melt, are located in the Khumbu valley, within may be five km of the Pyramid station. So, how can one be sure about the controlling factor behind this pattern - Is it the glacier cover as claimed, or it is just the proximity of the grid point? In fact, data from LCN11 in the same valley has a relatively large correlation coefficient (_0.5, though probably not significant) with calculated glacier melt, while far-away ‘ponds with glaciers’ (LCN 76 and 77) has small (0.2-0.3) correlation with the glacier melt. This requires explanation.

Answer: please see the answer above.

Incidentally, there seem to be some ambiguity regarding the definition of two pond classes: with and without glaciers. Table 3 uses 5n% as a threshold; text gives a threshold of 10n%; Table 4 says LCN3 has 30n% glacier cover, while Figure 3 claims LCN3 is a pond without glacier. These differences need to be clarified and the sensitivity of the conclusions to this choice of threshold value may be discussed.

Answer: the threshold of 5% reported in the heading of Table is a mistake. The second suggestion is not clear when the reviewer says: “while Figure 3 claims LCN3 is a pond without glacier”… we do not know where this is discussed.

Correction: Table 3 has been corrected.

Also, the authors may discuss the spatial pattern of changes as seen in figure 7. For example, looking at this figure it seems statistically significant differences may emerge in trends from the set of ponds near Ngzumpa glacier (Gokyo valley) and Khumbu glacier (Khumbu valley), irrespective of glacier cover extent. If so, then what is the relevant control, having more than 5n% glacier area or the ponds being in the same valley?

Answer: According to the suggestion we tested the significance of possible differences of surface area changes (1992-2013 period) among ponds located in different river basins. Moreover we tested the significance of possible differences of surface area changes among ponds with different glacier cover.

Correction: a new figure in the Supplementary Material has been added showing box-plots representing surface area changes of ponds located in different river basins. A parametric test (ANOVA) shows no significant difference among the different river basins. The same Figure reports box-plots representing surface area changes among ponds with different glacier cover. A parametric test (ANOVA) shows in this case significant differences between ponds with different glacier cover within basins.

In addition, the ponds with glacier cover seem to be larger (table 2). Could it be that the difference in shrinkage are correlated with pond size? A possibly larger intrinsic climate sensitivity of the smaller ponds could be an alternate explanation for the differences seen between the signal from the two class. This possibility needs to be ruled out as well to justify the conclusions reached.

Answer: According to the suggestion we tested the significance of possible differences of surface area changes (1992-2013 period) among ponds with different size.

Correction: a new figure in the Supplementary Material has been added showing box-plots representing surface area changes among ponds with different size. A parametric test (ANOVA) shows no significant difference.

Other comments:

1) Many of figures presented needs to be carefully redone, checking the axes labels for missing units, choosing proper x and y range so that all data-points are seen, putting legends that are missing, giving complete and accurate plot captions etc. Some examples: i) what are the units of vertical scales in figure 3, 4a, 4b, 6a, ... ii) Figure 3 horizontal axis: tics read 06,07,07,08,... . Also horizontal separation of the points

are inconsistent with time stamps given in table SI4. iii) what are the criteria for the selecting the ponds whose records are presented in figure 6? why LCN 24 is not shown? iv) What are the filled and unfilled boxes in figure 8a? v) similarly colored solid lines used for LCN 139, 11, 77, 76 vi) indistinguishable colors for various p values used in Fig 7a vii) error bars need be added in 4c, 4d

Answer: Following the comments received by all the reviewers all figures and tables have been checked and redone.

Correction: i) the units have been written in the caption; ii) checked and redone; iii) there was an error, LCN24 has been inserted; iv) the legend has been added; v) corrected; vi) corrected; vii) error bars have been added

2) In all these unconnected glacial ponds, particularly those with significant glacier coverage in their basin, could it be checked if the corresponding glacier drains into the pond?

Answer: The hydrological basins have been digitalized using ArcGIS® hydrology tools as carried out by other authors (e.g., Pathak et al., 2013), each basin has been then visually checked.

Correction: this methodological aspect has been inserted.

3) As acknowledged by the authors the study area is full of debris covered glaciers. The applicability of the glacier melt model used for debris covered glacier must be discussed.

Answer: The glaciers within the pond basins are not debris covered. In this region debris covered glaciers are usually glaciers of a certain size with a developed flat ablation area. In all considered pond basins, the glacier are very small, steep (31°), clings to the mountain peaks, without having developed debris covered ablation area.

Correction: following the suggestion of the reviewer we specified in the text these features of glaciers within the pond basins.

4) It is known that SOI toposheets derived from winter time areal imagaries may contain significant errors. Some of the authors have published results using high resolution Corona KH4 images from 1962 in this area. Could the same images be used to verify the baseline 1962 extents of the ponds studied? Corona data should help in filliing the large time gap between 1962 and 1992.

Answer: We did not used only Corona image for digitalizing all 64 considered ponds because many of them in this image are snow-covered, but, we checked the quality of the map comparing the size of some ponds in both data sources.

Correction: "The topographic map of the Indian survey of 1963 (hereafter TISmap-63, scale 1:50,000) was used to complement the results achieved using the declassified Corona KH-4 (15 Dec 1962, spatial resolution 8 m). Thakuri et al., 2014 describe the co-registration and rectification procedures applied to the Corona KH-4 imagery. Unfortunately, on these satellite images many ponds are snow-covered. Therefore here the ponds surface area digitalized on TISmap-63. The accuracy of this map has been tested comparing the surface areas of 13 ponds digitalized on both data sources (favoring the cloud and shadow free ponds). Figure SI1 shows the proper correspondence of these comparisons. Furthermore, in order to estimate the mean bias associated with TISmap-63, we calculated the mean absolute error (MAE) (Willmott and Matsuura, 2005) between data, which resulted sufficiently low (3.6%), assuring in this way the accuracy of ponds surface area digitalized on TISmap-63."

5) Which climate data is used for the correlation studies? Pyramid data or reanalysis/ gridded products? If pyramid data is used then what is need of describing the others? If the gridded/reanalysis data are used then why not study the correlations for a period longer than the time-window of 2000-2013? What happens if the analysis is extended to all the ponds and for the duration of 1962-2013 using the GPCC precipitation data?

Answer: As described above the correlation studies have been done using the Pyramid data due to the continuous series of annual ponds surface area are available only for the 2000-2013 period and land meteorological data are available for 1994-2013 period. This explains, answering to the reviewer, why a time-window longer than 2000-2013 does not exist. Extending the analysis to the 1962-2013 is not possible because before 2000 we have just two years in which it was possible to digitalize the ponds (1963 and 1992).

Gridded/reanalysis data are not used here for correlation studies, but to obtain information, as written in the paper, on climatic trends in the antecedent period (before 1994). For this reason they have been compared with land data and the best products have been chosen.

Correction: following this suggestion and all other comments received in particular from reviewer 1 a need of clarification clearly emerges. Therefore the method section of the paper has been restructured and these concepts clarified.

6) The details of the computation of the mean pond area change and its uncertainty may be explicitly pointed out.

Answer: as even suggested by another reviewer the section related the uncertainty computation is too hermetic.

Correction: Therefore it has been rewritten.

7) While the authors do a good job of pointing the reader to the appropriate references, at times they may become distractions. For example while both the following cited references are great read in their own ritght, the citations here may be a bit far-fetched - "The current study is focused on the southern Koshi (KO) Basin, which is located in the eastern part of central Himalaya (CH) (Yao et al., 2012; Thakuri et al., 2014) (Fig. 2)". Also refer to Major comment (2) in this context.

Correction: we deleted Yao et al., 2012

8) How are the periods of 1992-2000, 2000-2008, 2008-2011 and 2011-2013 used in table 3 selected?

Answer: the periods have been selected in relation to the availability of satellite imagery

9) The conclusion has lengthy discussions about glacier changes and only a few words on the multi-temporal pond extent data described in the rest of the paper. The connection between the claimed signal from pond area change and glacier changes in the region is not explicitly mentioned as well.

Answer: the conclusions have been rewritten and the “connection” has been more explicitly mentioned

10) Some typographical errors: l 67 "opeping" l 122 : "montly comulated" l 194: morphologicalal

Answer: The suggestion has been followed

P. Buri (Referee)

Summary:
The authors investigate surface area changes of ponds over a period of fifty years (1963-2013) in a high-elevation Himalayan region using a topographic map (1963) as well as various Landsat satellite images (1992-2013). They relate the observed area changes to precipitation, temperature and glacier melt trends. The meteorological dataset used in this study is based both on a high-elevation weather station in the catchment (operating since the mid 1990's) and regional gridded and reanalysis data used to extend the record back in time to the 1960's, for which the authors have the first inventory of ponds (1963). The authors find a high sensitivity of ponds to a change in climate and try to use water bodies as proxies to detect behavior of precipitation and glacier melt.

General comments:

The paper is generally well written and structured in a clear way. However, I have some major issues regarding the methods applied that question partly your conclusions. In addressing these points (mentioned below) the paper may could be improved considerably and your original dataset and conclusions could be presented in a concise way and more scientific value could be added to your work. You relate changes in the climate to changes in the lake areas, as meteorological parameters are often represented in a highly limited way in remote and high-elevation regions. This is an interesting but also novel concept and addresses a relevant scientific question within the scope of the journal, as e.g. temperature and precipitation build the base for many research questions in various fields of the cryosphere. However, it is questionable if the approach used in this study can be used to reconstruct changes in the climate as lakes respond to many inputs as say yourself, so pond area is only an integrated variable (see point 4 below). The provided references appropriate and referenced in a helpful way in the text. At least one new study (published after submission of this manuscript, see major point 1 below) should be added. The statistical analysis and the results, respectively, are not fully clear everywhere in the manuscript (e.g. Table 3, see point 3 below). The methods description is rather complete, with methods explained either directly in the text or by referring the reader to further literature. They major issues to address are listed here:

> **Comment:** we thanks the reviewer for the revision of the paper. Generally, we hope that in the new version the key messages could emerge more clearly. All the suggestions have been followed. A new overall methodological section have been introduced.

Major issues:

1) Satellite images used for the analysis:
First, you need to indicate in the main text, including abstract, which satellite images you use (not only in the supplement) as this is a key information. You use Landsat (from Table 2 of supplement) and there might be an issue of too coarse resolution with Landsat. Pond area strongly depends on the accuracy of the derived outlines. This is a key issue and you should provide some errors in your delineation, mainly due to the resolution of the images. Watson et al. (2016), looking at supra-glacial ponds though, show that resolution is an issue and they state that Landsat products cannot be used for this purpose. So may cite this paper (which

came out after your submission) and also consider that issue. Maybe your ponds are very big and not affected by the coarse resolution of Landsat? A clear advantage of Landsat is that it allows going back in time – what the higher resolution products cannot as they are all for recent years. Also, from Table 3 of supplement there is an ALOS image listed, although it is not clear what is that used to. ALOS has a different resolution and so this should be discussed.

Answer: As suggested by the reviewer the supraglacial lakes in Mt Everest Region are very small. According to Watson et al. (2016) their size range from 0.09 to 0.36 10^4 m^2, while the unconnected ponds in the same region (this study) are on average 1.1 10^4 m^2, i.e., an order of magnitude larger. This is not the unique difference between the two kind of ponds. As described in the text, supraglacial ponds are strictly connected with glacier dynamics, thus, as describe by many authors (and by the same Watson et al. (2016)) their measurement is very uncertain. Landsat imagery is surely too coarse for these ponds.

Considering unconnected ponds, in general, we tracked the pond surface changes in many papers (Tartari et al., 2008, Thakuri et al., 2015; Salerno et al., 2012, Salerno et al., 2014). We wrote a specific work (Salerno et al., 2012), on the uncertainty related to the measurements of lakes from satellite imagery in the region, which is referenced also by Watson et al. (2016). In the methodological section there is a section devoted to the uncertainty of measurements.

Table 3 is a general summary of surface area changes related to all 64 considered ponds glaciers located within the basins. In the previous version of the paper was not explicitly written that the same table reported the uncertainty of measurements. This could have confused the reviewer, which though that we did not consider and discuss the uncertainty of measurements.

The ALOS was used to track the pond surface areas in 2008, this image was preferred considering the better resolution. In fact in table these period presents uncertainties slightly lower.

Correction: 1) the methodological section related to the uncertainty of measurements has been extended. 2) we corrected the caption of Table 3. Along the paper, where it was omitted, the uncertainty has been associated with relevant difference of measurement. The satellite images used for the analysis have been also reported in the main text and in the abstract.

2) Degree-day model for glacier melt:

The use of a degree-day model for glacier melt might be a key limitation, as this has been shown to be very sensitive to temperature fluctuations. Therefore the estimates of "glacier melt" might be erroneous, and responding too much to changes in temperature. I would suggest that you perform calculations with a better model. Also, a key concern is that you use a constant melt factor from another study - the model needs calibration. If you cannot do this, you should perform an uncertainty analysis by varying this factor in a given range. In addition, why did you only use one factor and not two for snow and ice? I would strongly recommend that you: 1. do an uncertainty analysis and see how sensitive your results are to changes in the degree-day factor 2. use a more appropriate model

Answer: This paper does not aim to provide an accurate estimation of the magnitude of the melt released from glaciers located in the pond basins. In fact, its value has never been discussed and mentioned. The melt factor could be unsuitable, but if it was wrong no analysis would be compromised. We compared its 2000-2013 trend vs the pond surface areas, and the correlation analysis is independent from the magnitude of the compared series. Consequently, we do not need different factors for snow and ice and to make a sensitive analysis.

Being interested in the melt trend and not in its absolute magnitude and considering that these small glaciers are ungauged, we do not more sophisticated melt models, which consider specific geometries and differentiated melt factors. We are aware of the autocorrelation between the maximum temperature and glaciers melt calculated from this variables, i.e., their fluctuation are similar. The added value is only due to that the positive temperature calculated for each glacier (elevation bends) are able to generate a melt, which we found to be significant related to the observed pond surface area changes. If ponds (and glaciers) were located some hundred of meters at higher elevation, surely the melt and Tmax would be less correlated and the application of the degree-day model would look less trivial. What is the knowledge contribution of the application of the degree-day model in this contest? Maximum temperature trend is here demonstrated to be responsible of processes able to modify the pond surface area. How processes? Glacier melt is a reasonable factor, due to we find significant relationships when glaciers are present in the pond basins, and no relationship with Tmax when glacier are not present in the basin.

Correction: these concepts has been inserted in the text.

3) Table 3:

There are some very contrasting changes and it is not entirely clear how these values were derived: e.g. for ponds with glacier coverage <5% from 1963 to 2011 there is a decrease of -7% (+-6%, which is a lot) and from 1963 to 2013 (only two years apart), there is a decrease of -25%. This could be due to accuracy in the delineation and the use of different data sources rather than real changes. Also, why are changes from intermediate periods, i.e. 2000 to 2013 (or 2000 to 2011), not shown in the table?

Answer: In the right of the Table 3 changes for each intermediate period are all referred to 1963, because they are expressed as commutative loss. Having fixed the reference year this kind showing results allows to create a trend. In fact these data are the same used in Figure 8. I f we were interested in the acceleration for each period, the same Table on the left provides the relative annual rate (for each period in this case). These data are discussed in Table 7. So you can directly compare periods.

In relation to the abrupt change observed by the reviewer (-7% vs -25%,i.e., -18%), we can start observing Table SI2. The resolution of the two images is the same. Moreover giving a look at fig. 8 Fig. 8. Probably here it looks much less strange. From 1992 to 2011 the decreasing is 20% (the computation can be done also from the table 3 from +13% to -7%). Surely -18% in two years is a lot, but in in line with the decreasing of precipitation observed since the early ‘90s (Fig. 8). Furthermore the behavior of surface are change has been observed significantly correlated with precipitation.

Correction: the caption of the table has been changed to better clarify its content.

4) Aim of the paper:

You want to study lakes as proxies for climate, but you cannot indeed as lakes changes can only be explained if changes in a variety of climatic and glacier variables are known. What you can do is relating lake changes to climate and glacier changes and see if there is a consistent interpretation for both. This has to be changed in the intro and the paper in general.

Correction: the specific aims of the paper have been added.

5) Debris-covered and debris-free glaciers:

I strongly recommend that you carry out your analysis of glacier area changes separately for the two categories debris-covered and debris-free glaciers, and provide figures of how much of the glacier area in the catchment is covered by debris. Debris covered glaciers are known to shrink little in area and that area change is not a good indicator of glacier changes and melt (see e.g. lines 251-252).

Answer: The glaciers within the pond basins are not debris covered. In this region debris covered glaciers are usually glaciers of a certain size with a developed flat ablation area. In all considered pond basins, the glacier are very small, steep (31°), clings to the mountain peaks, without having developed debris covered ablation area.

Correction: following the suggestion of the reviewer we specified in the text these features of glaciers within the considered pond basins.

Specific comments:

I think you should also analyze and discuss the fact that some ponds undergo geometrical changes over such a long time due to changing boundary conditions. **A)** Depending on the location and size of a water body, possibly enhanced or reduced sediment supply from glaciers, landslides etc. could change the lake area considerably. Also groundwater may play a role for the hydrology of some ponds. And if you think these processes are negligible, mention this in the text at the beginning in the introduction or at the end in the discussion. **B)** Regarding the topographical analysis, there are some hidden steps which need to be explained better in the text, e.g. selection of basins, aspects etc. (see specific comments below) or how you distinguish between a connected and an unconnected pond, i.e. how far the latter is located from the glacier tongue. There are sections in the text which need to be improved. **C)** Due to many different datasets, time periods and pond categories it is sometimes hard to follow step by step the selection and analysis of the data (is a certain result about ponds/season/years etc.). This could be improved by 1) using a clearer structure and repeating more frequently corresponding information in the text, and 2) splitting long sentences. **D)** This clarity is also lacking in a few figures, where it is sometimes not possible to get the right information of all plot elements. Some additional legend elements and a more precise caption would help substantially in these cases (see technical corrections below).

Answer: A) the variably connected with "secondary" boundary conditions has been discussed in the conclusions; B) following the suggestions provided by the reviewer, accepting the specific comments provided below, we hope to have provided more details on these aspects; C) following the suggestion received by another reviewer, a section related to the overall mythology has been inserted; D) All figures and captions have been improved following the suggestions received by reviewers

Technical corrections (text):

Line 11, ': : :ponds not directly connected to glaciers,', try to give a clearer definition to avoid mixing physical and hydrological connection, something like ': : :ponds not in direct contact with glacier ice' could fit.

Answer: done

Lines 14-15, wrong word order, write ': : :unconnected ponds have decreased significantly by approximately 10% over the last fifty years (1963-2013 period).'

Answer: done

Also: '10%' is area or number? Needs to be specified as it is ambiguous like that.

Answer: done

Line 16, word missing within ‘We inferred an increase in precipitation occurred until: : :’

Answer: done

Line 22, ‘remoteness’ is another main reason.

Answer: done

Line 36, ‘: : : body of research: : :’, try to use a better word.

Answer: done

Lines 46 and 54, ‘: : :high Asian mountains: : :’, better to use ‘high mountain Asia’ or ‘Asia’s high mountains’.

Answer: done

Line 47, ‘decreased evaporation’, add explanation why evaporation was assumed to have decreased.

Answer: done

Lines 59-61, wrong word order, write ‘Therefore the potential risk of GLOFs in the Himalaya has been,: : :’.

Answer: done

Line 61, ‘: : :these lakes’, which type do you mean here?

Answer: done

Line 67, write ‘: : :opening’.

Answer: done

Line 69, ‘: : :only influenced by glacier melting and precipitation.’, is this valid? What about e.g. evaporation, ground water, avalanches?

Answer: the mains terms of the water balance we consider at annual scale are as input, precipitation and glacier melt, and as output, the evaporation. If we considered ground water, avalanches we should also consider other terms as runoff, infiltration, seepage, sublimation…but this level of detail is not the aim of the work, and it is impossible to discern in this remote environments. These lakes are ungauged, remote. No information regarding the groundwater is available at those elevations, avalanches are never computed in the water balances because are they are episodic not easily quantifiable events.

Following the approach of other authors (e.g., Song et al., 2014; Wang et al., 2015, Salerno et al., 2015), precipitation, glacier melting, and evaporation are the main contributions in high elevated lake basins able to explain the causes of lake changes

Correction: the approach followed by these authors has been inserted.

Line 70, write ‘: : :lakes to potential indicators: : :’.

Answer: done

Line 72, not sure you can use ‘evapotranspiration’ here, but also in several other parts of the text. Don’t you mean ‘evaporation’ in general? Sometimes you use evaporation, sometimes evapotranspiration. Try to be consistent.

Answer: done

Line 73, write ‘A valuable: : :’.

Answer: done

Line 79, it seems to me that Hamerlik et al. (2013) used a threshold of 1 ha (page 3), better cite Biggs et al. (2005).

Answer: He initially used a threshold of 1 ha, but his analysis shown that the threshold was 2 ha (abstract)

Line 94, ‘: : :characterized by: : :’, be more concise.

Answer: done

Line 97, ‘For the last twenty years: : :’, give specific years.

Answer: done

Lines 97-98, wrong word order.

Answer: done

Line 106, ‘: : :these glaciers: : :’, which glaciers?

Answer: done

Line 118, write ‘: : :and subsequently expanded continuously: : :’.

Answer: done

Line 122, write ‘: : :monthly cumulated: : :’.

Answer: done

Lines 125 and 127, write ‘Jensen-Haise model’.

Answer: done

Lines 136, gap between ‘: : :Unit-Time: : :’.

Answer: done

Lines 138, gap between ‘: : :Prediction-Climate: : :’.

Answer: done

Line 154, write ‘: : :through: : :’.

Answer: done

Lines 156-159, sentences about selection are confusing, try to explain this more clearly.

Answer: done

Line 172, specify why you selected this T-index model. See also major comments above.

Answer: the choice has been described above.

Correction: this concept has been inserted in the text.

Line 174, ‘: : :close to the SNP.’, explain better why this field study on Glacier AX010 is the best solution and suitable in your opinion, specify where this glacier is located, which region, climate etc. See also major comments above.

Answer: this glacier is a small debris free glacier, located in the Dudh Koshi valley in same climatic and geographic setting of glaciers studied in this paper, just outside the SNP in the southwest part (27°42'N, 86°34'E). Several studies exist on this glacier . It is a reference glacier for long monitoring of mass balance changes. Some papers: http://onlinelibrary.wiley.com/doi/10.1029/2005JD005894/full, www.pnas.org/content/108/34/14011.full.pdf

Correction: this concept has been inserted in the text.

Line 175, why didn’t you apply the daily temperature per elevation band of each glacier?

Answer: the previous version was too hermetic and not clear.

Correction: the text has been corrected according to the suggestion of specifying better the use of the elevation bands.

Line 178, delete ‘Such’.

Answer: done

Line 179, write ‘: : :through: : :’.

Answer: done

Line 180, use proper reference instead of URL-address.

Answer: done

Line 182, use proper reference instead of URL-address.

Answer: done

Line 185, maybe more correct to use ‘mountainous terrain’ or ‘steep terrain’.

Answer: done

Line 189, use proper reference instead of URL-address.

Answer: done

Line 190, write ‘: : :effects as decribed in Salerno: : :’.

Answer: done

Line 194, write ‘: : :morphological: : :’.

Answer: done

Line 205, add reference to ‘: : :in the software R: : :’.

Answer: done

Line 213, ‘: : :trends has been tested: : :’ on how many years? Isn’t there a minimum of years to be able to speak about trends?

Answer: No there is not a minimum of years. However when a series is considered not such long, the associated significance should be considered with caution.

Correction: This specification has been inserted in the text

Line 233, description for Figure SI2b confusing and not consistent with actual plot.

Answer: not done. We did not understand the comment.

Line 240, remove ‘very’ or use ‘relatively’.

Answer: done

Line 240, write ‘: : :oriented towards south-southeast: : :’.

Answer: done

Lines 243-245, wrong word order, write ‘: : :in the last fifty years (1963-2013).’.
Also: 10% is ambiguous: is this area or number?

Answer: done

Line 257-258, This depends on the status of the glaciers, see e.g. Pellicciotti et al., 2010. You can have a decrease in area and decrease in glacier melt.

Answer: the suggestion has been considered

Lines 258-259, avoid using two times ‘However: : :’.

Answer: done

Line 261, ‘: : :extremely broad: : :’ not clear to me what you mean here, use clearer/better word(s).

Answer: done

Line 284, replace ‘These authors: : :’ with ‘They: : :’.

Answer: done

Lines 284-287, wrong word order, write ‘They observed: : :’. Too long sentence, make two out of it.

Answer: done

Line 291, delete ‘both’.

Answer: done

Line 296, write ‘: : :than the mean: : :’.

Answer: done

Line 298, write ‘: : : more than the: : :’.

Answer: done

Line 303, what do you mean with ‘: : :relevant: : :’? Try to be more clearly. Also: mentioning ‘maximum monsoon temperature’ and ‘glacier melt’ as main drivers of change is somehow redundant in my opinion, as the last is clearly directly dependent of the former one in your calculations. Maybe explain here better the dependencies.

Answer: we agree that it is redundant.

Correction: Therefore temperature has been deleted from the PCA and the text modified accordingly.

Lines 303-305, too long and complicated sentence, untangle and make two out of it.

Answer: not done. We did not understand the comment.

Line 315, write ‘: : :basin: : :’.

Answer: done

Line 317, maybe you can mention, that based on your findings it can be clearly seen, that glaciers act as buffers of the hydrological cycle.

Answer: glaciers are not the hydrological buffer, the glacier cover is the discriminant variable

Correction: The concept has been added in the new version.

Line 328, remove ‘very’ or use ‘relatively’.

Answer: done

Line 330, write ‘compare’.

Answer: done

Lines 333-335, wrong word order and too long sentence. Write ‘The surface area of ponds-without glaciers strongly decreased (-25_6%, $p<0.001$) from 1963 to 2013. In contrast, the surface area of ponds-with-glaciers decreased much less (-6_2%, $p<0.05$) for the same period.’

Also: refer to Table 3 in that sentence.

Answer: done

Lines 361-362, contradiction to line 355 and Figure 9b., should be the other way round I suppose.

Answer: the comparison should be done with ponds without glaciers (line 354).

Correction: we inserted the reference figures and type of lakes.

Lines 362-363, here you could think about glacier morphology to further explain differences in glacier melt at different elevations (area, steepness, debris), if this is valid in your case study.

Answer: see the comment above

Line 369, be more precise when using the term ‘glacial ponds’ in order to separate them from supraglacial ponds etc.

Answer: done

Line 372, missing word(s) in ‘The continued shrinkage of glaciers likely due to: : :’.

Answer: done

Line 376, avoid using ‘study’ two times.

Answer: done

Line 377, I wonder if the behavior of precipitation and glacier melt can be detected separately based on tracked pond areas. Maybe you can state something about this here.

Answer: done

Lines 382-387 & lines 389-391, did you directly observe constant (until the 1990s) or reduced glacier melt (in the early 2000s) or is this assumption based on the decreased max. air temperatures? It would be good if you could add here more background from your findings.

Answer: the concept has been clarified.

Correction: through the analysis of surface area changes of unconnected glacial ponds.

Line 403, write ‘: : :other climatic: : :’.

Answer: done

Line 409, verb missing.

Answer: done

Technical corrections (tables/figures):

Table 2:

Line 629, write ‘: : :of all considered: : :’.

Pond area, rounding error for max. value in 2nd and 3rd column (56.3 vs. 56.2)?

Basin, maybe you can add once in the paper how the basin is defined (=’hydrological’ catchment?) and how you calculated it (algorithm?).

Basin aspect, did you consider the calculation for directional values? Mean, median, range etc. of aspects have to be derived carefully, as e.g. the mean and median of the three values 45_, 345_ and 360_ doesn’t make sense if calculated normally. Add a short note how you deal with this once in the paper where ‘aspect’ occurs first.

Also: How did you derive the mean basin aspect? Add used method (‘vectorial mean’).

Glacier aspect, same as ‘basin aspect’, see comment above. Here it seems that the median is not within the range.

Answer: “Hydrological basin” has been inserted in many key points of the manuscript. The errors have been corrected. The method used for deriving the mean, median, etc.. of aspect has been described. The hydrological basin has been delineated with ArcGIS® hydrology tools.

Correction: the circular statistic has been used for computing the (vector) mean and median values of glaciers and basins aspect (Fisher, 1993). The delineation method has been described.

Table 3:

Asterisks, what do they stand for? Statistical significance level? Add explanation.

Answer: done

Table 4:

Basin aspect, again, how did you calculate mean and median basin aspect(s)? Asterisks, what do they stand for? Add explanation.

Answer: (see the answer above), done

Figure 1:
Line 684, you could add the source of the two pictures.

Answer: done

Figure 2:
a), use decimal degrees as written in text (line 91).
Also: black triangle and 'SNP' somehow misleading in inset map.
b), write ': : :isotherms corresponding: : :'.
Also: write 'max. temperature'
Line 715, remove ': : :'.

Answer: done (point a: we changed the text)

Figure 4:
Low image quality, especially axis labels. Try to improve.
Also: change x-axis labels to more 'intuitive' years, e.g. 1980, 1985,: : : and add year labels to all subplots a-d for better readability.
b), write 'Precipitation (anomaly)'

Answer: done

Figure 6:
Low quality, labels and lines.
Also: units missing.
a), y-range seems to be too small, missing points.
Also: wrong labels both at y-axis and in legend ('cumulate').
b), the left and right y-axes seem to be shifted vertically.
Line 777, a) and b) mixed?
Line 779, write ': : :Figures: : :'.

Answer: done, units in the caption

Figure 7:
Especially subplots a) and c) too small.
Also: size of circles in subplots b) and d) not clear, explanation below not clear as well.
Line 783, write 'Increased pond surface areas' and 'Decreased pond surface areas'.
Lines 785-786, description of subplots a) and c) not consistent with actual titles in plot (with/without glaciers).

Answer: done

Figure 8:
Add units for right y-axes (precipitation, melt). Also: make lines and bars in both sub plots identifyable, label them.

Answer: done, units in the caption

Figure 9:
Low quality, too small (axes labels).

Answer: done

Technical corrections (supporting information):

Figure SI1:

Last sentence in caption: write ‘In Table 1 the relevant coefficients of correlation are reported.’.

Answer: done

Figure SI2:

a), add more space in between x-axis-labels. b), change x-axis-labels to more ‘intuitive’ years (e.g. 1980, 1985, : : :).

Answer: done

Figure SI3:

Very low quality of all labels, axes, wrong number of digits etc., too small. Also: add units or write that the anomalies are relative or dimensionless.

Answer: done

Figure SI4:

Low quality of all labels, too small. Second last sentence in caption: write ‘: : :considering Tmax and Tmean.’.

Answer: done

References:

Biggs, J., P. Williams, M. Whitfield, P. Nicolet and A.Weatherby, 2005. 15 years of pond assessment in Britain: results and lessons learned from the work of Pond Conservation. Aquatic Conservation: Marine and Freshwater Ecosystems 15: 693–714.

Pellicciotti, F., A. Bauder and M. Parola. Effect of glaciers on streamflow trends in the Swiss Alps. Water Resources Research, 46: W10522.

Watson, C.S., D.J. Quincey, J.L. Carrivick and M.W. Smith, 2016. The dynamics of supraglacial water storage in the Everest region, central Himalaya. Global and Planetary Change 142: 14–27.

Glacier melting and precipitation trends detected by surface area changes in Himalayan ponds

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Abstract. Climatic time series for high-elevation Himalayan regions are decidedly scarce. Although glacier shrinkage is now sufficiently well described, the changes in precipitation and temperature at these elevations are less clear. This contribution shows that the surface area variations of unconnected glacial ponds, i.e., ponds not directly connected to glacier ice, but that may have a glacier located in their hydrological basin, can be considered as suitable proxies for detecting past changes in the main hydrological components of the water balance. ~~on the south side of Mt. Everest~~. On the south side of Mt. Everest, glacier melt and precipitation have been found to be the main drivers of unconnected pond surface area changes (detected mainly with Landsat imagery). ~~Glacier melt and precipitation trends have been inferred by analyzing the surface area variations of ponds with various degrees of glacial coverage within the basin.~~ In general, unconnected ponds ~~over the last fifty years (1963-2013 period)~~ have decreased ~~here~~ significantly by approximately 10±5% in terms of surface area over the last fifty years (1963-2013 period) in ~~. In~~ the ~~Mt. Everest~~study region ~~during this period We~~. Here, ~~inferred~~ an increase in precipitation occurred until the mid-1990s followed by a decrease until recent years. Until the 1990s, glacier melt was constant. An increase occurred in the early 2000s, ~~and~~ while~~in the recent years, contrasting the observed glacier reduction,~~ a declining trend in maximum temperature has ~~decreased~~ caused a reduction in~~the~~ the glacier melt during the recent years.

1 Introduction

Meteorological measurements in high-elevation Himalayan regions are scarce due to the harsh conditions of these environments and their remoteness, which limit the suitable maintenance of weather stations (e.g., Vuille, 2011; Salerno et al., 2015). Consequently, the availability of long series is even more rare (Barry, 2012; Rangwala and Miller, 2012; Pepin et al., 2015). Generally, gridded and reanalysis meteorological data are used to overcome this lack of data and can be considered an alternative (e.g., Yao et al., 2012). However, in these remote environments their use for climate change impact studies at the synoptic scale must be performed with caution due to the absence of weather stations across the overall region, which limits the ability to perform land-based evaluations of these products (e.g., Xie et al., 2007). Consequently, the meager knowledge on how the climate has changed in recent decades in high-elevation Himalayan regions presents a serious challenge to interpreting the relationships between causes and recently observed effects on the cryosphere. Although glacier~~s~~ reduction in the Himalaya is now sufficiently well described (Bolch et al., 2012; Yao et al., 2012, Kääb, et al., 2012), the manner in which changes in climate drivers (precipitation and temperature) have influenced the shrinkage and melting processes is less clear (e.g., Bolch et al., 2012; Salerno et al., 2015), and this lack of understanding is amplified when forecasts are conducted.

In this context, ~~a substantial body of research~~the recent literature has already demonstrated the high sensitivity of lakes and ponds to climate (e.g., Pham et al., 2008; Williamson et al., 2008; Adrian et al., 2009; Lami et al., 2010). Some climate-related signals are highly visible and easily measurable in lakes. For example, climate-driven fluctuations in lake surface areas have been observed in many remote sites. Smol and Douglas (2007) reported decadal-scale drying of high Arctic ponds due to changes in the evaporation/precipitation ratio~~ratio of precipitation to evaporation~~. Smith et al. (2005), among other authors, found that lakes in areas of discontinuous permafrost in Alaska and Siberia have disappeared in recent decades. In the Italian Alps, Salerno et al. (2014a) found that since the 1980s, lower-elevation ponds have experienced surface area reductions due to increased evaporation/precipitation ratio for the effect of higher temperature, while higher-elevation ponds have increased in size and new ponds have appeared as a consequence of glacial retreat.

In high ~~Asian~~ mountain Asia~~s~~ and in particular in the interior of the Tibetan Plateau, the observed lake growth since the late 1990s is mainly attributed to increased precipitation and decreased evaporation (Lei et al., 2014; Song et al., 2015). In contrast, Zhang et al., 2015, attribute the observed increases in lake surface areas since the 1990s across entire Pamir-Hindu Kush-Karakoram-Himalaya region and the Tibetan Plateau region to enhanced glacier melting. Wang et al., 2015, reached similar conclusions in a basin located in the south-central Himalaya. In our opinion, the divergences in the causes leading to the lake surface area variations in central Asia are due to the fact that different types of glacial lakes (described below) have been considered in these studies.~~, which could be differentiated in relation to some features of glaciers located within their basin.~~

In general, in high~~ Asian~~ mountain Asia~~s~~, three types of glacial lakes can be distinguished according to Ageta et al. (2000) and Salerno et al. (2012): (i) lakes that are not directly connected with glacier ice~~s~~ but that may have a glacier located in their hydrological basin (unconnected glacial lakes); (ii) supraglacial lakes, which develop on the surface of a downstream portion of a glacier; and (iii) proglacial lakes, which are moraine-dammed lakes that are in contact with the glacier front. Some of these lakes store large quantities of water and are susceptible to glacial lake outburst floods (GLOFs). ~~Therefore, in the Himalaya, the potential risk of GLOFs has been, with good reason, widely investigated (e.g., Richardson and Reynolds, 2000; Benn et al., 2012).~~ Factors controlling the growth of ~~these~~ supraglacial lakes depend on the glacier features from which they develop (surface gradient, mass balance, cumulative surface lowering, and surface velocity) (Reynolds, 2000; Quincey et al., 2007; Sakai and Fujita, 2010; Salerno et al., 2012; Sakai, 2012, Thakuri et al., 2015). The causes of proglacial lake development are decidedly similar to those described for supraglacial lakes~~, and supraglacial lakes are potential precursors of these lakes~~ (e.g., Bolch et al., 2008; Salerno et al., 2012; Thakuri et al., 2015). Their filling and drainage is linked to the supply of meltwater from snow or glacial sources (Benn et al., 2001; Liu et al., 2015)~~), and the opeping and closure of englacial conduits (Gulley and Benn, 2007)~~. Therefore, ~~whereas~~ the lake Differently, unconnected glacial lakes do not have a close dependence on glacier dynamic sand this aspect makes them potential indicators of the water balance components in high-elevation lake basins i.e., precipitation, glacier melting, and evaporation. These main contributions would best explain the causes of lake changes (e.g., Song et al., 2014; Wang et al., 2015, Salerno et al., 2015).~~surface area variations of supraglacial and proglacial lakes are strictly related to glacier dynamics. Differently, unconnected glacial lakes do not have a close dependence on glacier dynamic sand this aspect makes them potential indicators of the water balance components in high-elevation lake basins i.e., precipitation, glacier melting, and evaporation. These main contributions would best explain the causes of lake changes (e.g., Song et al., 2014; Wang et al., 2015, Salerno et al., 2015).~~

A~~n~~ valuable opportunity for a fine-scale investigation on climate-driven fluctuations in lake surface area is particularly evident on the south slopes of Mt. Everest (Nepal), which is one of the most heavily glacierized~~glaciated~~ parts of the Himalaya (Scherler et al., 2011). Additionally, this region has the largest number of lakes~~is also characterized by the most glacial lakes~~ in the overall Hindu-Kush-Himalaya range (Gardelle et al., 2011), and a twenty-year series of temperature and precipitation data has recently been reconstructed for these high elevations (5000 m a.s.l.) (Salerno et al., 2015). Moreover, the ~~reduced dimensions~~relative small size of the water bodies in this region, which we can be defined as ponds according to Hamerlik et al. (2013) (a threshold of 2 10^4 m^2 exists between ponds and lakes), make ~~these environments~~them especially susceptible to the effects of climatic changes because of their relatively ~~low water volumes and~~ high surface area to depth ratios (Smol and Douglas, 2007~~Buraschi et al., 2005; Beniston, 2006~~).

This contribution examines the surface area changes of unconnected glacial ponds on the south side of Mt. Everest (an example is shown in ~~Figure~~ Fig. 1) during the last fifty years (1963-2013). ~~Generally, t~~This study aims to evaluate whether they might be used as proxy to infer past spatial and temporal trends ~~act as potential indicators of changes in~~of the main components of the hydrological cycle (precipitation, glacier melting, and ~~evapotranspiration~~evaporation) at high elevations~~ in the Himalayan range~~. Possible drivers of change are investigated through land climatic data, available in the area, and ~~r~~correlation analysis. Furthermore, morphological -boundary conditions (glacier cover, pond size, pond location, basin aspect, basin elevation) are analysed as possible factors controlling the pond surface area changes. The study is concluded comparing ~~in the last fifty years~~ gridded and reanalysis time series (evaluated vs land climatic data) with observed pond surface area changes in the last fifty years.

2 Region of investigation.

The current study is focused on the southern Koshi (KO) Basin, which is located in the eastern part of central Himalaya ~~(CH)~~ (~~Yao et al., 2012; (~~Thakuri et al., 2014) (Fig. 2). In particular, the region of investigation is the southern slopes of Mt. Everest in Sagarmatha (Mt. Everest) National Park (SNP) (27~~.75~~° 45’ to 28~~.11~~° 7’ N; 85~~.98~~° 59’ to 86~~.51~~° 31’ E) (Fig. 2a) (Amatya et al., 2010; Salerno et al., 2010). The SNP (1148 km^2) is the highest protected area in the world, extending from an elevation of 2845 to 8848 m a.s.l. (Salerno et al., 2013). Land cover classification shows that almost one-third of the territory contains temperate glaciers and less than 10% is forested~~of the territory is characterized by temperate glaciers and that less than 10% of the park area is forested~~ (Bajracharya et al., 2010), mainly with *Abies spectabilis and Betula utilis* (Bhuju et al., 2010).

The climate is characterized by monsoons, with a prevailing S-N direction (Ichiyanagi et al., 2007). For the ~~last twenty years~~1994-2013 period at the Pyramid meteorological station (5050 m a.s.l.) (Fig. 2a), the total annual accumulated precipitation is 446 mm, with a mean annual temperature of -2.45 °C. In total, 90% of the precipitation ~~is concentrated during~~falls between June-September. The probability of snowfall during these months is very low (4%) but reaches 20% at the annual level. Precipitation linearly increases to an elevation of 2500 m and exponentially decreases at higher elevations (Salerno et al., 2015).

Most of the large glaciers in the SNP are debris-covered, i.e., the ablation zone is partially covered with supraglacial debris (e.g., Scherler et al., 2011; Bolch et al., 2011; Thakuri et al., 2014).~~–~~ However, the glaciers located within the considered pond basins are very small, steep, clings to the mountain peaks, and thus they did not develop a debris covered ablation area. ~~In the SNP, ~~T~~t~~he glacier surfaces are distributed from approximately 4300 m to above 8000 m a.s.l., with more than 75% of the glacier surfaces lying between 5000 m and 6500 m a.s.l. The area-weighted mean elevation of the glaciers is 5720 m a.s.l. in 2011 (Thakuri et al., 2014). ~~These glaciers~~ Glaciers in this region are identified as summer-accumulation glaciers that are fed mainly by summer precipitation from the South Asian monsoon system (Ageta and Fujita, 1996).

Salerno et al. (2012) ~~realized~~ performed the complete ~~cadaster~~ inventory of ~~all~~ lakes and ponds in the SNP by digitizing ALOS-08 imagery and assigning each body of water a ~~univocal~~ numerical code (LCN, lake cadaster number) according to Tartari et al. (1998). They reported a total of 624 ~~lakes~~ water bodies in the park, including 17 proglacial ~~lakes~~ponds, 437 supraglacial ~~lakes~~ponds, and 170 unconnected ~~lakes~~ponds. Previous studies revealed that the areas of proglacial ~~lakes~~ ponds increased on the south slopes of Mt. Everest ~~since~~ after the early 1960s (Bolch et al., 2008; Tartari et al., 2008; Gardelle et al., 2011, Thakuri et al., 2015). Many studies have indicated that the current moraine-dammed or ice-dammed ~~lakes~~ ponds are the result of coalescence and growth of supraglacial ~~lakes~~ ponds (e.g., Fujita et al., 2009; Watanabe et al., 2009; Thompson et al., 2012, Salerno et al., 2012). Such ~~lakes~~ ponds pose a potential threat due to GLOFs. Imja Tsho (Lake) is one of the proglacial lakes in the Everest region that developed in the early 1960s as small pond and subsequently ~~continuously~~ expanded continuously (Bolch et al., 2008; Somos-Valenzuela et al., 2014, Fujita et al., 2009; Thakuri et al., 2015).

3 Data and Methods

3.1 Overall methodological approach

This section ~~aims to~~ provides a ~~road map~~ brief description ~~on~~of the overall methodological approach applied in this study. Whereas in the following sections, data and methods are ~~specified~~ described in detail.

An intra-annual analysis has been carried out throughout the year 2001 on a limited set of unconnected ponds ~~with the aim of~~for ~~defining~~detecting the months ~~presenting~~characterized by the lowest surface area intra-annual variability and consequently the best period of the year to select the satellite images necessary for the inter-annual analysis.

An inter-annual analysis has been carried out during the 2000-2013 period (hereafter we refer to this analysis as "*short-term inter-annual analysis*"), considering the wide availability of satellite imagery in this period, on some selected unconnected ponds (hereafter we refer to these ponds as "*selected ponds*") to continuously track the inter-annual variations in surface area. This analysis aims to investigate the possible drivers of change (precipitation, evaporation and glacier melt) considering the availability of continuous series of annual pond surface areas ~~on the one side,~~ and climatic data from a land station located in the area ~~on the other~~. The study has been carried out through a correlation analysis and a Principal Component Analysis (PCA).

An inter-annual analysis has been carried out ~~during~~ from 1963 to 2013 (hereafter we refer to this analysis as "*long-term inter-annual analysis*") on a wider unconnected pond population (hereafter we refer to this population as "*all considered ponds*") and on glaciers located within their hydrological basin. Two kinds of analyses have been carried out on this set of data: 1) Pond surface area changes have been related to certain morphological boundary conditions. This analysis allows to investigate ~~on~~the factors controlling the pond surface area changes. The significance of the observed differences has been evaluated with specific statistical tests; 2) Pond surface area changes have been related to climatic data. This analysis aims to point out the capability of unconnected ponds to infer on the detected drivers of change also in the past when land climatic data did not exist. This study needed a preliminary analysis to reconstruct the climatic trends before the year 1994. Selected regional gridded and reanalysis datasets have been compared with land weather data available for the 1994-2013 period.

3.~~1~~ 2 Climatic data~~.~~

The monthly mean of daily maximum, minimum, and mean temperature and ~~montlly~~monthly ~~comulated~~cumulated precipitation time series used in this study have been ~~recently~~ reconstructed for the elevation of the Pyramid Laboratory (5050 m a.s.l.) (Fig. 2) for the 1994-2013 period (Salerno et al., 2015). The potential ~~evapotranspiration~~evaporation for the period (2003-2013) has been calculated by applying the Jensen~~ and ~~-Haise model (Jensen and Haise, 1963) using the mean daily air temperature and daily solar radiation recorded continuously during ~~this~~ the 2003-2013 period at Pyramid Laboratory. The Jensen~~ and ~~-Haise model is considered to be one of the most suitable evaporation estimation methods for high elevations (e.g., Gardelle et al., 2011; Salerno et al., 2012).

To obtain information on climatic trends in the antecedent period (before ~~the 1990s~~1994), we used some regional gridded and reanalysis datasets. We selected the closest grid point to the location of the Pyramid Laboratory, and all data were aggregated monthly to allow a comparison at the relevant time scale. With respect to precipitation, we test the monthly correlation between the Pyramid data and the GPCC (Global Precipitation Climatology Centre), APHRODITE (Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources), Era-Interim reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF), and CRU (Climate Research Unit - Time Series) datasets. For mean air temperature, we considered the Era-Interim, CRU, GHCN (Global Historical Climatology Centre), and NCEP-CFS (National Centers for Environmental Prediction- Climate Forecast System) datasets, whereas for maximum and minimum temperatures, we used the Era-Interim and NCEP-CFS datasets (details on the gridded and reanalysis products are reported in Table SI1).

3.~~2~~ 3 Pond digitization.

3.3.1 Long-term inter-annual analysis

Pond surface areas were manually identified and digitized using a topographic map from 1963 and more recent satellite imagery from 1992 to 2013. The topographic map of the Indian survey of the year 1963 (hereafter TISmap-63, scale 1:50,000) was used to complement the results ~~achieved using~~obtained from the declassified Corona KH-4 (15 Dec 1962, spatial resolution 8 m). Thakuri et al.~~,~~ (2014) described the co-registration and rectification procedures applied to the Corona KH-4 imagery. Unfortunately, on these satellite images many ponds are snow-covered. Therefore here we considered the ponds surface area digitalized on TISmap-63. The accuracy of this map has been tested comparing the surface areas of 13 ponds digitalized on both data sources (favouring the cloud and shadow free ponds). Figure SI1 shows the proper correspondence of these comparisons. Furthermore, in order to estimate the mean bias associated with TISmap-63, we calculated the mean absolute error (MAE) (Willmott and Matsuura, 2005) between data, which resulted sufficiently low (3.6%), assuring in this way the accuracy of ponds surface area digitalized on TISmap-63.

In total, five ~~intermediate periods~~scenes ~~(details on data sources are provided in Table SI2)~~ were considered according to the availability of satellite imagery.~~ ~~ Landsat images have been mainly used, except in 2008, when in the region the ALOS image, presenting a better resolution, was ~~availability~~available (details on data sources are provided in Table SI2).

We ~~selected~~ tracked only those ponds present continuously in all these five periods to exclude possible ephemeral ~~environments~~water bodies. As described below, 64 ponds haves been tracked from 1963 to 2013 (Fig. 2a).

3.3.2 Short-term inter-annual analysis

From the ~~2000 (~~2000-2013 period~~)~~, due to a wider availability of satellite imagery (and in particular the Landsat imagery)~~in the region for the last decade~~, 10 ponds were selected among the pond population (64 ponds) considered in the long-term analysis (1963-2013) to continuously track the inter-annual variations in surface area in the recent years. The largest ponds, free from cloud cover, and with diverse glacier coverages (from 1% to 32%) within their hydrological basin were favored in the selection (details on data sources used for these ~~lakes~~ ponds are provided in Table SI3).

3.3.3 Intra-annual analysis

The intra-annual variability in pond surface area has been investigated throughout the year 2001 through the availability of 5 cloud-free satellite images from June to December (details on data sources used for these ~~lakes~~ ponds are provided in Table SI4). The first ~~semester~~ months of the year ~~was~~ were excluded from the analysis because many ponds were frozen until April/May. Even in this case, the main criterion ~~drove~~driving the ponds selection was the ~~ponds were selected based on the~~ absence of cloud cover from the satellite images over the pixels representing the pond surface area. Only ponds for which a continuous series of data was ~~tracked~~retrieved from June to December were selected. Moreover ~~for all images, and~~ the largest ~~lakes~~ ponds ~~to the reduce the uncertainty in the shoreline delineation~~ ~~with various degrees of glacial coverage~~ were favored in order to reduce the uncertainty in the shoreline delineation. Thus, 4 ~~lakes~~ ponds ~~with these characteristics~~ were selected, and their intra-annual variability is tracked in Figure 3. ~~Based on Figure 3,~~ W~~w~~e observe a common significant increase in pond surface area during the summer months, likely due to monsoon precipitation and high glacier melting rates. ~~The acceleration~~This increase in surface area disappears on average during the fall. Some single ponds present a dispersion of around 5% between October and December (LCN4 and LCN77). However, the same Figure points out that just averaging this information on a population only a little bit larger, the dispersion between October and December becomes almost zero (1%). Therefore these months are ~~period from October to December is~~ the best period to select the satellite images necessary for the inter-annual analysis of pond surface area. In fact, during these months, the ponds are not yet frozen, the sky is almost free from cloud cover, and, as observed in Figure 3, the inter-annual analysis on average is not affected by intra-annual seasonality. Consequently all images for the inter-annual analysis have been selected from these months (Table SI1; Table SI2). Generally, climatic inferences coming from the analysis of surface area of ponds surely needs to consider a wider number of ponds in order to reduce the intra-annual variability due to the local conditions of each lake.

3.~~3~~4 Glacier surface areas and melt.

Glacier surface areas within the ~~pond~~ basins containing the ponds were derived from the Landsat 8 remote imagery (October 10, 2013) taken by the Operational Land Imager (OLI) with a resolution of 15 m. The satellite imagery used to ~~trace~~ track the inter-annual variations in glaciers since the early 1960s is reported in Table SI2. Detailed information of digitization methods are described in Thakuri et al., 2014.

To simulate the daily melting of the glaciers associated with the 10 selected ponds, we used a simple T-index model (Hock, 2003). This model is able to generate daily melting discharges as a function of daily air temperature above zero, the glacier elevation bands (using the Digital Elevation Model –DEM- described below)~~,~~, and a melt factor (0.0087 m d^{-1} °C^{-1}) provided by Kayastha et al. (~~2008~~2000) from a field study (Glacier AX010) located close to the SNP (southwest). The Glacier AX010 glacier is a small debris free glacier, located in the Dudh Koshi valley in same climatic and geographic setting of glaciers considered here.

The choice of using a simple model of melting is due to the fact that this paper does not have the specific objective to provide an accurate evaluation of the magnitude of the melt water released from glaciers located in the pond basins, but rather to estimate its trend, as function of the temperature, in order to evaluate if the glacier melt is a possible driver of changes of the pond surface areas. Being interested in the melt trend and not in its absolute magnitude and considering that these small glaciers are ungauged, we do not need more sophisticated melt models, which consider specific geometries and differentiated melt factors.

T-index model has been applied here considering the daily temperature of the Pyramid Laboratory corrected using the monthly lapse rates reported in Salerno et al., 2015 for each 50 m glacier elevation band. The melt estimated for each band has been then summed to calculate the total melt ~~realized by~~for each glacier.

3.~~4~~ 5 Morphometric parameters

The parameters related to the ponds basin as the area, slope, aspect, and elevation were calculated ~~throught~~through the ~~Digital Elevation Model (~~DEM~~)~~ derived from the ASTER GDEM (Tachikawa et al., 2011). ~~The ASTER GDEM tiles for the Mt. Everest region were downloaded from .~~. The vertical and horizontal accuracy of the GDEM are ~20 m and ~30 m, respectively (Tachikawa et al., 2011; Hengl and Reuter, 2011). We decided to use the ASTER GDEM instead of the Shuttle Radar Topography Mission (SRTM) DEM considering the higher resolution (30 m and 90 m, respectively) and the large data gaps of the SRTM DEM in this study area (Bolch et al., 2011). Furthermore, the ASTER GDEM shows better performance in mountainous terrains (Frey et al., 2012). Hydrological basins have been digitalized using ArcGIS® hydrology tools as carried out by other authors (e.g., Pathak et al., 2013). The circular statistic has been used for computing the (vector) mean and median values of glaciers and basins aspect (Fisher, 1993).

3.~~5~~ 6 Uncertainty of measurements

All of the imagery and map~~s~~ were co-registered in the same coordinate system of WGS 1984 UTM Zone 45N. The Landsat scenes were provided in standard terrain-corrected level (Level 1T) with the use of ground control points (GCPs) and necessary elevation data (LANDSAT SPPA Team, 2015~~https://earthexplorer.usgs.gov~~). The ALOS-08 image used here was orthorectified and corrected for atmospheric effects as described in Salerno et al. (2012).

Concerning the accuracy of the measurements, we refer mainly to the work of Tartari et al. (2008), Salerno et al. (2012), and Salerno et al. (2014a) which address in detail the problem of uncertainty in the ~~morphologicalal~~ morphometric measurements related to ponds and glaciers obtained from remote sensing imagery, maps and photos. The uncertainty in the measurement of a shape's dimension is dependent both upon the Linear Error (LE) and its perimeter. In particular for ponds~~, (~~(as discussed ~~also~~ by many authors, ~~by Fujita et al. (2009), and Gardelle et al. (2011) in the calculation of LE),~~ only the Linear Resolution Error (LRE) needs to be considered (e.g., Fujita et al., ~~(~~2009~~)~~, ~~and~~ Gardelle et al., ~~(~~2011~~)~~). ~~as the co-registration error does not play a key role. For instance, the ponds considered here are~~

~~small, and comparisons are made at the entity level and not at the pixel level.~~ Therefore we did not consider the co-registration error because the comparison was not performed pixel by pixel, at the entity level (pond) (Salerno et al., 2012, Salerno et al., 2015, Thakuri et al., 2015; Wang et al., 2015). The LRE is limited by the resolution of the source data. In the specific study of temporal variations of ponds, Fujita et al. (2009) and Salerno et al. (2012) assumed an error of ±0.5 pixels, assuming that on average the lake margin passes through the centers of pixels along its perimeter. The uncertainties in the changes in pond surface area— were derived using a standard error propagation rule, i.e., the root sum of the squares (uncertainty =— $\sqrt{e_1^2+e_2^2}$), where e_1 and e_2 are uncertainties from the first and second scene) of the mapping uncertainty in two scene Salerno et al., 2012; Thakuri et al., 2015).

3.~~6~~ 7 Statistical analysis~~.~~

In the short-term inter-annual analysis, t~~T~~he degree of correlation among the data was verified through the Pearson correlation coefficient (r) after testing that the quantile-quantile plot of model residuals follows a normal distribution (not shown here) (e.g., Venables and Ripley, 2002). All tests are implemented in the software R (R Development Core Team, 2008) with the significance level at $p < 0.05$. The normality of the data is tested using the Shapiro–Wilk test (Shapiro and Wilk, 1965; Hervé, 2015). Razali and Waph, 2011 demonstrate that the Shapiro-Wilk test presents the highest power for small sample size. The data were also tested for homogeneity of variance with the Levene's test (Fox and Weisberg, 2011). All comparisons conducted in this study are homoscedastic.

To evaluate the significance of differences in surface area changes of ponds population, both in time and respect certain morphological boundary conditions, some parametric and non-parametric tests have been used. We ~~used~~ applied the paired t-test to compare the means of two normally distributed series. If the series were not normal, as a non-parametric ANOVA, we used the Friedman test for paired comparisons and the post-hoc test according to Nemenyi (Pohlert, 2014), while for non-paired comparisons we applied the Kruskal-Wallis test and the post-hoc test according to Nemenyi-Damico-Wolfe-Dunn (Hothorn et al., 2015). The significance of the temporal trends has been tested using the Mann Kendall test ($p < 0.10$) (Mann, 1945; Kendall, 1975; Guyennon et al., 2013). When a time series is not very long, the associated significance level should be considered with caution.

We conducted a Principal Component Analysis (PCA) as described in Wold et al. (1987) between pond surface area variations and climatic variables to obtain information on relationships among the data and to look for reasons that could justify the observed changes in the pond~~s~~ size (e.g., Settle et al., 2007; Salerno et al., 2014a,b; Viviano et al., 2014).

4. Results

4.~~2~~ 1 Pond and glacier surface area variations

Among the 170 unconnected ponds inventoried in the 2008 satellite imagery (Salerno et al., 2012) in the SNP, we ~~selected~~tracked, according to the criteria described above, a total of 64 ponds (approximately 1/3) (Fig. 2a). Table 2 provides a general summary of their morphological features. We ~~prefer to~~ use the median values to describe these ~~environments~~ water bodies because, in general, we observed that these morphological data do not follow a normal distribution. The population consists of ponds larger than approximately 1 hectare (1.1 10^4 m^2), located on ~~very~~ relatively steep slopes (27°), and mainly oriented towards ~~the~~ south-southeast (159°). These ponds are located at a median elevation of 5181 m a.s.l. and within an elevation zone ranging from 4460 to 5484 m a.s.l..

The observed changes in the surface area of all the considered ponds are listed in Table 3. In general, all unconnected ponds ~~in the last fifty years (1963-2013)~~ decreased by approximately 10±5% in surface area in the last fifty years (1963-2013), with a significant difference based on the Friedman test (p<0.01). Figure 4d and Table 3 show that, until the 2000s, the ponds had a slight but not significant increasing trend (+7±4%, p>0.05). Since 2000, they have decreased significantly (-1.7±0.6% yr^{-1}, p<0.001 corresponding to -22±18%).

As for glaciers, Figure 4c reports the glacier surface area changes~~glaciers surface differences~~ observed across the SNP (approximately 400 km^2) observed by Thakuri et al., 2014. They reported a decrease of -13±3% from 1963 to 2011. We updated this series to 2013 and found ~~a further~~ loss of surface area of ~~(~~-18±3%~~)~~. For the glaciers located in the basins ~~with the ponds~~containing the ~~selected~~considered ponds, we tracked changes little bit larger. Their overall surface was 32.2 km^2 in 1963 and 25.0 km^2 in 2013, with a decrease of -26±20% (Fig. 4c; Table 3). According to many authors (e.g., Loibl et al., 2014), as we observe here, the main losses in area over the last decades in the Himalaya have been observed in smaller glaciers.

~~Once we have having analyzed how climate and glacier surface areas have changed over the last fifty years, we can now attempt to understand the causes that have led to the variations observed in the pond population. Usually and Iintuitively, an increase in glacier melt is associated with a decrease in glacier surface area, as observed here. However, if this inbound componentthe glacier melt was the most significantpredominant element of the water balance, the ponds would be increased. HoweverWhereas, the ponds have decreased since 2000s; thus, the weaker precipitation observed in recent decades seems to have played a more determining role. Nonetheless, thiese general considerationss analysis is extremely broad because it does not consider ,, for example, a possible different relationship between pond surface area and the degree of glacier coverage in the basin. Therefore, a deeper analysis has been carried out, as shown in the following, to annually trace track the surface areas of 10 selected ponds from 2000 to 2013.~~

5. Discussion

~~4~~5.1 Short-term inter-annual analysis: investigation on potential drivers of change~~.~~

Considering the wide availability of satellite imagery during the 2000-2013 period, an inter-annual analysis has been carried on 10 selected ponds in order to investigate the possible drivers of change. This was made possible exploiting the continuous series of annual pond surface areas on the one side, and climatic data from Pyramid station on the other.

5.1.1 Trends ~~of~~in pond surface areas

Table 4 provides the morphometric characteristics of 10 selected ponds. We observe that the median features of these ponds are comparable with the entire pond population (Table 2), highlighting the good representativeness of the selected case studies. Figure ~~SI3~~ SI2 shows, for each pond, the annual surface area variations that occurred during the 2000-2013 period. All the selected ponds show a significant (p<0.05) decreasing trend according to what has been observed for the whole pond population during the same period~~ (Table 3; Fig. 4)~~.

5.1.2 Trends ~~of~~in possible drivers of change

The selected ~~These continuous annual series have been compared with some~~ possible drivers of change are: temperature (daily maximum, minimum and mean), precipitation, potential evaporation, and glacier melt of the pre-monsoon, monsoon (Fig. 5), and post-monsoon seasons. Pyramid data have been used for computing or aggregating these variables. The assumption behind this analysis is that these series can be considered representative both along the altitudinal gradient and in the different valleys of the SNP. The scarcity of land weather data at these elevations makes licit this assumption, although, at this regard, the detected drivers of change will be analyzed in this respect in the last paragraph.

All these trends are noted in Figure SI3, and a correlation table comparing pond surface area variations and potential drivers of change is presented in Table SI5. In general, we observe from this table that the highest correlations are found for the monsoon period. The reason is because 90% of the precipitation and the highest temperatures are recorded during this period (Salerno et al., 2015). Consequently, the main hydrological processes in the Himalaya occur during the monsoon season. Focusing on this season, we first observe from Figure SI3 a large and significant precipitation decrease (-11 mm yr^{-1}; $p<0.1$) ~~(Fig. 6a; Fig. SI4)~~. Even the mean temperature decreases, but slightly and not significantly ~~(Fig. SI4)~~. This is a result of a significant decrease in maximum temperature (-0.08 °C yr^{-1}; $p<0.05$) ~~(Fig. 6b; Fig. SI4)~~ balanced by an increase in minimum temperature ~~(Fig. SI4)~~. The potential evaporation, calculated on the basis of the mean temperature and global radiation, is constant during the summer period. These trends have been more broadly discussed in Salerno et al., 2015. ~~These authors, for a longer period (since 1994),~~ They observed, ~~–~~ for a longer period (since 1994), that the mean air temperature has increased by 0.9 °C ($p<0.05$) at the annual level. However, the ~~but that~~ warming has occurred mainly outside the monsoon period and mainly in the minimum temperatures. Moreover, as we observed here for the ~~last decade~~2000-2013 period, a decrease in maximum temperature from June to August (-0.05 °C yr^{-1}, $p<0.1$) has been observed. In terms of precipitation, a substantial reduction during the monsoon season (47%, $p<0.05$) has been observed.

The glacier melt related to each glacier within the pond basins has been calculated considering both ~~the both~~ maximum and mean daily temperatures. The averages for all selected cases are analyzed for each season in Figure ~~SI4~~SI3, which reveals that the only period producing a sensible contribution is the monsoon period if the maximum daily temperatures are considered the main driver of the process. The reason can be easily observed in Figure 2b, which shows the 0 °C isotherms corresponding to the mean and maximum temperatures. Only the 0 °C isotherm related to the daily maximum temperature during the monsoon period is located higher than the mean elevation of the analyzed glaciers. The T-index model only calculates the melting associated with temperatures above 0 °C, thereby explaining this pattern. In other words, the diurnal temperatures influence the melting processes much more than the nocturnal ones, which are considered in the mean daily temperature. Figure 6b shows that the trend is significantly decreasing (3% yr^{-1}, $p<0.05$), according to the decrease observed in maximum temperature.

5.1.3 Detection of drivers of change

As anticipated, the highest correlations ~~between ponds surface areas~~pond surface areas ~~- and potential drivers~~ are found for the monsoon period. Based on Table SI5, we observe that precipitation, maximum ~~monsoon~~ temperature, and ~~relevant~~ glacier melt (calculated from temperature) are the more correlated variables ~~main drivers of change~~. The PCA shown in Figure 5 attempts to provide an overall overview of the relationships, during the monsoon period, among the trends related to the potential drivers of change and the pond surface areas. This representation helps to further summarize the main components of the water balance system that influence the pond surface areas, i.e., glacier melt and precipitation. We observe that evaporation is not an ~~sensible~~ important factor at these elevation and that the evaporation/precipitation ratio is approximately 0.41. Therefore, a hypothetical variation in the precipitation regime affects the pond water balance two and half times more than the same variation in the evaporation rate. Moreover, from Figure 5, we observe that there are some ponds that are more correlated with the monsoon precipitation (i.e., LCN76, LCN141, LCN77, LCN11, and LCN93) and others that are more correlated with the glacier melt (i.e., LCN68, LCN3, and LCN9). A few ponds seem influenced by both drivers (i.e., LCN24 and LCN139). The coefficients of correlation are reported in Table 4. According to the grouping observed with the PCA.~~,~~

Figure 6 shows good fits between the pond surface area trends and the main drivers of change. Based on Table 4, ponds with higher glacier coverage within the ~~basis~~ basin show higher correlations with the glacier melt, and, in contrast, ponds with lower glacier coverage show higher correlations with precipitation, i.e., the glacier coverage is the discriminant variable. In our case study, the threshold between the two groups appears to be a glacier coverage of 10%.

5.2 Long-term inter-annual analysis

An inter-annual analysis has been carried out ~~during~~ from 1963 to 2013 on all 64 considered pond in order to investigate 1) which morphological boundary conditions control the pond surface area changes and 2) the capability of unconnected ponds to infer on the detected drivers of change also in the past when land climatic data did not exist.

5.2.1 Morphological boundary conditions controlling the pond surface area changes ~~4.5 Change in ponds surface area versus morphological boundary conditions.~~

We analyzed whether all 64 considered ponds experienced changes in surface area in relation to certain morphological boundary conditions, such as the mean elevation of the basin, the pond surface area, the main three valleys of SNP (Fig. 2a), and the glacier cover. In this case, evaluated the normality of data, we apply the ANOVA test as well as the relevant post-hoc test described above. Figure SI4 shows the surface area changes observed during the 1992-2013 period vs morphological factors. The same analysis has been carried out also on 1963-1992 period reporting decidedly similar results (not shown here). We observe that the pond surface area changes are independent from both elevation, valley, and pond size, whereas significant differences can be observed between ponds with and without glacier cover. In particular, ponds-with-glaciers experienced a lower surface area reduction. This analysis reconfirms that the glacier cover at these altitudes is the main discriminant parameters in the ~~the~~ hydrological cycle of unconnected ponds.

We now analysed whether ponds with and without glacier cover within their hydrological basin experienced changes in surface area in relation to ~~certain morphological boundary conditions, such as~~ the aspect ~~or~~ and the elevation of the basin. The two classes hasve been defined accordingly to the observed threshold of 10%. Hereafter, we define these ponds as ponds without glaciers in the basin (ponds-without-glaciers), neglecting in this way relatively small glacier bodies, which could possibly be confused with snowfields. The opposite class is defined as ponds with glaciers in the basin (ponds-with-glaciers). Among ponds-with-glaciers, Table 2 shows that they are characterized by a median glacier coverage of 19%, oriented toward the east-southeast and relatively steep (31°). The observed changes according to this new classification are reported in Table 3.

In this ~~case~~analysis, we apply the Kruskal-Wallis test as the relevant post-hoc test described above. Figure ~~9~~ 7 shows the surface area changes observed during the 1992-2013 period. The changes were independent of both elevation and aspect for ponds-without-glaciers (Fig. ~~9a~~7a; Fig. ~~9c~~7c), whereas significant differences can be observed for ponds-with-glaciers. Ponds located at higher elevations experienced greater decreases (Fig. ~~9b~~7b). In particular, ponds over 5400 m a.s.l. decreased significantly ($p<0.01$) more than ponds located below 5100 m a.s.l. In terms of aspect, the south-oriented ponds (Fig. ~~9d~~7d) experienced greater decreases, which was significantly different from southeast ($p<0.01$) and southwest ($p<0.01$) orientations.

The trac~~k~~king of pond surface area~~s~~ provides ~~furthermore~~important information on precipitation and glacier melt trends in space. Ponds-without-glaciers allows to understand that ~~tThe decline of~~the precipitation in the SNP ~~since 1992~~generally ~~occurr~~occur~~ed~~ homogeneously at all elevations and in all valleys independent of the~~ir~~ orientation (Fig. 7a; Fig. 7c). Based on the greater loss of surface area for ponds-with-glaciers at lower elevations, we can infer that glacier melt is actually higher at these elevations, surely due to the effect of higher temperatures (Fig. 7b). Even in valleys oriented in directions other than south, we observe greater losses in surface area for ponds-with-glaciers (Fig. 7d). Small glaciers lying in perpendicular valleys, which are much steeper than the north-south-oriented valleys (following the monsoon direction), are likely melting more due to their small size and higher gravitational stresses (e.g., Bolch et al., 2008; Quincey et al., 2009).

5.2.2 Pond surface areas as proxy of past changes of the hydrological cycle

Climate reconstruction

To reconstruct the climatic trends before ~~the 1990s~~1994, we compared the annual and seasonal precipitation and temperature time series recorded at Pyramid station since 1994 (Salerno et al., 2015) with selected regional gridded and reanalysis datasets (Table SI1). Table 1 shows the coefficient of correlation found for these comparisons. Era Interim ($r = 0.92$, $p<0.001$) for mean temperature (Fig. 4a) and GPCC ($r = 0.92$, $p<0.001$) for precipitation (Fig. 4b) provide the best performance at the annual level. Figure SI5 shows the location of Era Interim and GPCC nodes close to the region of investigation and in particular in relation to the Pyramid station. ~~All these~~The ~~visual~~ comparisons between gridded/reanalysis and land data are ~~shown~~ visualized in Figure ~~SI1~~SI6. We observe that precipitation increased significantly until the middle 1990s (+25.6%, $p< 0.05$, 1970-1995 period), then it started to decrease significantly (-23.9%, $p< 0.01$, 1996-2010 period), as observed by the Pyramid station and described by Salerno et al., 2015. The mean temperature ~~shows~~ reveals a continuous increasing trend (+0.039 °C yr^{-1}, $p< 0.001$. 1979-2013 period) that has accelerated since the early of 1990s.

Furthermore, Table 1 shows the low capability of all the products to correctly simulate monsoon temperatures and in particular the daily maximum ones. Figure ~~SI2a~~ SI7a reports visually the~~se~~ correlations at monthly level for maximum temperature, while Figure ~~SI2b~~ SI7b highlights the misfit in the time between the maximum, mean, and minimum temperature trends during the monsoon period.

Analysis of ponds surface area in the last fifty years

~~Based on the findings related to the main drivers of changes that have influenced the 10 selected ponds, the overall pond population (all 64 ponds) has been subdivided into two classes defined in relation to the glacier cover (%) in their basins. In 2013, 25 ponds presented a glacier cover > 10% (i.e., 40% of the total ponds), and 39 ponds (i.e., 60% of the total ponds) featured glacier coverages less than this threshold. Hereafter, we define these ponds as ponds without glaciers in the basin (ponds-without-~~

~~glaciers), neglecting in this way relatively small glacier bodies, which could possibly be confused with snowfields. The opposite class is defined as ponds with glaciers in the basin (ponds-with-glaciers). Among ponds-with-glaciers, Table 2 shows that they are characterized by a median glacier coverage of 19%, oriented toward the east-southeast and very relatively steep (31°).~~

~~The observed changes according to this new classification are reported in Table 3.~~ The maps in Figure ~~7~~ 8 show the spatial differences between the two pond classes and ~~comparing~~ compare the relative annual rate of change. Generally, no difference can be observed at valley level, as confirmed by the test applied above (Fig. SI4). It is interesting to visually observe most of the pond-without–glaciers increased in the 1963-1992 period, while pond-with–glaciers increased in the 1992-2000 period. ~~Quite~~Almost all the considered ponds decreased during 2000-2013 period.

~~, whereas~~ Figure ~~8~~ 9 trackes their trends over time. We have already discussed (Fig. 4d) that, in general, all unconnected ponds over the last fifty years have decreased by approximately 10%. Additionally, the presence of glaciers within the pond basins results in divergent trends. The surface area of ponds-without-glaciers strongly decreased (-25±6%, $p<0.001$)~~,~~, from 1963 to 2013 (Fig. 9a). ~~strongly decreased (-25±6%, p<0.001), whereas, for the same period,~~ In contrast, the surface area of ponds-with-glaciers decreased much less (-6±2%, $p<0.05$) for the same period (Fig. 9b~~Table 3~~). Differences in behavior are also noticeable ~~during the intermediate~~among the periods pointed out in Table 3. In this case, we compare the median values of the relative annual rates of change. From 1963 to 1992, ponds-without-glaciers increased slightly (0.9±0.5% yr^{-1}, $p<0.1$), whereas the other ones remained constant (0.0 ±0.1% yr^{-1}). From 1992 to 2000, ponds-without-glaciers decreased slightly (-1.1±1.9% yr^{-1}, $p>0.1$), whereas the other ones increased slightly but significantly (+0.7±0.5% yr^{-1}, $p<0.05$). In the most recent period (2000 to 2013), both categories decreased, but ponds-without-glaciers decreased more (-2.3±0.7% yr^{-1}, $p<0.001$; -1.5±0.4% yr^{-1}, $p<0.001$).

The significance of the divergent trend observed between the two groups has been tested for two periods (1963-1992 and 1992-2013). Based on a Kruskal-Wallis test, in the first period, p~~P~~onds-without-glaciers ~~featured~~ ~~had~~presented significantly ($p<0.01$) higher increases than ponds-with-glaciers ~~in the first period~~ (+13±12%; 0±3%, respectively). Differently, in the second period~~-~~ ponds-without-glaciers shown higher and significantly ($p<0.01$) ~~higher~~ decreases ~~in the second period~~ (-38±6%; -6±2%, respectively).

Focusing the attention on Figure 9. this analysis concludes by assessing what we have learned from pond surface areas for the last fifty years. An increase in precipitation occurred until the middle 1990s followed by a decrease until ~~recently~~recent years. This is shown observing the GPCC precipitation series, but it is also confirmed by the behavior of ponds-without-glaciers (Fig. 9a). With regard to the glacier melt, until the 1990s it was constant. Then, an increase occurred in the early 2000s, while in the recent years a declining was observed (Fig. 9b). This is the trend shown by ponds-with-glaciers. Furthermore, since 1994 the glacier melt, calculated directly from the maximum temperature, which has been recorded by the Pyramid Laboratory, is fully in agreement with the behavior of ponds-with-glaciers. Before 1994 suitable maximum temperature cannot be derived from Gridded and Reanalysis products (Table 1 and Fig. SI7), but the ponds are able to point out that the glacier melt in those years has been constant. ~~We observed that~~ ~~S~~simply tracking the glacier surface areas~~-~~ did not yield information on the temporal behavior of glacier melt. ~~In this regard, a~~A decrease in glacier surface area has been identified over the last fifty years (Fig. 4c), but this reduction does not correspond to an increase in glacier melt, as normally expected. As discussed by other authors (Thakuri et al., 2014; Salerno et al., 2015; Wagnon et al., 2013), on the south slopes of Mt. Everest, the weaker precipitation ~~is~~could be the main cause of glacier shrinkage. In recent years, glaciers are accumulating less than they were decades ago; thus, their size is declining. In contrast, the tracking of pond surface areas demonstrates that glacier melt did not have a trend congruent to the glacier shrinkage being influence more to the maximum temperature trend.

Conclusion

The main contribution provided by this study is to have demonstrated for our case study that surface areas of unconnected ponds could be tracked to detect the behavior of precipitation and glacier melt in remote and barely accessible regions where, even for recent decades, few or no time series exist. Local end peculiar morphological conditions of each pond (possibly enhanced or reduced sediment supply, landslides, groundwater, etc…) could influence the pond surface area. However, the significant relationships found here on a wide pond population demonstrate that these factors are secondary respect to the main components of the hydrological cycle.

~~Unfortunately, before the 2000s, the availability of high-resolution satellite imagery is very limited. However, with the limited data at our disposal, important information on the evolution of certain main components of the hydrological cycle at high elevations has been discerned: an increase in precipitation occurred until the middle 1990s followed by a decrease until recently. Until the 1990s, the glacier melt was constant. Then, an increase occurred in the early 2000s. In recent years, the declining trend observed for maximum temperature has reduced the glacier melt.~~

In high-elevation Himalayan areas, unconnected glacial ponds have demonstrated a high sensitivity to climate change. In general, over the last fifty years (1963-2013), unconnected ponds have decreased significantly by approximately 10±5%. We attribute this change to both a drop in precipitation and a decrease in glacier melt caused by a decline in the maximum temperature in the recent years. Evaporation has little effect at these elevations and has remained constant over the last decade, during which the main decline in ponds surface area has been observed.

An increase in precipitation occurred until the middle 1990s followed by a decrease until recently. With regard to the glacier melt, until the 1990s it was constant. Then, an increase occurred in the early 2000s, while in the recent years a declining. Simply tracking the glacier surface areas did not yield information on the temporal behavior of glacier melt. A decrease in glacier surface area has been identified over the last fifty years, attributed by other authors to mainly the observed weaker precipitation. In contrast, the tracking of pond surface areas demonstrates that glacier melt did not have a trend congruent to the glacier shrinkage being chiefly influenced ~~more to~~by the maximum temperature trend.

In conclusion, a question arises in regard to the portability of this method. Here, portability refers to the degree to which the proposed method is replicable in other remote environments. In the Himalaya, other land based climatic series at high elevations are decidedly scarce (Barry, 2012; Rangwala and Miller, 2012; Pepin et al., 2015; Salerno et al., 2015). ~~This constraint limits the ability to further test the ability of glacier ponds to detect the main water balance components in other Himalayan high elevation regions. Therefore, ~~T~~t~~he inferences developed here could be simply applied and trends in precipitation and glacier melt inferred for the overall mountain range. Observing differences in the magnitude of changes between the two classes that differ in glacier coverage (threshold of 10%) across different periods, along an elevation gradient, or according to the basin aspect, as carried out here, could improve the confidence of the inferred findings. In contrast, in other mountain ranges with other ~~the ~~climatic conditions, the inferences developed here might not be valid, and station-observed climatic data would be required to test the ability of glacier ponds to detect the main water balance components.

Author contributions

F.S. and G.T. designed research; F.S. N.G. and S.T. analyzed data; F.S. wrote the paper. F.S. N.G. S.T. G.V. and G.T. check the data quality~~ check~~.

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Table 1. Coefficients of correlation between precipitation and temperature time series recorded at Pyramid station for the 1994-2013 period and gridded and reanalysis datasets (pre-monsoon, monsoon, and post-monsoon seasons as the months of February to May, June to September, and October to January, respectively). Bold values are significant with $p<0.01$.

		APHRODITE	GPCC	CRU	ERA Interim
Precipitation	**annual**	0.43	**0.75**	0.34	0.33

		NCEP CFS	GHCN	CRU	ERA Interim
Minimum Temperature	**pre monsoon**	**0.64**			**0.81**
	monsoon	0.47			**0.72**
	post monsoon	**0.70**			**0.65**
	annual	**0.72**			**0.92**
Mean Temperature	**pre monsoon**	**0.79**	**0.83**	**0.8**	**0.87**
	monsoon	0.61	0.51	0.42	**0.67**
	post monsoon	**0.79**	**0.77**	0.57	**0.82**
	annual	**0.81**	**0.85**	**0.89**	**0.92**
Maximum Temperature	**pre monsoon**	**0.83**			**0.88**
	monsoon	0.54			0.45
	post monsoon	**0.82**			**0.86**
	annual	**0.70**			**0.80**

Table 2. General summary of the morphological features of all ~~the~~ 64 considered ponds (data from 2013). Ponds are grouped according to the glacier cover present into each pond basin.

Topography	**Glacier cover <10% median (range)**	**Glacier cover >10% median (range)**	**All lakes median (range)**
Pond elevation (m a.s.l.)	5181(4460-5484)	5159(4505-5477)	5170(4460-5484)
Pond area (10^4 m^2)	0.8(0.1-6.2)	1.3(0.3-56.3)	1.1(0.1-56.3)
Basin area (10^4 m^2)	30(2-430)	130(30-2300)	70(2-2300)
Basin slope (°)	25(10-39)	29(23-41)	27(10-41)
Basin aspect (°)	163(68-256)	141(94-280)	159(68-280)
Basin mean elevation (m a.s.l.)	5293(4760-5531)	5400(5119-5945)	5315(4760-5945)
Basin/Pond area ratio (m^2/m^2)	60(3-485)	67(10-523)	64(3-523)
Glacier area (%)	0(0-9)	19(10-61)	0.5(0-61)
Glacier slope (°)	-	31(21-38)	-
Glacier aspect (°)	-	166(150-250)	-
Glacier mean elevation (m a.s.l.)	-	5680(5470-7500)	-

Table 3. General summary of surface area changes related to all 64 considered pond~~s~~ ~~surface area changes~~ from 1963 to 2013. The surface area changes of the glaciers located within the basins are also reported. For each comparison the uncertainty of measurement is also shown. On the right the cumulative loss respect to 1963 is reported for eac intermediate period (these data are used for Fig. 8). On the left the relative annual rate are calculated (these data are used for Fig. 7).

Period	**Pond surface area change**			**Glacier surface area change**
	Cumulative loss (%)			Cumulative loss (%)
Glacier coverage	< 10%	> 10%	All ponds	All basins
1963-1992	**+13±12 ·**	**0 ±3**	**+3 ±7**	**8 ±8**
1963-2000	-1 ±6	+9 ±2 *	+7 ±4	-2 ±8
1963-2008	-4 ±5	+3 ±2	+1 ±4	-13 ±9 **
1963-2011	-7 ±6	0 ±2	-2 ±5	-14 ±14 **
1963-2013	**-25 ±6 *****	**-6 ±2 ***	**-10 ±5 ****	**-26 ±20 ****
1992-2013	**-38 ±6 *****	**-6 ±2 ***	**-13 ±5 ****	**-34 ±15 *****

Period	**Pond surface area change**		
	Relative annual rate (% yr^{-1})		
Glacier coverage	< 10%	> 10%	All ponds
1963-1992	**0.9 ±0.5 ·**	**0.0 ±0.1**	**+0.5 ±0.3**
1992-2000	**-1.1 ±1.9**	**+0.7 ±0.5 ***	**-0.4 ± 0.1**
2000-2008	-0.3 ±1.0	-1.6±0.6	-0.7 ±0.7
2008-2011	0.0 ±2.8	0.0 ±1.6	0.0 ±2.2
2011-2013	-12.9 ±4.4 ***	-5.8 ±2.5 *	-11±3.5 **
2000-2013	**-2.3±0.7 *****	**-1.5 ±0.4 *****	**-1.7 ±0.6 *****

*significance: p<0.001 '***'; p<0.01 '**'; p<0.05 '*'; p<0.1 '·'*

Table 4. Morphometric features of 10 selected ponds considered in the 2000-2013 analysis. Data are from 2013. Coefficients of correlation are for the monsoon season. The relationships with the other seasons are reported in Table SI5.

Pond Code	Glacier Cover (%)	Pond Elevation (m a.s.l.)	Basin Aspect (°)	Basin Slope (°)	Basin Area (km^2)	Pond Area (10^4 m^2)	Basin Elevation (m a.s.l.)	Coefficient of Correlation (Ponds surface area vs Precipitation)	Coefficient of Correlation (Ponds surface area vs Glacier melt)
LCN139	1	4749	75	30	0.6	4.6	5596	0.50	0.35
LCN93	2	5244	116	23	0.7	0.6	5502	0.70 **	0.39
LCN141	3	5316	152	27	1.4	2.6	5701	0.72 **	0.37
LCN11	3	5029	229	24	1.2	1.8	5372	0.76 **	0.49
LCN77	7	4920	142	26	8.6	18.3	5507	0.55 *	0.29
LCN76	9	4800	140	25	13.6	59.2	5457	0.65 **	0.23
LCN24	10	4466	162	28	23.0	54.0	5477	0.44	0.65 **
LCN9	13	5202	117	36	0.7	0.6	5792	-0.27	0.61 **
LCN3	30	5261	154	35	2.0	11.7	5981	0.17	0.87 ***
LCN68	32	5006	232	35	1.2	3.2	5686	0.12	0.65 **
Median	8	5018	147	28	1.3	3.9	5551		

*significance: p<0.001 '***'; p<0.01 '**'; p<0.05 '*'; p<0.1 '·'*

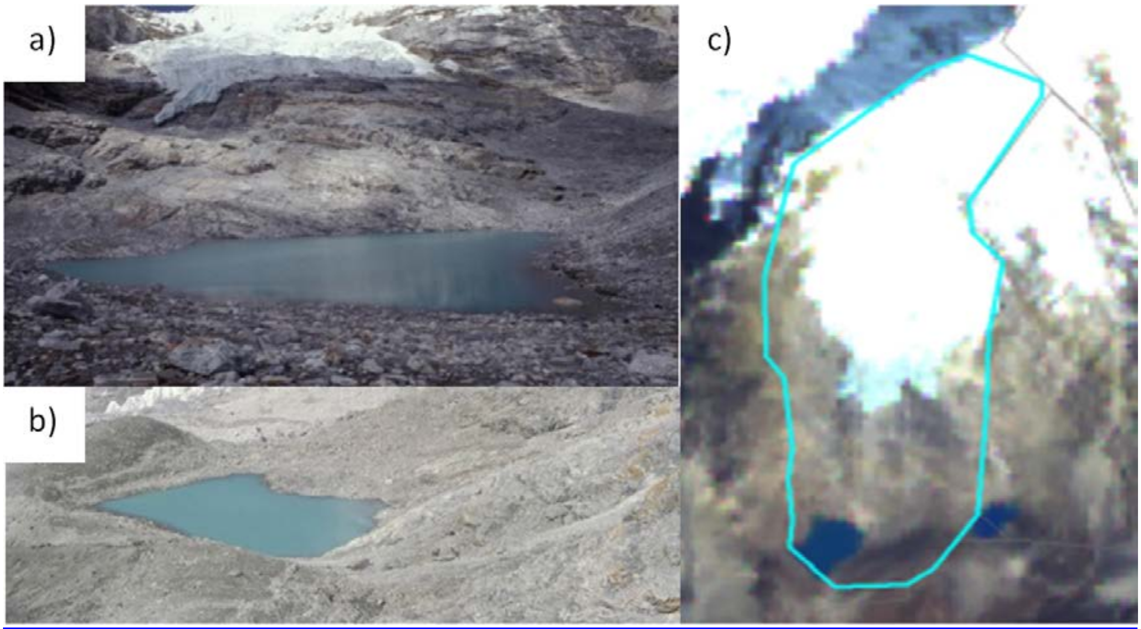

Figure 1. Example of an unconnected glacial pond (LCN5) with a glacier within the basin. Pictures were taken in September 1992 (Gabriele Tartari): a) view looking north showing the distance between the glacier and the pond surface; b) from east showing the frontal moraine. c) LCN5 basin tracked on ALOS 2008 imagery.

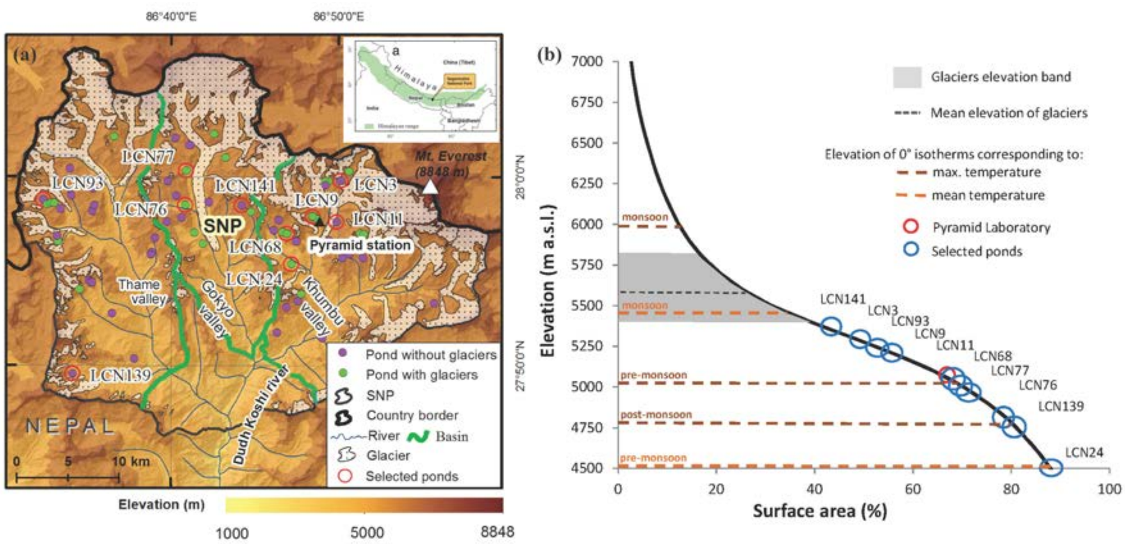

Figure 2. a) Location of the study area in the Himalaya and a detailed map of the spatial distribution of all 64 unconnected ponds ~~analyzed~~ considered in this study. b) Hypsometric curve of SNP. Along this curve, the locations of 10 selected ponds are shown. The 0 °C isotherms corresponding to the mean and maximum temperature in 2013 are plotted for the pre-, post-, and monsoon period according to the lapse rates reported in Salerno et al., 2015. The mean glacier elevation distribution (mean ± 1 standard deviation) of 10 selected ponds and the location of the ~~...~~Pyramid meteorological station are also reported.

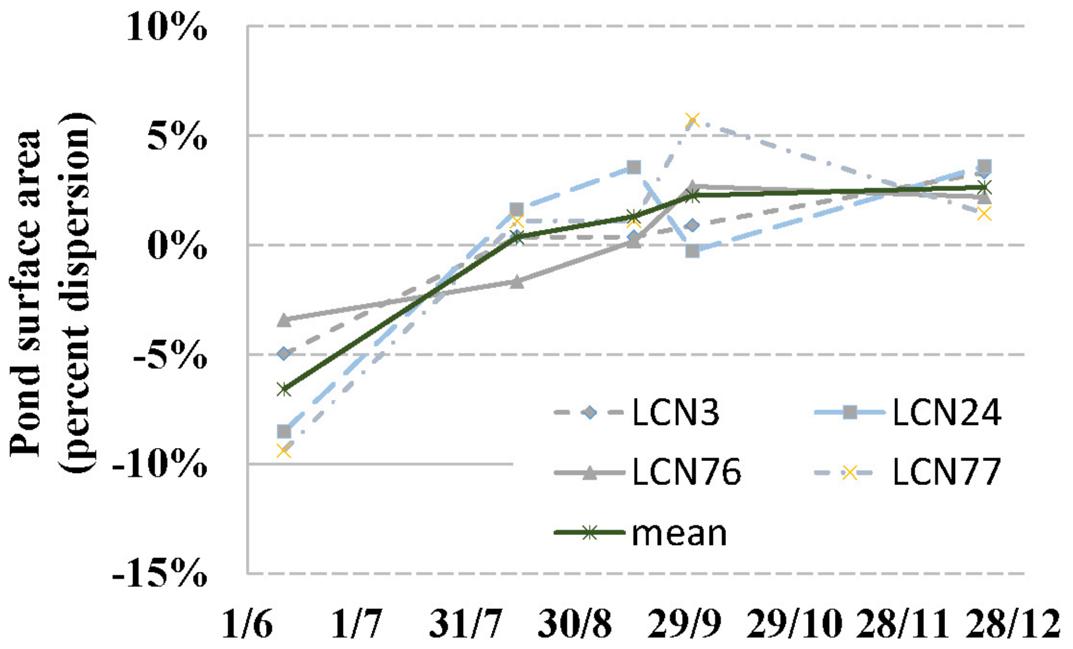

Figure 3. Intra-annual analysis (June-December) of selected pond surface areas. Percent dispersions are computed dividing the anomalies by the mean.

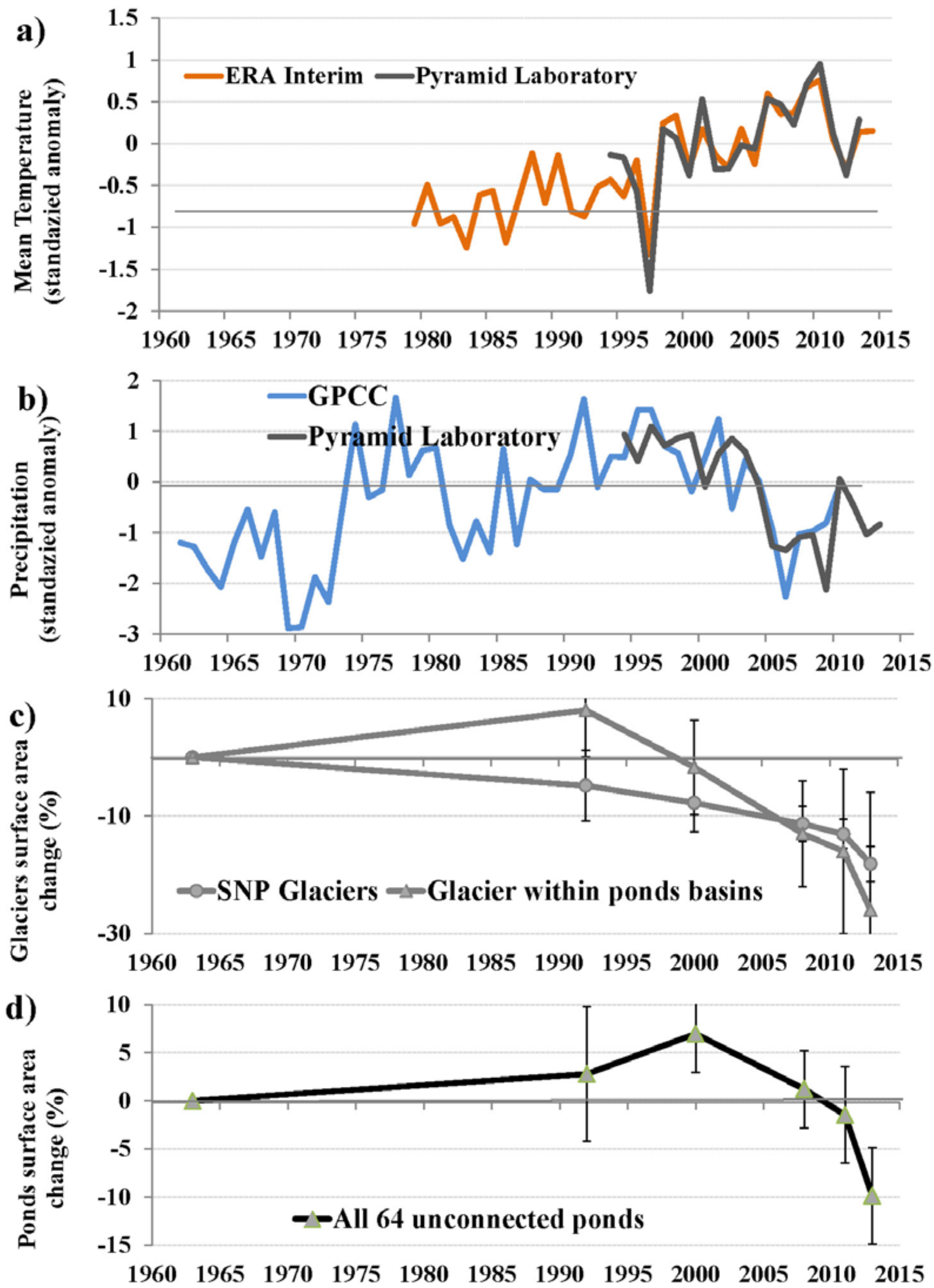

Figure 4. Trend analysis of climate, glaciers and ponds surface area for the last fifty years in the SNP: a) Era Interim mean annual temperature compared with Pyramid's land-based data; b) GPCC annual precipitation and Pyramid's land-based data; c) Glacier surface area variations for the overall SNP (Thakuri et al., 2014) and for glaciers located in basins ~~with~~ of 64 considered ponds. d) Surface area variations of ~~the~~ all 64 considered ponds. Y-axis units: a) and b) Trends are expressed in terms of standardized anomalies divided by the standard deviation (dimensionless); c) and d) Relative variations with respect to 1963. Errors bars represent the uncertainty of measurements.

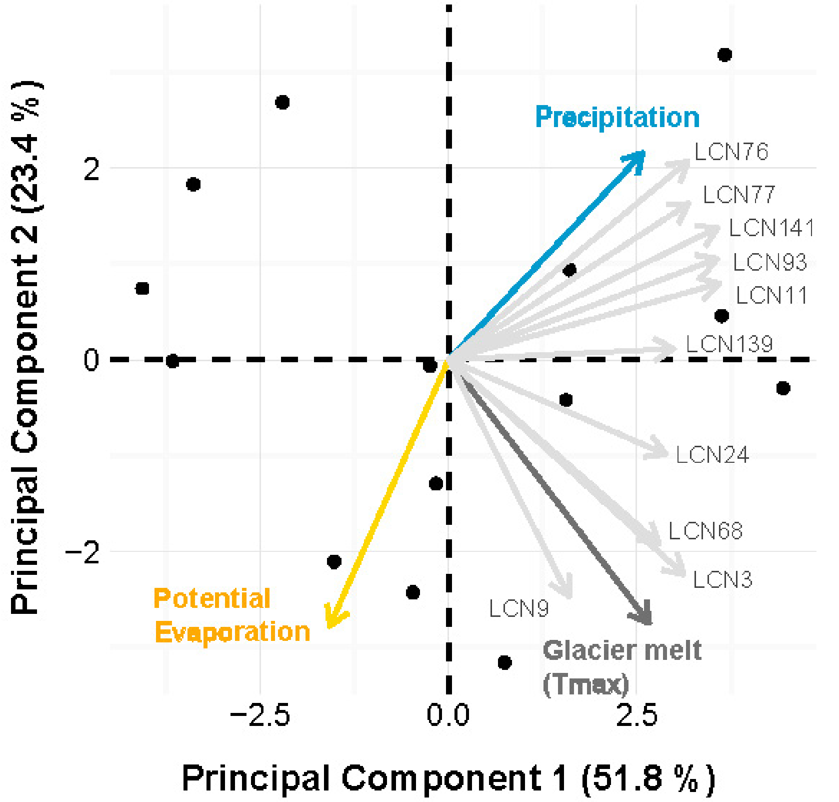

Figure 5. Principal Component Analyses (PCAs) between pond surface area from 2000 to 2013 and potential drivers of change (~~maximum temperature, ~~precipitation, glacier melt, and potential evaporation) related to the monsoon season. Coefficients of correlation are reported in Table SI5. All trends related to ponds and variables are provided in Figure ~~SI1~~ SI5 and ~~SI2~~SI6.

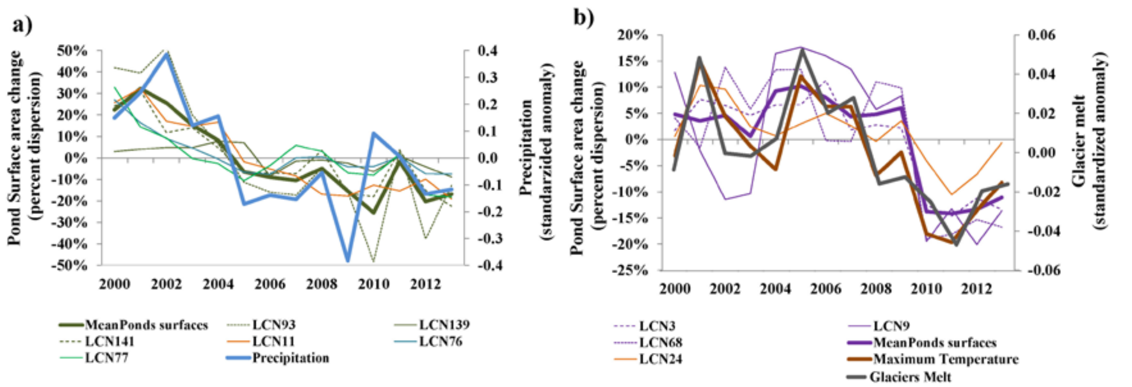

Figure 6. Annual trends from 2000 to 2013 related to pond surface area grouped according to the relevant main drivers of change (monsoon season): a) precipitation~~glacier melt (maximum temperature)~~, b) glacier melt ~~precipitation~~. Coefficients of correlation are reported in Table SI5. All trends related to ponds and variables are provided in Figures ~~SI1~~ SI5 and ~~SI2~~SI6. Standardized anomalies (dimensionless) are computed dividing the anomalies by the ~~mean~~standard deviation. Percent dispersions are computed dividing the anomalies by the mean.

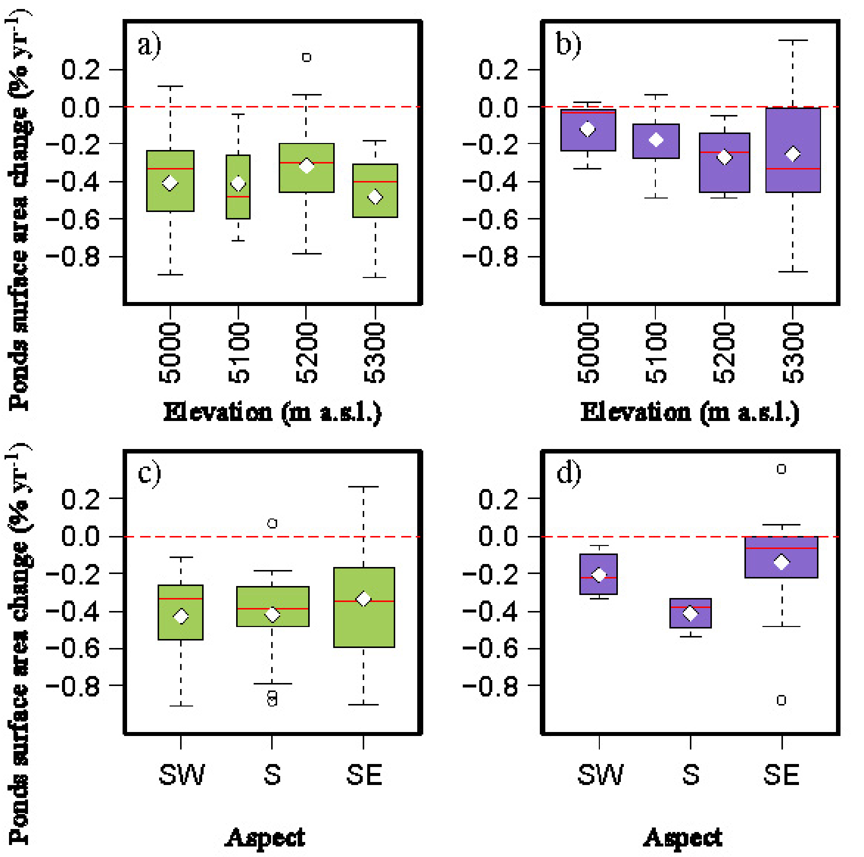

Figure 7. Pond surface area changes observed during the 1992-2013 period in relation to certain morphological boundary conditions in the basin: elevation (upper graphs) and aspect (lower graphs). On the left ponds-without-glaciers, and on the right ponds-with-glaciers. The white points in the boxplots

indicate the mean, whereas the red lines are the median.

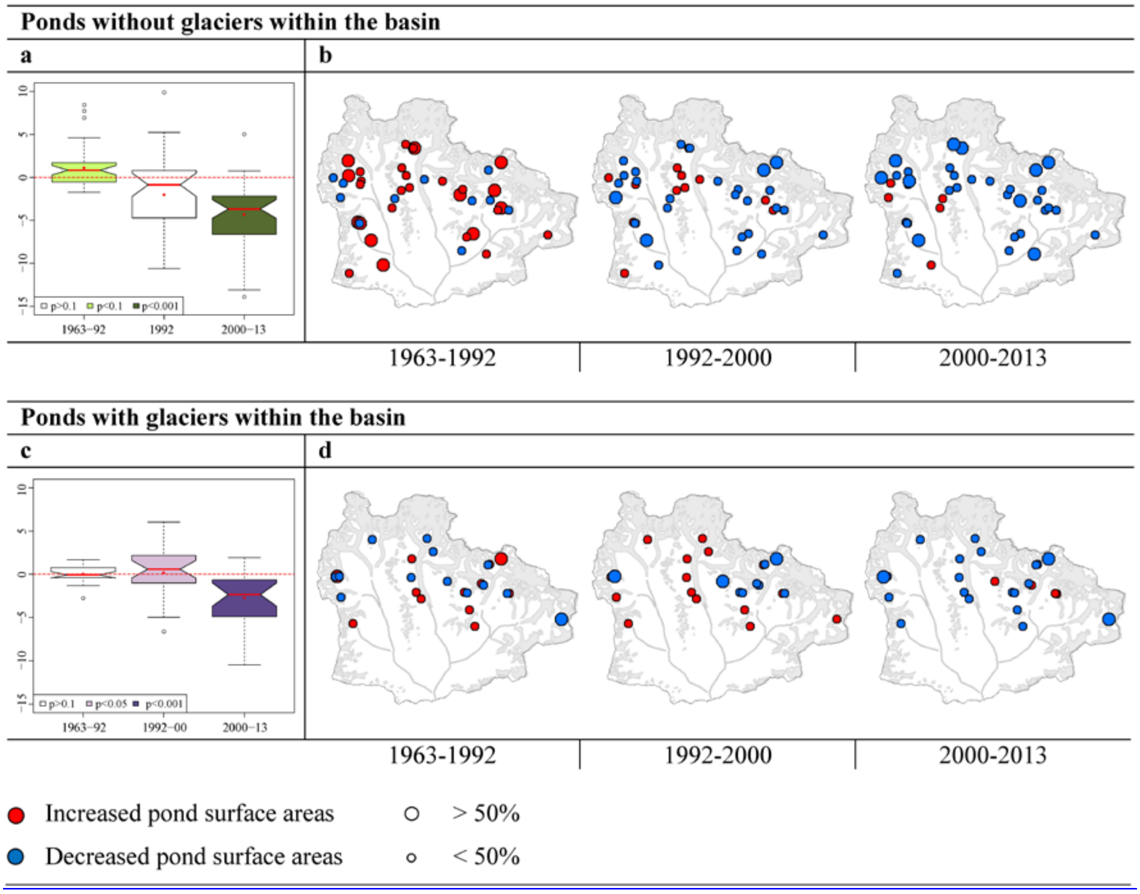

Figure ~~7~~8. Changes in pond surface area in the Mt. Everest region. The left boxplots represent the annual rates of change of ponds in the analyzed periods: (a) ponds without glaciers within the basin, (c) ponds with~~out~~ glaciers within the basin. The ~~blue~~ red points in the boxplots indicate the mean, whereas the red lines ~~is~~ are the median. Data are expressed as % yr^{-1}. On the right side, the maps (b, d) visualize the variations that occurred in the pond population during the same three periods considered in the relevant boxplots on the left. Reference data are reported in Table 3. All percentages refer to the initial year of the analysis (1963).

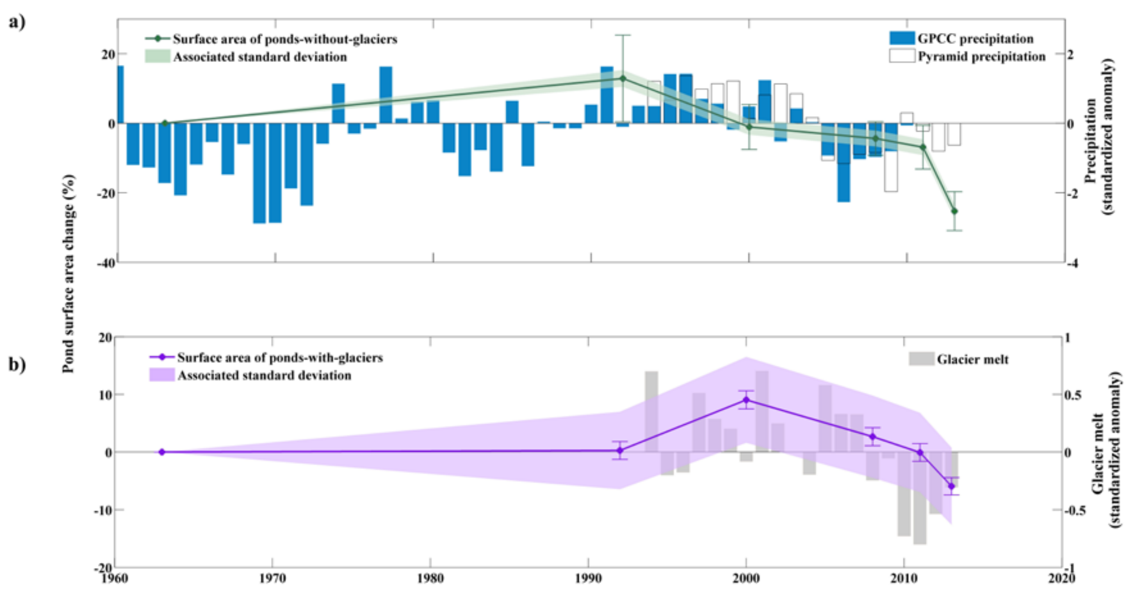

Figure ~~8~~9. ~~Trend analysis for the last fifty years of pond surface area in the SNP for a) ponds-without-glaciers and b) ponds-with-glaciers.~~ Comparison for the last fifty years between the annual precipitation and the glacier melt with the surface areas for a) ponds-without glaciers and b) ponds-with-glaciers. Standardized anomalies (dimensionless) are computed dividing the anomalies by the standard deviation. Error bars represent the uncertainty of measurements.

Supporting Information

Table SI1 *List of gridded and reanalysis data investigated in this study with relevant technical specifications.*

Meteorological variables	Product	Version	Temporal resolution	Temporal coverage	Spatial resolution	Spatial coverage	Produced by	Web site	Reference
Gridded data									
Temperature	**GHCN CAMS** (Global Historical Climatology Centre, the Climate Anomaly Monitoring System)	-	monthly	1948-present	0.5°	Global land (89.75°S - 89.75°N, 0.25°E - 359.75°E)	Climate Prediction Center (CPC) of the National Centers for Environmental Prediction (NCEP).	http://www.esrl.noaa.gov/psd/data/gridded/data.ghcncams.html	Fan, van den Dool (2008)
Temperature/Precipitation	**CRU TS** (Climate Research Unit -Time Series)	V3.2	monthly	1901-2011	0.5°	Global	Climate Research Unit - University of East Anglia	http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__ACTIVITY_3ec0d1c6-4616-11e2-89a3-00163e251233	Harris et al. (2015)
Precipitation	**APHRODITE**	V1101	daily	1951-2007	0.25°	Regional land (15°S - 55°N, 60°E - 150°E)	APHRODITE (Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources) project in collaboration with the Research Institute for Humanity and Nature and the Meteorological Research Institute of the Japan Meteorological Agency	http://www.chikyu.ac.jp/precip/products/index.html	Yatagai et al. (2012)
Precipitation	**GPCC** (Global Precipitation Climatology Centre)	V6	monthly	1901-2010	0.5°	Global	Deutscher Wetterdienst (National Meteorological Service of Germany) in the framework of the World Climate Research Program	http://www.esrl.noaa.gov/psd/	Schneider et al. (2013)
Reanalysis data									
Temperature/Precipitation	**NCEP CFS** (National Centers for Environmental Prediction- Climate Forecast System)	V2	hourly	1979-present	0.5°	Global	National Centers for Environmental Prediction (NCEP)	http://cfs.ncep.noaa.gov/cfsr/	Saha et al. (2010)
Temperature/Precipitation	**ERA Interim**	-	6-hourly	1979-present	0.75°	Global	ECMWF (European Centre for Medium-Range Weather Forecasts)	http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/	Dee et al. (2011)

Table SI2. *Data sources used for tracing the inter-annual variations of glaciers and ponds since the early 1960s*

Abbreviation used in the text	**Topographic map**	**Acquisition date**	**Scale**	**Acquisition technique**
TISmap-63	Topographic map of Indian Survey	1963	1:50 000	Vertical aerial photographic survey 1957-1959 and field survey in 1963 (Yamada, 1998)

Abbreviation used in the text	**Satellite image**	**Acquisition date**	**Spatial resolution (m)**	**Sensor**	**Scene ID**
Landsat-92	Landsat 5	17 Nov 1992	30	TM	ETP140R41_5T19921117
Landsat-00	Landsat 7	30 Oct 2000	15[a]	ETM+	LE71400412000304SGS00
ALOS-08	ALOS	24 Oct 2008	10	AVNIR-2	ALAV2A146473040
Landsat-11	Landsat 7	30 Nov 2011	15[a,b]	ETM+	LE71400412011334EDC00
Landsat-13	Landsat 8	10 Oct 2013	15[a]	OLI	LC81400412013283LGN00

a Pan-sharpened images; b SLC-off image

Table SI3. *Data sources used for the inter-annual variations analysis carried out during the 2000-2013 period*

Satellite image	Acquisition date	Spatial resolution (m)	Sensor	Scene ID
Landsat 7	30 Oct 2000	15 (pan sharpened)	ETM+	LE71400412000304SGS00
	17 Oct 2001			LE71400412001290SGS00
	20 Oct 2002			LE71400412002293SGS00
	8 Nov 2003			LE71400412003312ASN01
	10 Nov 2004			LE71400412004315PFS00
	28 Oct 2005			LE71400412005301PFS00
	16 Nov 2006			LE71400412006320PFS00
	19 Nov 2007			LE71400412007323PFS00
	07 Dec 2008			LE71400412008342SGS00
	08 Nov 2009			LE71400412009312SGS00
	11 Nov 2010			LE71400412010315PFS00
	30 Nov 2011			LE71400412011334EDC00
	17 Nov 2012			LE71400412012321PFS00
Landsat 8	10 Oct 2013	15 (pan sharpened)	OLI	LC81400412013283LGN00

Table SI4. *Data sources used for the intra-annual variations analysis carried out during the 2001 year*

Satellite image	Spatial Resolution (m)	Sensor	Acquisition date	Scene ID
Landsat 7	15 (pan sharpened)	ETM+	11 Jun 2001	LE71400412001162SGS00
			14 Aug 2001	LE71400412001226SGS00
			15 Sep 2001	LE71400412001258SGS00
			17 Oct 2001	LE71400412001290SGS00
			20 Dec 2001	LE71400412001354SGS00

Table SI5. *Correlation Coefficient Matrix between pond surface area variations during the 2000-2013 period and selected drivers of change.*

Driver/Pond Code		LCN139	LCN93	LCN141	LCN11	LCN77	LCN76	LCN24	LCN9	LCN3	LCN68
Mean Temperature (Tmean)	pre-	-0.40	-0.53	-0.51	-0.34	-0.45	-0.51	-0.06	-0.04	-0.10	-0.18
	monsoon	0.02	0.18	0.14	0.27	0.05	0.15	0.54	0.08	0.32	0.09
	post-	-0.41	-0.36	-0.27	-0.35	-0.20	-0.29	0.06	-0.03	-0.04	-0.24
	annual	-0.47	-0.52	-0.45	-0.37	-0.36	-0.42	0.08	-0.06	-0.10	-0.29
Minimum Temperature	pre-	-0.51	-0.52	-0.54	-0.43	-0.52	-0.54	-0.15	-0.26	-0.33	-0.40
	monsoon	-0.31	-0.20	-0.25	-0.17	-0.23	-0.05	0.21	-0.40	-0.38	-0.42
	post-	-0.49	-0.47	-0.45	-0.51	-0.32	-0.37	-0.02	-0.18	-0.27	-0.36
	annual	-0.54	-0.52	-0.53	-0.54	-0.53	-0.54	-0.10	-0.31	-0.41	-0.51
Maximum Temperature (Tmax)	pre-	-0.16	-0.33	-0.29	-0.12	-0.23	-0.37	0.22	0.29	0.35	0.25
	monsoon	0.38	0.44	0.40	0.51	0.30	0.25	0.65	0.58	0.83	0.61
	post-	-0.19	-0.10	0.02	-0.07	0.05	-0.06	0.29	0.17	0.28	0.02
	annual	-0.06	-0.12	-0.01	0.08	0.05	-0.09	0.45	0.42	0.54	0.29
Glacier Melt (Tmax)	pre	-0.15	-0.34	0.48	0.05	-0.16	-0.26	0.22	0.21	0.27	0.03
	monsoon	0.35	0.39	0.37	0.49	0.29	0.23	0.65	0.61	0.87	0.65
	post	0.23	0.45	0.41	0.37	0.56	0.52	0.30	0.37	0.23	0.12
	annual	0.32	0.24	0.36	0.48	0.36	0.27	0.51	0.60	0.68	0.41
Glacier Melt (Tmean)	pre	-0.45	-0.42	-0.45	-0.31	-0.54	-0.38	-0.35	-0.47	-0.51	-0.51
	monsoon	-0.05	-0.01	-0.03	0.15	-0.14	-0.07	0.44	0.06	0.24	-0.02
	post	-0.03	-0.08	0.03	-0.25	0.11	-0.01	-0.39	-0.22	-0.46	-0.50
	annual	-0.07	-0.03	-0.05	0.11	-0.16	-0.09	0.39	0.01	0.17	-0.09
Precipitation	pre-	0.46	0.73	0.69	0.83	0.41	0.59	0.75	-0.22	0.37	0.21
	monsoon	0.50	0.70	0.72	0.76	0.55	0.65	0.44	-0.27	0.17	0.12
	post-	0.39	0.52	0.67	0.62	0.30	0.45	0.60	-0.09	0.36	0.16
	annual	0.50	0.64	0.69	0.74	0.55	0.61	0.41	-0.38	0.10	0.03
Potential Evaporation	pre-	-0.54	-0.54	-0.52	-0.37	-0.30	-0.40	-0.22	-0.22	-0.37	-0.54
	monsoon	-0.32	-0.45	-0.52	-0.36	-0.52	-0.52	0.04	-0.08	-0.04	-0.17
	post-	0.17	0.47	0.31	0.25	0.52	0.53	0.52	-0.02	0.10	0.27
	annual	-0.47	-0.41	-0.52	-0.36	-0.44	-0.44	0.27	-0.20	-0.14	-0.24

p<0.001
p<0.01
p<0.05

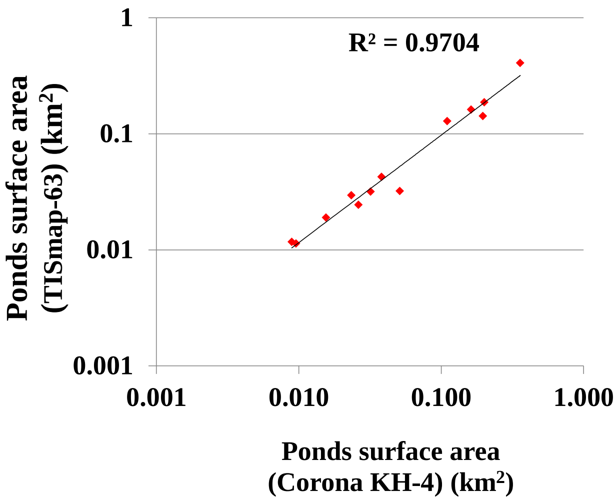

Figure SI1. *Scatter-plot between ponds surface areas digitalized on Corona (KH-4) and TISmap-63*

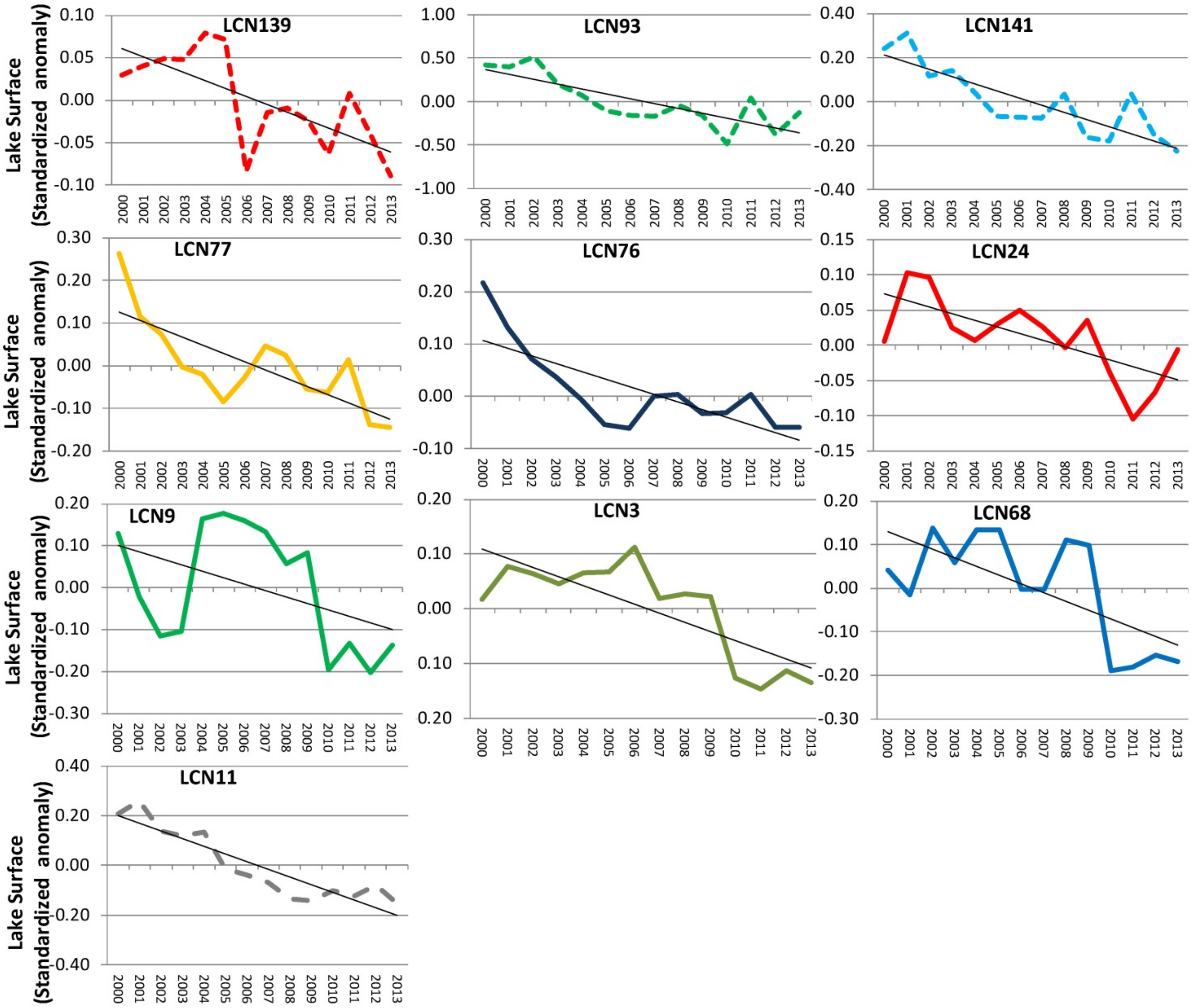

Figure SI2. *Surfaces area variations during the period 2000-2013 of 10 selected ponds. Standardized anomalies (dimensionless) are computed dividing the anomalies for the standard deviation.*

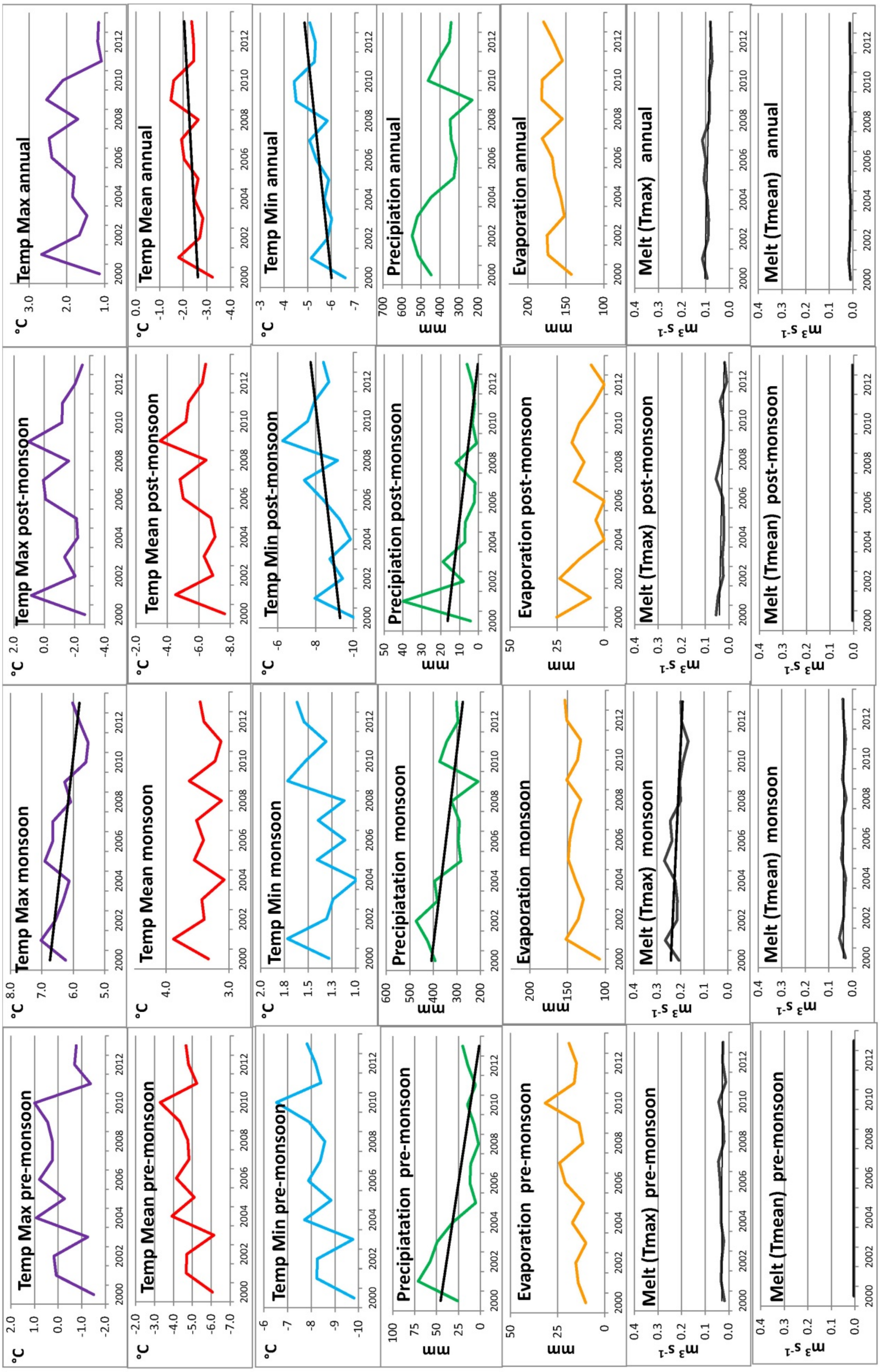

Figure SI3. *Climatic trends for the period 2000-2013 at the Pyramid Laboratory (5050 m a.s.l.) for mean (Tmean), maximum (Tmax), minimum temperature, precipitation, potential evaporation, and glacier melt calculated for each glacier considering Tmax and Tmean. The regression line is indicated only in those graphs for which the trend is significant.*

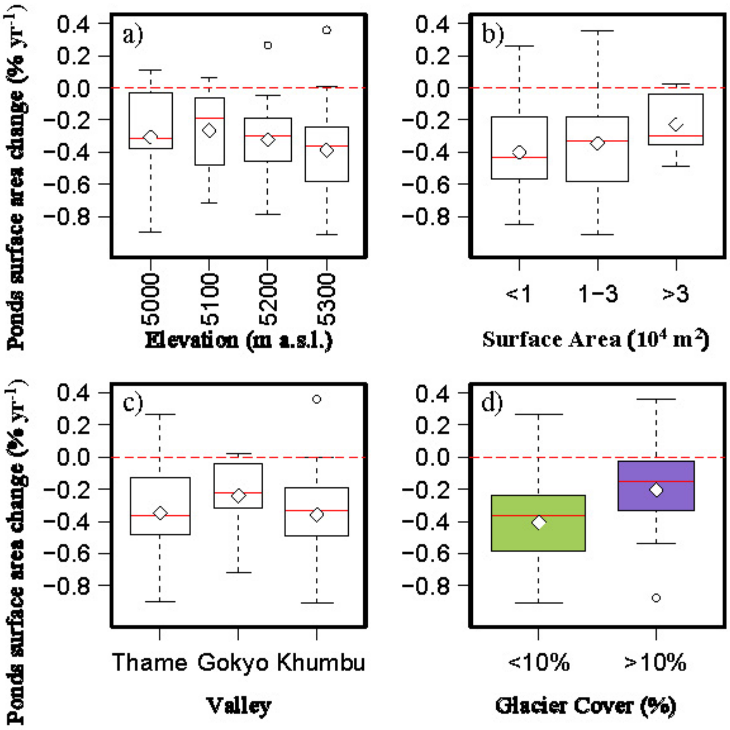

Figure SI4. *Surface area changes observed during the 1992-2013 period for all 64 considered ponds in relation to certain morphological boundary conditions: a) elevation; b) pond surface area; c) valley; d) glacier cover. The white points in the boxplots indicate the mean, whereas the red lines are the median.*

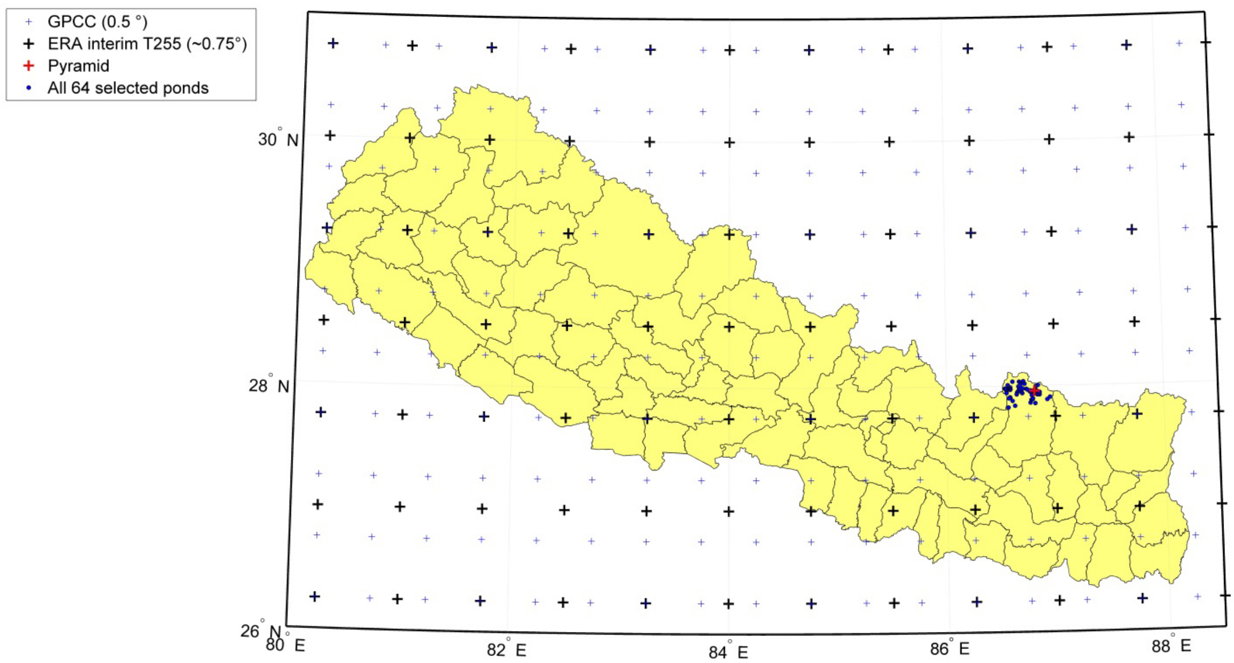

Figure SI5. *Map of Nepal showing the location of 64 considered lakes in Sagarmatha National Park, Era Interim, and GPPC nodes*

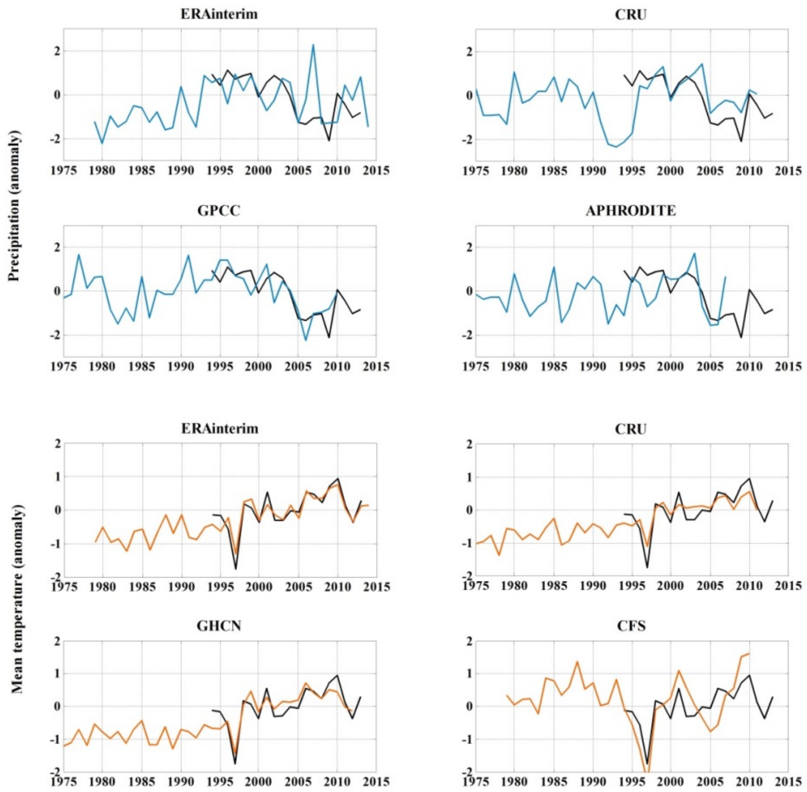

Figure SI6. *Comparison between annual precipitation and mean temperature time series recorded at Pyramid station since 1994 (black lines) with the selected regional gridded and reanalysis datasets. In Table 1 the relevant coefficients of correlation are reported*

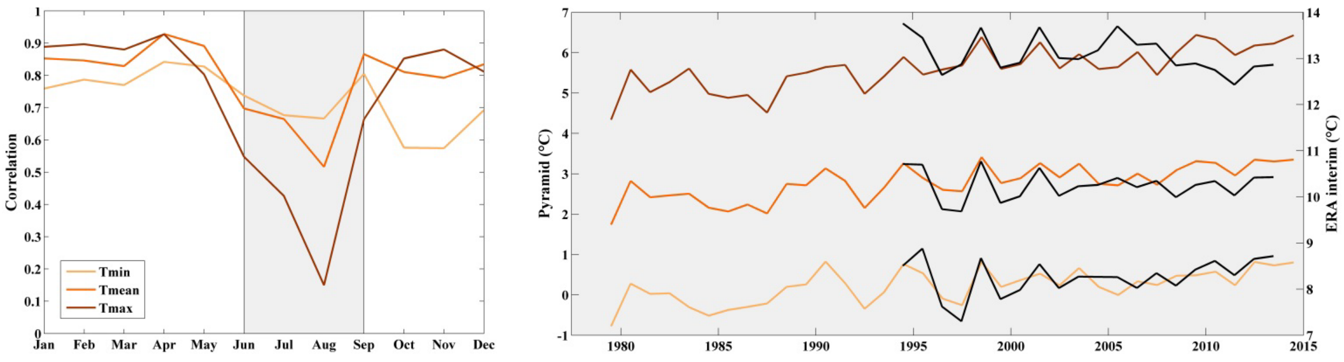

Figure SI7. *a) Monthly coefficients of correlation between temperature recorded at Pyramid Station and Era Interim data (1994-2013 period)during the monsoon season. b) Temporal comparison among Era Interim and Pyramid data (black lines).*

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Supporting Information

Table SI1 *List of gridded and reanalysis data investigated in this study with relevant technical specifications.*

Meteorological variables	Product	Version	Temporal resolution	Temporal coverage	Spatial resolution	Spatial coverage	Produced by	Web site	Reference
Gridded data									
Temperature	**GHCN CAMS** (Global Historical Climatology Centre, the Climate Anomaly Monitoring System)	-	monthly	1948-present	0.5°	Global land (89.75°S - 89.75°N, 0.25°E - 359.75°E)	Climate Prediction Center (CPC) of the National Centers for Environmental Prediction (NCEP).	http://www.esrl.noaa.gov/psd/data/gridded/data.ghcncams.html	Fan, van den Dool (2008)
Temperature/Precipitation	**CRU TS** (Climate Research Unit -Time Series)	V3.2	monthly	1901-2011	0.5°	Global	Climate Research Unit - University of East Anglia	http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__ACTIVITY_3ec0d1c6-4616-11e2-89a3-00163e251233	Harris et al. (2015)
Precipitation	**APHRODITE**	V1101	daily	1951-2007	0.25°	Regional land (15°S - 55°N, 60°E - 150°E)	APHRODITE (Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources) project in collaboration with the Research Institute for Humanity and Nature and the Meteorological Research Institute of the Japan Meteorological Agency	http://www.chikyu.ac.jp/precip/products/index.html	Yatagai et al. (2012)
Precipitation	**GPCC** (Global Precipitation Climatology Centre)	V6	monthly	1901-2010	0.5°	Global	Deutscher Wetterdienst (National Meteorological Service of Germany) in the framework of the World Climate Research Program	http://www.esrl.noaa.gov/psd/	Schneider et al. (2013)
Reanalysis data									
Temperature/Precipitation	**NCEP CFS** (National Centers for Environmental Prediction- Climate Forecast System)	V2	hourly	1979-present	0.5°	Global	National Centers for Environmental Prediction (NCEP)	http://cfs.ncep.noaa.gov/cfsr/	Saha et al. (2010)
Temperature/Precipitation	**ERA Interim**	-	6-hourly	1979-present	0.75°	Global	ECMWF (European Centre for Medium-Range Weather Forecasts)	http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/	Dee et al. (2011)

Table SI2. *Data sources used for tracing the inter-annual variations of glaciers and ponds since the early 1960s*

Abbreviation used in the text	**Topographic map**	**Acquisition date**	**Scale**	**Acquisition technique**
TISmap-63	Topographic map of Indian Survey	1963	1:50 000	Vertical aerial photographic survey 1957-1959 and field survey in 1963 (Yamada, 1998)

Abbreviation used in the text	**Satellite image**	**Acquisition date**	**Spatial resolution (m)**	**Sensor**	**Scene ID**
Landsat-92	Landsat 5	17 Nov 1992	30	TM	ETP140R41_5T19921117
Landsat-00	Landsat 7	30 Oct 2000	15[a]	ETM+	LE71400412000304SGS00
ALOS-08	ALOS	24 Oct 2008	10	AVNIR-2	ALAV2A146473040
Landsat-11	Landsat 7	30 Nov 2011	15[a,b]	ETM+	LE71400412011334EDC00
Landsat-13	Landsat 8	10 Oct 2013	15[a]	OLI	LC81400412013283LGN00

a Pan-sharpened images; b SLC-off image

Table SI3. *Data sources used for the inter-annual variations analysis carried out during the 2000-2013 period*

Satellite image	Acquisition date	Spatial resolution (m)	Sensor	Scene ID
Landsat 7	30 Oct 2000	15 (pan sharpened)	ETM+	LE71400412000304SGS00
	17 Oct 2001			LE71400412001290SGS00
	20 Oct 2002			LE71400412002293SGS00
	8 Nov 2003			LE71400412003312ASN01
	10 Nov 2004			LE71400412004315PFS00
	28 Oct 2005			LE71400412005301PFS00
	16 Nov 2006			LE71400412006320PFS00
	19 Nov 2007			LE71400412007323PFS00
	07 Dec 2008			LE71400412008342SGS00
	08 Nov 2009			LE71400412009312SGS00
	11 Nov 2010			LE71400412010315PFS00
	30 Nov 2011			LE71400412011334EDC00
	17 Nov 2012			LE71400412012321PFS00
Landsat 8	10 Oct 2013	15 (pan sharpened)	OLI	LC81400412013283LGN00

Table SI4. *Data sources used for the intra-annual variations analysis carried out during the 2001 year*

Satellite image	Spatial Resolution (m)	Sensor	Acquisition date	Scene ID
Landsat 7	15 (pan sharpened)	ETM+	11 Jun 2001	LE71400412001162SGS00
			14 Aug 2001	LE71400412001226SGS00
			15 Sep 2001	LE71400412001258SGS00
			17 Oct 2001	LE71400412001290SGS00
			20 Dec 2001	LE71400412001354SGS00

Table SI5. *Correlation Coefficient Matrix between pond surface area variations during the 2000-2013 period and selected drivers of change.*

Driver/Pond Code		LCN139	LCN93	LCN141	LCN11	LCN77	LCN76	LCN24	LCN9	LCN3	LCN68
Mean Temperature (Tmean)	pre-	-0.40	-0.53	-0.51	-0.34	-0.45	-0.51	-0.06	-0.04	-0.10	-0.18
	monsoon	0.02	0.18	0.14	0.27	0.05	0.15	0.54	0.08	0.32	0.09
	post-	-0.41	-0.36	-0.27	-0.35	-0.20	-0.29	0.06	-0.03	-0.04	-0.24
	annual	-0.47	-0.52	-0.45	-0.37	-0.36	-0.42	0.08	-0.06	-0.10	-0.29
Minimum Temperature	pre-	-0.51	-0.52	-0.54	-0.43	-0.52	-0.54	-0.15	-0.26	-0.33	-0.40
	monsoon	-0.31	-0.20	-0.25	-0.17	-0.23	-0.05	0.21	-0.40	-0.38	-0.42
	post-	-0.49	-0.47	-0.45	-0.51	-0.32	-0.37	-0.02	-0.18	-0.27	-0.36
	annual	-0.54	-0.52	-0.53	-0.54	-0.53	-0.54	-0.10	-0.31	-0.41	-0.51
Maximum Temperature (Tmax)	pre-	-0.16	-0.33	-0.29	-0.12	-0.23	-0.37	0.22	0.29	0.35	0.25
	monsoon	0.38	0.44	0.40	0.51	0.30	0.25	0.65	0.58	0.83	0.61
	post-	-0.19	-0.10	0.02	-0.07	0.05	-0.06	0.29	0.17	0.28	0.02
	annual	-0.06	-0.12	-0.01	0.08	0.05	-0.09	0.45	0.42	0.54	0.29
Glacier Melt (Tmax)	pre	-0.15	-0.34	0.48	0.05	-0.16	-0.26	0.22	0.21	0.27	0.03
	monsoon	0.35	0.39	0.37	0.49	0.29	0.23	0.65	0.61	0.87	0.65
	post	0.23	0.45	0.41	0.37	0.56	0.52	0.30	0.37	0.23	0.12
	annual	0.32	0.24	0.36	0.48	0.36	0.27	0.51	0.60	0.68	0.41
Glacier Melt (Tmean)	pre	-0.45	-0.42	-0.45	-0.31	-0.54	-0.38	-0.35	-0.47	-0.51	-0.51
	monsoon	-0.05	-0.01	-0.03	0.15	-0.14	-0.07	0.44	0.06	0.24	-0.02
	post	-0.03	-0.08	0.03	-0.25	0.11	-0.01	-0.39	-0.22	-0.46	-0.50
	annual	-0.07	-0.03	-0.05	0.11	-0.16	-0.09	0.39	0.01	0.17	-0.09
Precipitation	pre-	0.46	0.73	0.69	0.83	0.41	0.59	0.75	-0.22	0.37	0.21
	monsoon	0.50	0.70	0.72	0.76	0.55	0.65	0.44	-0.27	0.17	0.12
	post-	0.39	0.52	0.67	0.62	0.30	0.45	0.60	-0.09	0.36	0.16
	annual	0.50	0.64	0.69	0.74	0.55	0.61	0.41	-0.38	0.10	0.03
Potential Evaporation	pre-	-0.54	-0.54	-0.52	-0.37	-0.30	-0.40	-0.22	-0.22	-0.37	-0.54
	monsoon	-0.32	-0.45	-0.52	-0.36	-0.52	-0.52	0.04	-0.08	-0.04	-0.17
	post-	0.17	0.47	0.31	0.25	0.52	0.53	0.52	-0.02	0.10	0.27
	annual	-0.47	-0.41	-0.52	-0.36	-0.44	-0.44	0.27	-0.20	-0.14	-0.24

p<0.001
p<0.01
p<0.05

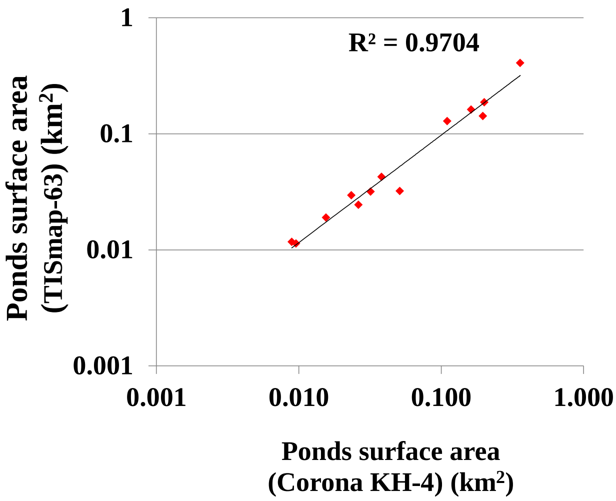

Figure SI1*. Scatter-plot between ponds surface areas digitalized on Corona (KH-4) and TISmap-63*

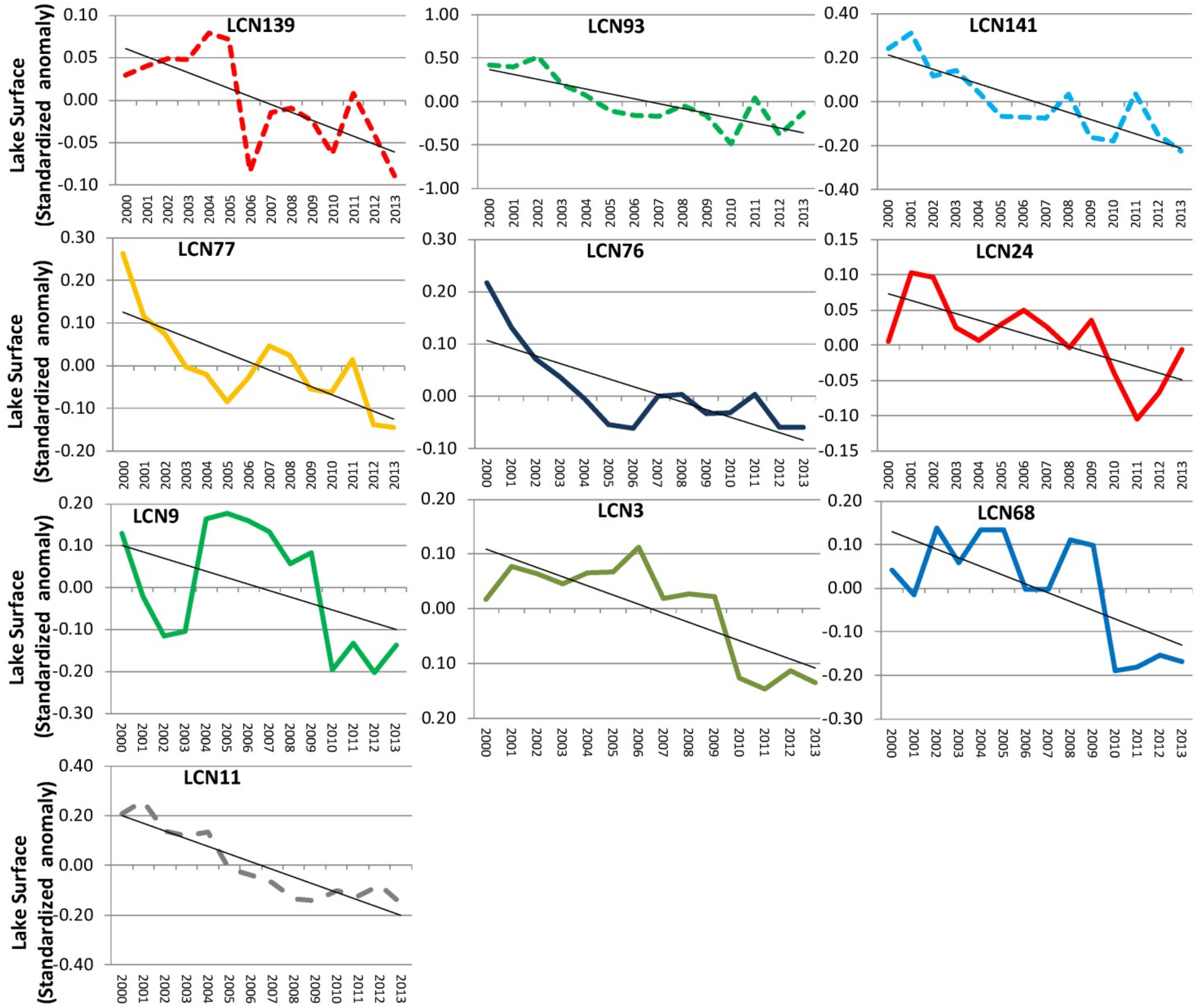

Figure SI2. *Surfaces area variations during the period 2000-2013 of 10 selected ponds. Standardized anomalies (dimensionless) are computed dividing the anomalies for the standard deviation.*

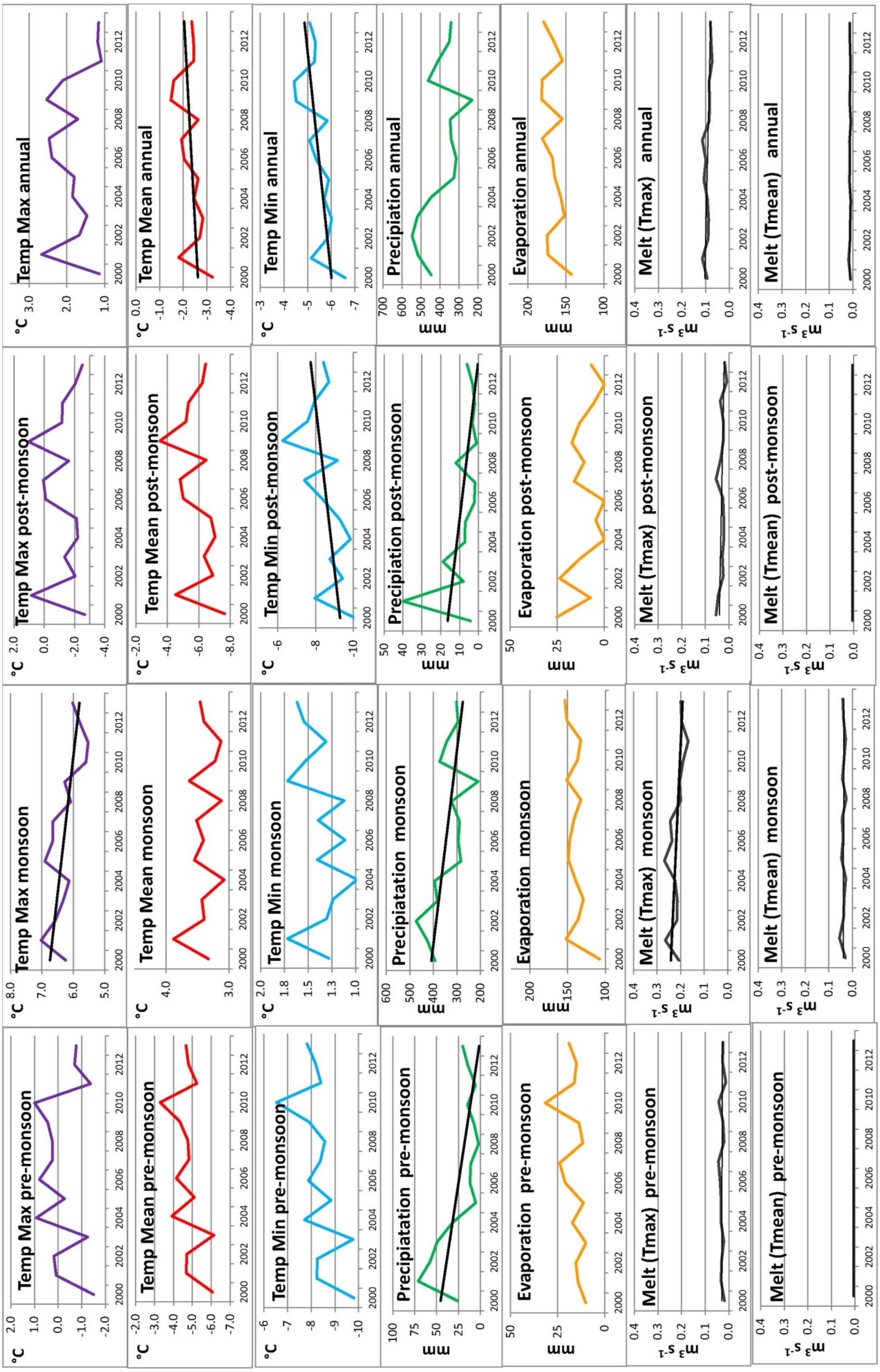

Figure SI3. *Climatic trends for the period 2000-2013 at the Pyramid Laboratory (5050 m a.s.l.) for mean (Tmean), maximum (Tmax), minimum temperature, precipitation, potential evaporation, and glacier melt calculated for each glacier considering Tmax and Tmean. The regression line is indicated only in those graphs for which the trend is significant.*

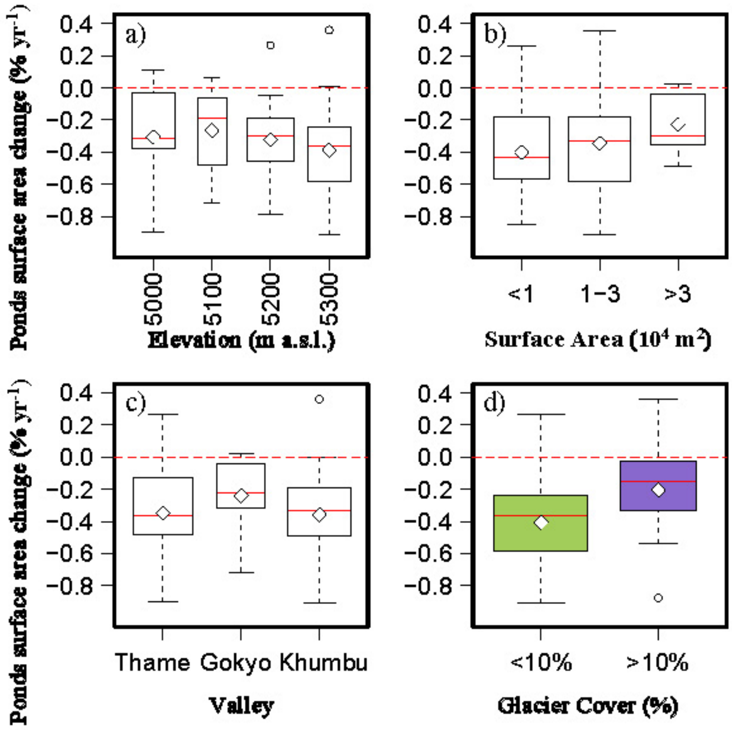

Figure SI4. *Surface area changes observed during the 1992-2013 period for all 64 considered ponds in relation to certain morphological boundary conditions: a) elevation; b) pond surface area; c) valley; d) glacier cover. The white points in the boxplots indicate the mean, whereas the red lines are the median.*

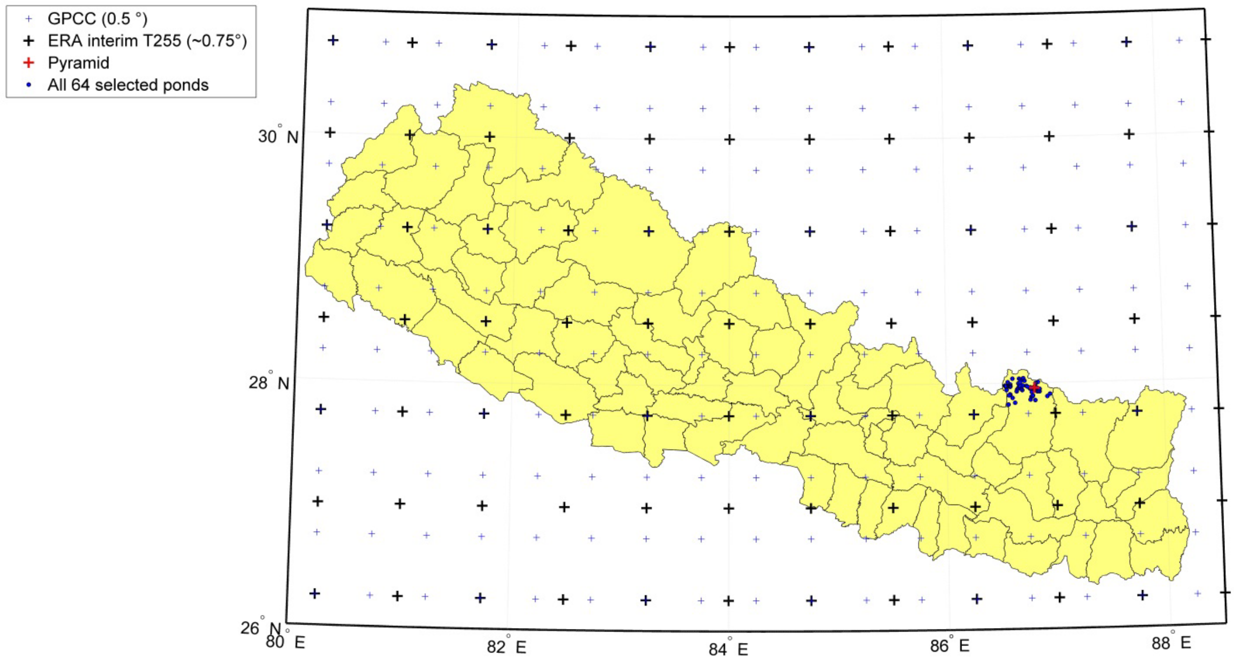

Figure SI5. *Map of Nepal showing the location of 64 considered lakes in Sagarmatha National Park, Era Interim, and GPPC nodes*

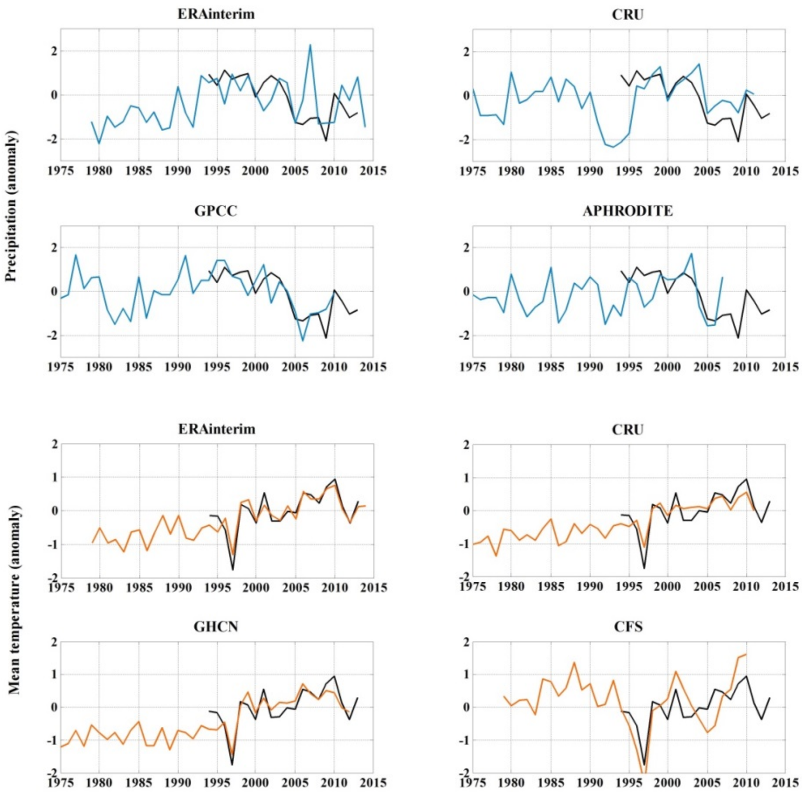

Figure SI6. *Comparison between annual precipitation and mean temperature time series recorded at Pyramid station since 1994 (black lines) with the selected regional gridded and reanalysis datasets. In Table 1 the relevant coefficients of correlation are reported*

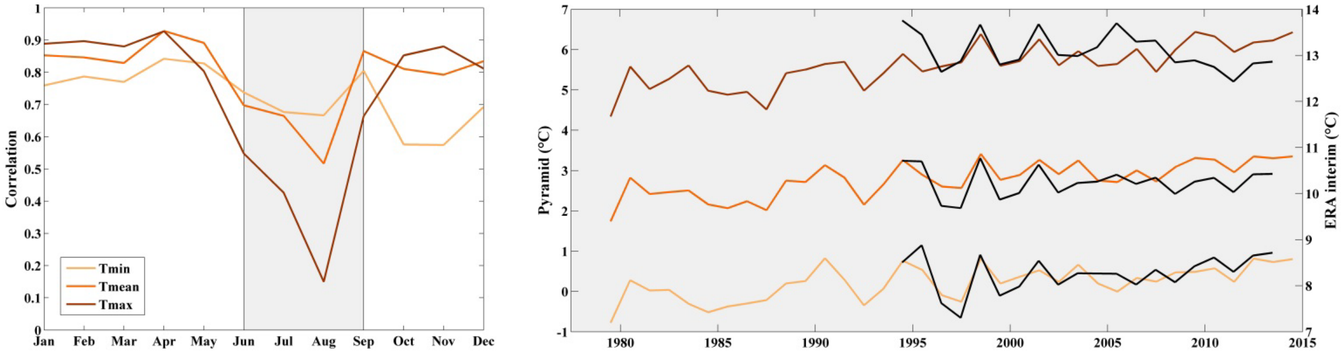

Figure SI7. *a) Monthly coefficients of correlation between temperature recorded at Pyramid Station and Era Interim data (1994-2013 period)during the monsoon season. b) Temporal comparison among Era Interim and Pyramid data (black lines).*

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