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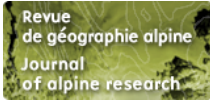
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## AUTHOR'S NOTE

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## Introduction

- 1 There are numerous parameters to characterise the term “snow”: snowfall, duration, depth, extension or even density of snow cover. However, “snow” is generally one of the least known climatic variables and the most difficult to integrate into models. This

holds true in the Himalayas where it is difficult to assess precipitation from both a quantitative and qualitative point of view. As a result, the climatic and hydrological processes that drive water resources are only understood in a rather unsatisfactory manner, limiting reliable estimation of the contribution of liquid precipitation, snowmelt, glacial melt and groundwater to river flows (Pellicciotti *et al.*, 2012). Consequently, while rising temperatures (Pörtner *et al.*, 2019; Wester *et al.*, 2019) and glacier melt (Brun *et al.*, 2017; Shea *et al.*, 2015) are proven expressions of climate change, there remain margins of error in estimating this melt or in explaining how hydro-systems function (Eeckman *et al.*, 2017; Savéan *et al.*, 2015).<sup>1</sup> Thus, the knowledge to help us understand the consequences of climate change on water resources still needs to be largely improved (Bharati *et al.*, 2014; Immerzeel *et al.*, 2010). This realisation led us to cross qualitative and quantitative results from research in geography and hydrology to analyse the dynamics of snowfall in the Upper Khumbu, at the foot of Mount Everest in Nepal.

- 2 Our purpose here is to present this approach. We hypothesised that (i) knowledge acquired from people in this region can fill gaps in hydro-climatic data sets, and (ii) the analysis of hydrological and climatic models based on quantitative data allows us to fine-tune our interpretation of qualitative data.
- 3 After describing the cross-reference method used, we analyse the way of combining the information from various measurements and calculations with the knowledge gathered from inhabitants. The focus lies on snow in its two forms: precipitation (snowfall) and snow cover (snow on the ground).

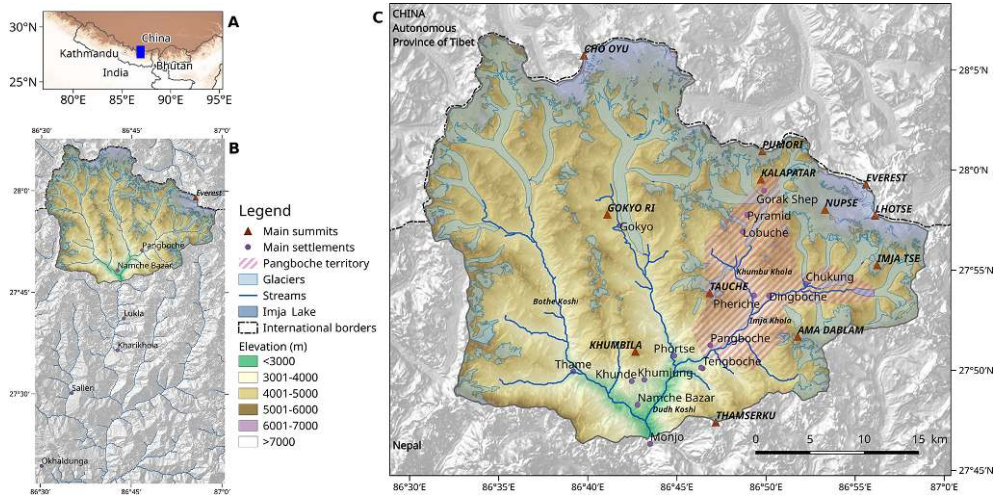
## Methodological Framework

### Foundational Insertion in a Multidisciplinary Project at the Foot of Everest

- 4 This study was conducted as part of the multidisciplinary PAPRIKA project (Cryospheric Responses to Anthropogenic Pressure in the Hindu Kush-Himalaya Regions, 2010–2013), which focused on water resource availability in the context of climate change in the Nepalese Himalaya (Aubriot *et al.*, 2012). In addition to frequent exchanges between project members, collective fieldwork particularly fostered cross-disciplinary interactions. During their respective PhDs, hydrologist M. Savéan shared two weeks of fieldwork with the geographers in 2013, and geographer O. Puschiasis carried out several periods of fieldwork with the hydrologists in 2010, 2011 and 2015, which proved foundational for the emergence of new interdisciplinary questions. Crossing points of view thus became “generative of scientific convergences” (Riaux and Massuel, 2014).
- 5 Our fieldwork site is located in the upper Khumbu, the upstream part of the Dudh Koshi Valley (which drains the southern face of Mount Everest) in eastern Nepal (Fig. 1). Part of Sagarmatha National Park, this region which is extremely touristy is well documented in both physical and social sciences (Puschiasis, 2015). It benefits from the presence of the Nepal Academy of Science and Technology’s “Pyramid” research laboratory (Fig. 1), which has hosted a meteorological and atmospheric station since the 1990s. Our study focuses more precisely on the village of Pangboche (3,940 and 4,100 m)—the last permanent settlement in the Upper Khumbu—and its territory (Fig.

2). The latter is organised over approximately 150 km<sup>2</sup> around several areas of agro-pastoral activities. In addition to Pangboche, it encompasses all the hamlets up to Gorak Shep (5,300 m) and Chukung (4,730 m). In 2012, there were 70 families, or 280 inhabitants, living at least six months of the year in this territory and they mostly belonged to the Sherpa ethnolinguistic group.

Figure 1



Location of study site. A. General location. B. Solukhumbu region with observation sites. C. Study site and "Pangboche territory"

Figure 2



Pangboche in winter and spring from the opposite side – left, February 2011 – right, May 2010.

Pictures: O. Puschiasis

## Heterogeneous and Incomplete Meteorological Data, Particularly Snow Data

- In the Himalayas, as in any other mountain range, where the variability of temperatures and precipitation is high due to the great heterogeneity of the environments (altitudinal differences, slope exposure, orientation and steepness of the valleys), the phenomenon is amplified by the size of the range (2,700 km from west to east), its very strong altitudinal gradient, its subtropical latitude, and by its façade effects (the south of the range is watered while the north is drier because of its

relatively sheltered position). Added to this is the combination of the Asian monsoon flow that brings 80% of annual precipitation to the central Himalayas over the period from June to September (Bookhagen and Burbank, 2010) and westerly flows that can bring moisture and precipitation in winter (*Ibid.*). The complexity of the environment would require a large number of climatological stations and observations to understand its climate and the way it evolves. However, difficulties in accessing the high mountains limit the density and long-term maintenance of stations. Records at daily and sub-daily time steps, mainly of precipitation and temperature, also present uncertainties especially with regards to the site or the measuring device (Eeckman *et al.*, 2017; Savéan *et al.*, 2015). Snow measurements that rely on instrumentation particularly suffer from this. As for satellite images used to assess the extent of snow cover, they are often “biased” by the spatial and temporal resolution of the sensors or by the presence of clouds. Therefore, knowledge of the cryosphere (solid water in the form of ice or snow) is still limited (Bolch *et al.*, 2012; Bouchard *et al.*, 2019; Gurung *et al.*, 2011). All these factors complicate the development and interpretation of climate models in the Himalayas (Nepal *et al.*, 2017; Savéan *et al.*, 2015).

## Data on Climate Perceptions Collected Through Interviews

- 7 The so-called “qualitative” data on how the inhabitants perceive meteorological or climatological variations was collected from observations and field surveys with permanent and non-permanent residents. Altogether, nearly 200 interviews were conducted in 2010 and 2011, 88 of which were done in the village itself and on Pangboche territory. The majority of interviewees were pluriactive (mostly farmers and locals working in tourism aged 35–49), a quarter being over 50 (see Puschiasis, 2019). The sample was equally made up of men and women. For our comparison, only data concerning snow, temperature and particular events such as avalanches were retained. They have been completed by a study of the agropastoral practice calendars and by the identification of temporal indicators, such as religious rituals recorded during interviews and observations made *in situ*. These interviews, which have been recorded, translated and transcribed, were most often conducted in Nepali or Sherpa with the help of an assistant.
- 8 The acquisition of this type of data requires a prolonged stay in the field to multiply observations and to facilitate interactions with villagers (Olivier de Sardan, 2008). Despite the wealth of the material collected, this method presents several limitations: in addition to those regarding translation is the disparity of the data according to location and season (Aubriot, 2014) as well as the uncertainties concerning temporalities since interviewed people frequently idealise the past and use a fuzzy time step (de la Soudière, 1999). Moreover, the processing of qualitative data can give rise to difficulties in interpretation since the perceptions recorded during the surveys concern very broad and profuse subjects. It consists of various sorting operations that introduce a bias. The interpretation of perceptions is in fact as subjective as the perceptions themselves (Meze-Hausken, 2004). All of these limitations justify our interest in using quantitative data to shed light on the information gathered via interviews.

## Hydrological Data: Measured, Spatialised or Simulated

- 9 In hydrology, quantitative data prepared for comparison differs according to its mode of acquisition, which falls into three categories:
1. observed data at a small number of field stations
  2. spatialised data from regular spatial grids provided by international databases
  3. simulated data from the Hydrological Distributed Snow Model (HDSM) (Savéan *et al.*, 2015).
- 10 The observed precipitation data analysed in this paper is from the local Pyramid station (Fig. 1) (5,035 m; 2000–2016) and the more distant Okhaldunga station (1,720m) about 50 km southwest of the study area (Fig. 1B) which provides a longer time series (1977–2012)<sup>2</sup>. This data is supplemented by grid data from the APHRODITE model (Yatagai *et al.*, 2012). Each grid element represents an area of about 4 km<sup>2</sup>. The partitioning procedure between snowfall and rainfall is described by Savéan *et al.* (2015) and Eeckman *et al.* (2017).
- 11 The snow cover analysis was performed from 1977 to 2007 using the HDSM model. It was supplemented, from 2000 to 2012, by the MOD10A1 product (Hall *et al.*, 2002) derived from the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite sensor at a daily time step and a 15 arcs-secs resolution. All snowpack data is subject to significant uncertainties with regards both quantity and extent (Bouchard *et al.*, 2019).

## Crossing Qualitative and Quantitative Data

- 12 By cross-analysing the data, we seek to overcome disciplinary barriers and to find a common vocabulary in order to consolidate knowledge, fill lacunae and limit uncertainties.

## Shared Data and Missing Data

- 13 Although the point of gathering the populations' own knowledge to decipher what they perceive, understand and experience of local climatology is no longer questioned (Smadja *et al.*, 2015), the approach by which this knowledge is cross-referenced with that of climate sciences has so far rarely been undertaken. The works often identified concern rural areas, mainly on the African continent (Dahlberg and Blaikie, 1999; Meze-Hausken, 2004; Peyrusaubes, 2010; Ulrich *et al.*, 2013) and South Asia (Manandhar *et al.*, 2010; Thapa *et al.*, 2015; Vedwan and Rhoades, 2001), or more recently in Europe (Furberg *et al.*, 2018; Metzger, 2015). In most of these articles, the comparison methodology only focuses on whether perceptions are consistent with the quantitative data that still serves as a benchmark. Manandhar *et al.* (2010) additionally supplement their analysis with the use of the  $\chi^2$  statistical test which assesses the dependence between two variables.
- 14 Table 1 highlights the available data by the type of snow-related variable, but also shows the unavailable data (white cells). It is worth noting that qualitative data relates to the village and the whole territory, providing information dating back to the 1950s. Quantitative data is spatialised and simulated for Pangboche territory.

Table 1

≈	Qualitative data	Quantitative data		
		measured	spatialised	simulated
Precipitation (snowfall),	Interviews (1950-2011)	Pyramid (2000-2012)	APHRODITE (1977-2007)	HDSM (1977-2007)
Duration of snow cover	Interviews (1950-2011)		MOD10A1 (2000-2012)	HDSM (1977-2007)
Snow cover area	Interviews (1950-2011)		MOD10A1 (2000-2012)	HDSM (1977-2007)
Height of snow cover	Interviews (1950-2011)			
Equivalent volume of water in snow stock				HDSM (1977-2007)

Snow data collected via interviews, modelling or in situ measurements.

- 15 Five criteria were selected to characterise snow: precipitation (snowfall), snow cover (area of snow that remains on the ground), the height of snow cover, the duration of snow cover (number of days with snow on the ground) and the equivalent volume of water in the snow stock, which depends on its density. This distinction was not explicitly clear in conversations with the inhabitants of Pangboche, who spoke of snow in general without differentiating for example between snowfall and snow cover. It was necessary to extract from the interviews the parts corresponding to the five criteria, knowing that villagers never refer to the density and thus to the water corresponding to the snow stock. As for the depth of the snow, even if mentioned by inhabitants, simulated data is only available from the year 2000 onwards. Only information collected about snowfall, the extent of snow cover and the duration of the snow cover make it possible to cross-reference qualitative and quantitative data from 1977 to 2012.

## Common Interpretation Keys

- 16 Only information that is “useful” for comparison has been retained in both datasets. For quantitative data, sorting is done according to the variables, their duration, their location and the purpose of the comparison. For qualitative data, since the eclecticism of the different perceptions is in itself an outcome (Byg and Salick, 2009), sorting was particularly difficult.
- 17 In order to harmonise the temporal benchmarks used by hydrologists and geographers, three common keys were defined:
- seasonality, provided by monthly averages of quantitative data and by people’s perceptions of seasonal variations of snow;
  - trends recorded during interviews among the population and statistically obtained from quantitative time series;



- noteworthy events, statistically evaluated using quantitative data and recalled by the population when perceived as such. These especially include snowy years.
- 18 These interpretation keys are obtained by calculation methods applied to quantitative data and after a manual processing of qualitative data. This interview excerpt illustrates how villagers talk about snow and how this processing is carried out:
- Normally there is a lot of snow during the winter in Pangboche. But since the Panga avalanche, there are only a few centimetres of snow, it does not last, and it comes later, especially after Losar. I remember when I was young there could be more than 1 to 1.5 metres of snow on the ground three to four times during the season. (63-year-old man, April 2011, Pangboche).
- 19 When this villager talks about the variations in snow he has observed, he refers in a fairly succinct way to elements that correspond to the three interpretation keys in our analysis: he evokes an event (the 1995 Panga avalanche, near Gokyo; Fig. 1C); he gives a trend (“it only falls a few centimetres”); he talks about seasonality (“after Losar”, the Tibetan New Year). All the interviews concerning snow were analysed in order to highlight the elements relating to these three keys and the recurrent aspects of the changes in snow mentioned by the inhabitants of Pangboche. This makes it possible to compare them with the quantitative data and to validate or not their concordance.
- 20 In this study, we do not simply go back and forth between the two types of data (qualitative and quantitative) using common interpretation keys. The performance of Mann-Kendall time trend tests (Kendall, 1975) on quantitative data, the result of which is compared with qualitative data, supports the crossing of data; it has been systematically applied to confirm the dependence, or not, between them.

## Snow: Easily Identifiable by Villagers but Difficult to Measure with Equipment

### “There Is No Longer Any Snow in Winter”: A Statement That Needs Some Clarification

- 21 The most significant trend for the people of Pangboche is the decrease in snow in winter (Puschiasis, 2019). In the past, it used to entirely cover in white the surrounding peaks (Ama Dablam 6,812 m and Tauche 6,110 m). Today, these peaks, home of tutelary deities, are becoming darker. “There is no longer any snow in winter” is the most frequent remark made by villagers when mentioning the trends observed regarding snow. But how is this sentence to be interpreted? Does it not snow anymore? Does it snow less? Or does the snow no longer hold on the ground, leaving the feeling that there is “no more snow”?
- 22 It is common to hear that the snow “doesn’t hold” (75-year-old man), “doesn’t stay on the ground” (56-year-old woman), “doesn’t leave any trace when you walk” (42-year-old man). Thirty-year-olds rather mention having given up skiing (Fig.3), a very basic version of this sport but which used to be their favourite childhood game. This information can be used as a marker to record a snow scarcity since the end of the 1990s, both in terms of quantity and the area covered. As such, 2011 was perceived by inhabitants as a remarkable year because there was a lot of snow. After heavy snowfall in October, the winter was quite dry until February, when snow fell in abundance and

even lasted for three weeks in Pangboche village, allowing winter games to be practised once again.

Figure 3

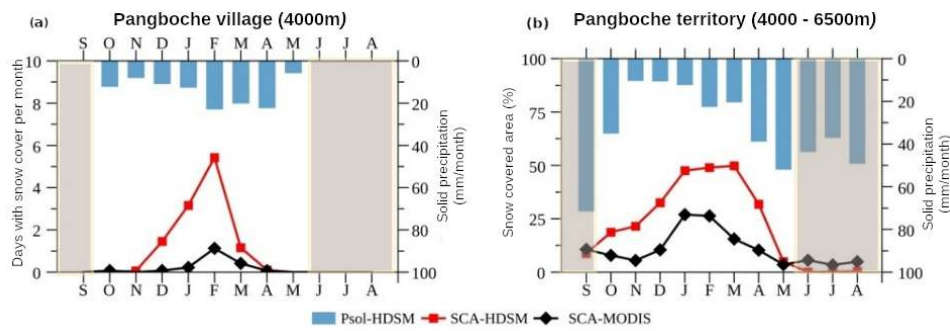


Winter Games in Pangboche in February 2011. On the left, a young man sets off on the slopes of Pangboche on skis that his father, a guide, received as a gift after an expedition. In the middle, a picture of handmade skis made out of PVC pipes cut in half lengthwise and attached to shoes with pieces of cord. On the right, children from the village have fun using a rudimentary sled.

Pictures: O. Puschiasis

- 23 These comments about less snow cover should be seen in the context of shorter periods of snow cover. Indeed, some people mention that the years when the whole village was covered with snow for five months in a row (from mid-October to mid-March) and made it difficult for people and animals to move around, are now exceptional or even non-existent, whereas it was the norm before. The fact that villagers were prevented from going about their activities as usual is engraved in their memories, as Vedwan and Rhoades (2001) have also shown regarding the influence of climate on economic and cultural activities.
- 24 Furthermore, winter was structured around two religious rituals for the villagers. Snowfall began during *Mani Rimdu* (a major Buddhist ritual) between late October and mid-November, and dwindled from Losar onwards, between mid-January and mid-February. These points of reference no longer seem to be relevant today as there is reportedly less snowfall between these two festivals (Puschiasis, 2019). However, the inhabitants note increasingly frequent late snowy spells in March-April. They interpret them as being due to a shift in the winter season: the change of season no longer coincides with festivities, which used to be a temporal marker.
- 25 As the idea of comparing different types of data according to three interpretation keys came to us after collecting the data, our enquiries are lacking precision regarding the duration of snow cover and snowfalls. Quantitative data therefore allows us to fine-tune the interpretation. For this, the village of Pangboche corresponds to a point, whether it is the satellite pixel or the model calculation cell. Solid precipitation is observed between October and March, but snowy periods are short, less than 10 days from October to April, whether simulated by HDSM or extracted from MODIS satellite data (Fig. 4a). Qualitative data confirm these informations because according to the inhabitants the number of snowy days in the village “can be counted on the fingers of one hand”, with the exception of the year 2011.

Figure 4



Monthly mean solid precipitation and comparison of monthly mean duration of snow proposed by HDSM and MODIS: a) in Pangboche village; b) on Pangboche territory. PsoI = solid precipitation; SCA = % of territory covered by snow. The periods corresponding to the monsoon are shaded.

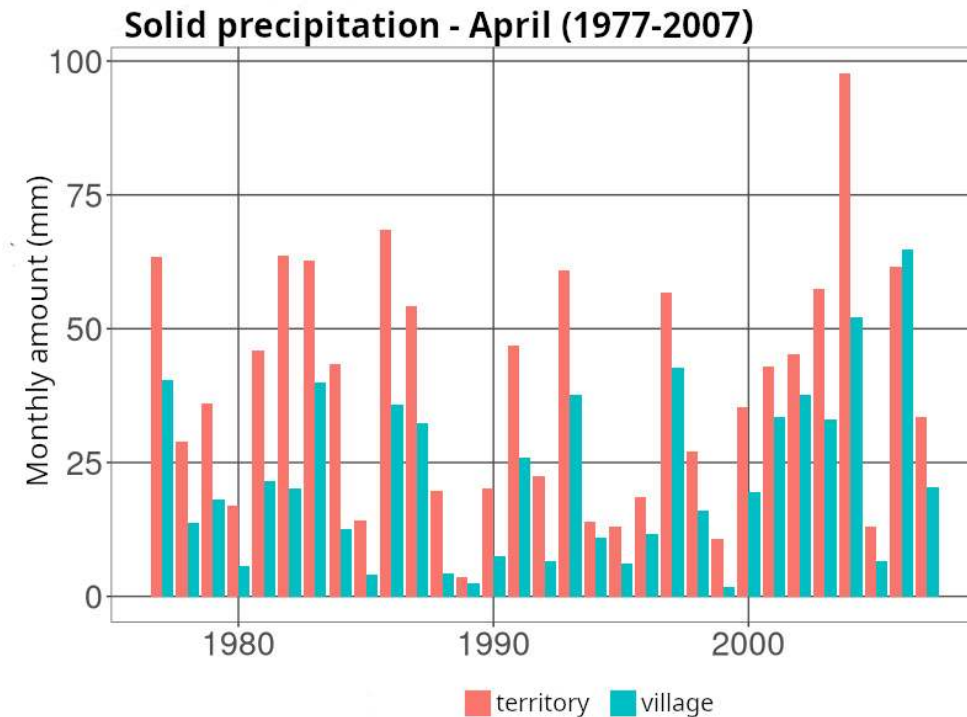
Sources: HDSM simulations 1977–2007 for data with HDSM suffix and MOD10A1 spatialised grid product 2000–2012 for data with MODIS suffix.

- 26 Given the size of Pangboche territory, it presents multiple configurations. Over this area, Figure 4b shows, like the one for the village (Fig. 4a), the same averaged quantities. It is however not surprising to note fairly large differences within the territory since the altitudes taken into consideration are much higher than those of the village and the dynamics of the climate system is more complex. Villagers talk about the presence of snow for 1 to 5 months by referring to the surrounding peaks which, even if they are less white, still receive visible snowfall. However, they do not mention monsoon snowfalls that appear in the quantitative data (Fig. 4b). This does not mean that they do not see them but are more likely to talk about snow that remains on the ground for several days at a time and in sufficient quantity to be noticeable and to have an impact on activities, than about monsoonal snowfall deposited mainly on peaks and glaciers at night but that melts rapidly at village and field elevations. Hence the use of crossing qualitative and quantitative data. Furthermore, the differences noticed between the snow-covered surfaces simulated by HDSM and observed by MODIS (Fig. 4b) are probably due to the fact that monthly averages are calculated over two different periods (1977–2007 and 2000–2012) and do not cover the same spatial resolution.
- 27 Moreover, apart from the case of major snowy events, the importance of quantitative data about the village needs to be put into perspective whereas data on the territory must be emphasized. Indeed, the uncertainty weighing on quantitative data is greater with regards one point, that of the modelling pixel where the village is located, than on the whole territory which comprises a significant number of pixels over which it can be distributed. Moreover, the village is almost the lowest point in the study area, with higher temperatures than at high altitude and with a southerly exposure: it therefore receives less snow. That's why villagers say that “the snow does not hold” in Pangboche (Fig.4).
- 28 According to the results of the Mann-Kendall tests applied to the HDSM model (between 1977 and 2007, see section 2.4), the annual average height of snow and duration of snow cover do not follow any significant temporal trend either in the village or on the territory. Villagers do not mention snow height, so these results cannot be compared with quantitative data. Regarding the duration of snow cover, we notice a lack of consistency between qualitative and quantitative data, raising the question of whether, leaving aside the uncertainty inherent in quantitative data, the

populations' perceptions relating to the most recent years (post-2007) would not be biased by inter and intra-annual variability of snowfall, at least as far as Pangboche territory is concerned. In those two cases, the comparison between the two types of data does not allow any conclusion to be drawn here.

- 29 According to inhabitants, snowfall occurs later in the season, a trend that is roughly confirmed by monthly total rainfall for April, in particular between 2000 and 2004, despite considerable variability from one year to another (Fig. 5).

Figure 5



Cumulative snowfall in the village and on Pangboche territory for the month of April between 1977 and 2007.

Source: HDSM modelling 1977–2007.

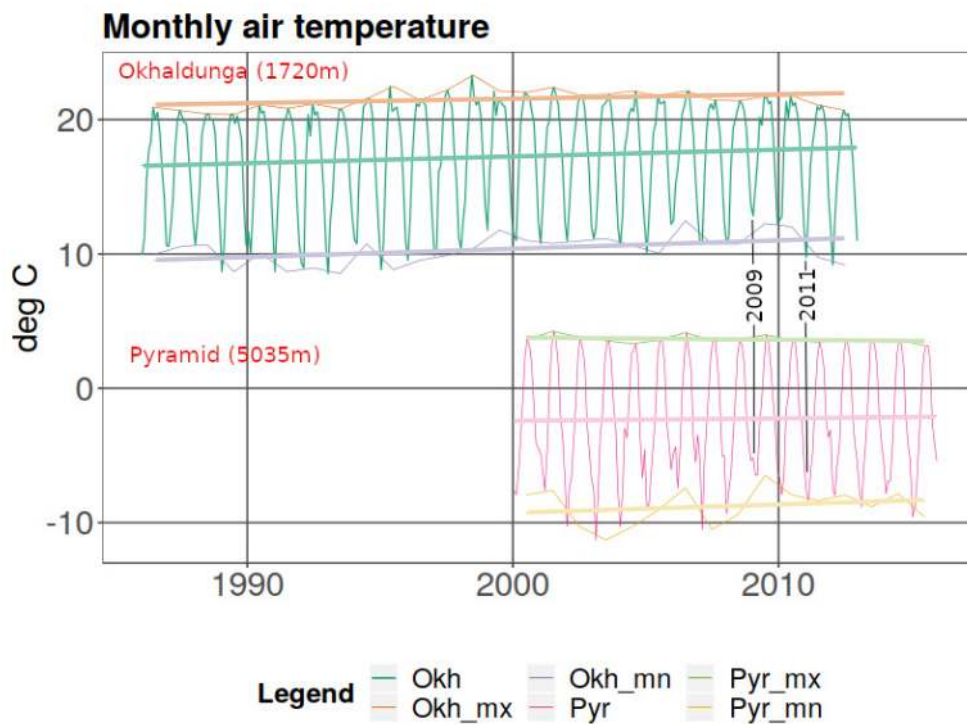
- 30 The comparison between quantitative and qualitative data also highlights the limits of satellite data interpretation, especially since the small amounts of night-time snowfall have often melted by the time the MODIS satellite sensor passes at around 10.30 in the morning. Access to data from interviews and to field observations allows us to find out whether the absence of snow in the images is due to a lack of snowfall or to a smattering of night-time snow (which is the commonest case) that melted rapidly before the satellite pass by.

### An Increase in Perceived and Measured Temperatures

- 31 A change in temperature—which affects snowfall and snow accumulation—is perceived by people who report: higher minimum temperatures than in the past; fewer “harsh” winters of intense cold and heavy snowfalls; and “milder” winters which they associate with less snow and with streams thawing earlier (Puschiasis, 2019).

- 32 In Figure 6, temperature recordings at Okhaldunga and at the Pyramid (Fig. 1) show a significant upward trend, as confirmed by the Mann-Kendall test:  $0.041^{\circ}\text{C}/\text{year}$  at Okhaldunga and  $0.052^{\circ}\text{C}/\text{year}$  at the Pyramid. These values are high compared with those generally given in the literature: from  $0.01$  to  $0.03^{\circ}\text{C}/\text{year}$  on average over the last 25 years in the Himalayas (Stocker, T.F. *et al.*, 2013). Though warming is undeniable, caution is nevertheless necessary regarding the generalisation of these values. They have been established over relatively short periods (26 years and 15 years respectively) and for local stations that may be subject to site-related effects (exposure, steepness, village environment, etc.)

Figure 6



Okh = Okhaldunga, Pyr = Pyramid, min. = minimum, max. = maximum.

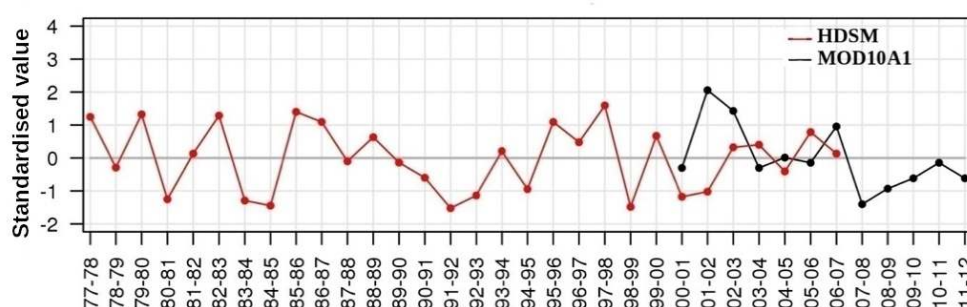
Maximum and minimum envelopes of monthly mean temperatures recorded at Okhaldunga (1,700m: 1986–2012) and Pyramid (5,035m: 2001–2015) with their respective trends.

### Significant Extreme Events

- 33 One event, the avalanche on 11 November 1995, is regularly mentioned in interviews (Puschiasis, 2019). Following an accumulation of more than three metres of snow in Panga near Gokyo (Fig. 1C), the avalanche damaged many houses and swept away bridges, fields and animals. A 60-year-old resident of Dingboche recalls: "In autumn 1995, during the Mani Rimdu Festival, there was a big avalanche. Since then, there has been less snow". Most of the people interviewed confirm this witness account. However, November 2006 was an exception with an avalanche killing villagers from Pangboche in the midst of ascending Ama Dablam, opposite the village. This tragic event also serves as a time marker but is not mentioned as often as the Panga one.

- 34 In the quantitative data we have looked for indicators of extreme years with large amounts of snow and tried to see whether, as in the qualitative data, the area of snow cover has decreased since 1995. Figure 7 shows that 1995–96 was a particularly snowy year, which is consistent with the Panga avalanche mentioned by villagers. We also note that according to the HDSM model, after the abundance of snow in 1994–95, the extent of snow cover has always remained below the one of that period, which explains why the avalanche is used as a reference by inhabitants. The heavy snowfall of 2006, which triggered the deadly avalanche, also coincides with large snow cover compared to the following years according to the MOD10A1 data. However, the analysis of the curves (HDSM, 1977–2007) does not show a general trend towards a reduction in snow cover on Pangboche territory.

Figure 7



Standardised annual average of the extent of snow cover in the Pangboche area. Sources: HDSM modelling 1977–2007 and MOD10A1 product 2000–2012. “Years” are counted from October to September.

## Discussion

- 35 This complementarity between data shows the usefulness of sharing knowledge acquired by researchers from different disciplines.
- 36 However, the cross-analysing method has some limitations. It highlights a problem of spatial scale (Dahlberg and Blaikie, 1999; Mérot *et al.*, 2013): data from interviews is collected for one-off observations (village, pass, summit, etc.) which is not the scale of modelled data. Quantitative data on precipitations or temperatures are subject to site-related effects (exposure, steep sides, etc.), which are not taken into account in this study. Snowfall modelling cannot reproduce in detail the processes on the scale of a village or territory (Eeckman *et al.*, 2017; Savéan *et al.*, 2015). Moreover, our method reveals a discrepancy between the time series modelled over the period 1977–2007 and the enquiries conducted in 2011 (but going back to 1950 for the collection of information via interviews).
- 37 Despite these shortcomings, the originality of this paper lies in the fact that there are few recent studies that use both quantitative and qualitative data on snow in the mountains, and even fewer on the Himalayas. Shrestha *et al.* (2020) compare the perceptions of local populations in Mustang (Nepal)—which, north of the Upper Range, has a drier continental climate—with the results of a biophysical analysis. The authors here show that there is a good correlation between trends in people’s perception of the weather (temperature increase), vegetation degradation and the decrease in measured

and perceived snow cover. Most other works using both types of data seem to focus more on land degradation on the African continent, using remote sensing and relying on local ecological knowledge (Herrmann *et al.*, 2020; Yiran *et al.*, 2012).

- 38 All the interdisciplinary studies reviewed concur with the need to take into account the knowledge of the populations as a precious source of information, to validate or invalidate measured or missing data. Here we show that the use of quantitative data also proves valuable for interpreting qualitative data. Although there are notable uncertainties about both types of data, we have seen the importance of crossing points of view.
- 39 Quantitative data thus prompts us to put qualitative data into some perspective. Indeed, it may seem to villagers that there has been no snow in some years, whereas measured data shows that this is not the case. Similarly, snowfall emerges to be heavy some years only because it follows years with little snow. It also appears that there has to be sufficiently extensive snow cover for it to be recorded in the collective memory. Quantitative data also makes it possible to establish the temporal framework of perceptions that are sometimes difficult to evaluate and judge.
- 40 As for qualitative data, they enrich quantitative data thanks to the precise knowledge inhabitants have of their living space. They evoke facts that can go back fifty years or so ago, whereas measured and spatialised quantitative data is either dependent on the stations where they are collected, or on satellite sensors that have been available only for a recent period.
- 41 For better results, it would have been interesting to include qualitative data directly in the modelling process, which was not possible because the comparative work which led to this idea, was carried out once the modelling had been finalised; likewise, prior knowledge of the climate modelling results would have enabled even more in-depth interviews.
- 42 Nevertheless, this experience is a first step towards achieving an interdisciplinary approach to geo-hydrology (Massuel *et al.*, 2018; Wesselink *et al.*, 2017). The fact that few authors pursue this path is mainly due to the current inability of hydroclimatic models to take into account qualitative information. This weakness highlights the under-representation of local knowledge in climate change research (Ford *et al.*, 2016). The difficulties of implementing interdisciplinary approaches (spatial, temporal and processing scales) are a research field in themselves.

## Conclusion

- 43 Crossing qualitative and quantitative data allows the interpretation of climate variability to be completed. In the Upper Khumbu, this comparison shows (i) less snow on the ground, with less frequent and less significant snowfalls (except for a few episodes that are now considered exceptional by villagers), (ii) an increase in measured and felt temperatures that would explain that there is less snow on the ground; and (iii) a shift in the timing of snow precipitations which still has to be quantitatively verified.
- 44 This article highlights the importance of understanding people's perceptions rather than only physical data, as villagers are the first to experience the effects of weather and climate variations. Collecting their knowledge and comparing it with quantitative data via multi-scale and multidisciplinary approaches is therefore essential in the

current scientific and societal context where understanding future environmental changes are a major issue in the Everest region and throughout the world.

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## NOTES

1. The works cited in this article are mainly the results of two ANR projects PAPRIKA (2010–2013) and PRESHINE (2014–2018) which brought together glaciologists, hydrologists, atmospheric chemists, modellers, agronomists and geographers. A wide range of research conducted in the Himalayas can be accessed by consulting the publications cited in these projects.
2. Precipitation observations at a few other sites in the Dudh Koshi basin were used to calibrate the HDSM model; for details see Savéan *et al.* (2015).

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## ABSTRACTS

In the Nepalese region of Mount Everest, snow data is fragmentary and unreliable, as in many mountainous regions of the world. To get a better understanding of solid precipitation and how it has evolved over the last decades, and thus to improve our knowledge of hydro-climatic variations, we crossed quantitative data (measured, spatialised and simulated) produced from work in hydrology, with qualitative data (field interviews) derived from work in human geography. Here we present an innovative comparison method based on three key factors: seasonality, trends and notable events. Although quantitative and qualitative data show a similar decrease in snowfall in the Upper Khumbu Valley, which is taken as a case study, there are discrepancies that highlight the uncertainties present in the two data sets. This method of crossing data from different disciplines proves very useful for mountain areas where meteorological stations and precise surveys are lacking, and where the wealth of local people’s knowledge is not sufficiently taken into account.

Dans la région népalaise de l’Everest, les données sur la neige sont fragmentaires et peu fiables comme dans de nombreuses régions montagneuses du monde. Pour mieux appréhender les précipitations solides et leur évolution au cours des dernières décennies, et ainsi améliorer la connaissance des variations hydroclimatiques, nous avons croisé des données quantitatives (mesurées, spatialisées et simulées) issues de travaux en hydrologie, et des données qualitatives (entretiens sur le terrain) issues de travaux en géographie humaine. Nous présentons ici une méthode de comparaison innovante basée sur trois clés de lecture communes : la saisonnalité, les

tendances et les événements notables. Si de façon similaire les données quantitatives et qualitatives mettent en évidence la diminution des chutes de neige dans la vallée du haut Khumbu prise comme cas d'étude, des divergences soulignent les incertitudes présentes dans les deux jeux de données. Ce travail de croisement de données issues de disciplines différentes s'avère d'une grande utilité pour les zones de montagne où les stations météorologiques et les relevés précis font défaut, et où les connaissances de la population sont riches, mais insuffisamment prises en compte.

## INDEX

**Mots-clés:** Himalaya, Everest, neige, changement climatique, données qualitatives, données quantitatives

**Keywords:** Himalayas, Everest, snow, climate change, qualitative data, quantitative data

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