USING UNMANNED AERIAL VEHICLES FOR GLACIER MONITORING IN THE HIMALAYAS

Jan 2016

Final report May 2014 – Jan 2016

Using unmanned aerial vehicles for glacier monitoring in the Himalayas

Final report May 2014 – January 2016

This project has been funded by UKaid from the UK Government; however the views expressed do not necessarily reflect the UK Government's official policies.

Dr. W.W. Immerzeel (Utrecht University)

P.D.A. Kraaijenbrink MSc (Utrecht University)

Dr. J.M. Shea (ICIMOD)

Dr. A.B. Shrestha (ICIMOD)

Prof. Dr. S.M. de Jong (Utrecht University)

CONTENTS

Annexes:

LIST OF FIGURES

1 PREFACE

This report describes the results of the “Using Unmanned Airborne Vehicles (UAV) for glacier monitoring in the Himalayas” project that was executed by the consortium comprising of Utrecht University, ICIMOD and FutureWater from May 2014 to January 2016.

In the project, the use of UAVs was tested for several Himalayan glaciers and the data were used to improve the understanding of the functioning of the large glacier tongues, which provide an important source of melt water for the people downstream.

The project was highly successful and resulted in highly accurate and detailed datasets, scientific papers, a professional documentary and capacity built and awareness raised on the scientific use of a technology that shows great promise for the future.

The consortium is grateful to UKAID for the financial support for the project.This work was also partially supported by core funds of ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom.

2 EXECUTIVE SUMMARY

2.1 The role of unmanned aerial vehicles in glaciology

Large rivers in many central and south Asian countries depend on melt water from the Himalaya [*Immerzeel et al.*, 2013], which is used for water supplies, agriculture, industry and hydroelectric power generation. Glacier melt from the Himalayan 'water towers' [*Viviroli*, 2004] can form a substantial component of streamflow in dry seasons. Debris-covered glaciers are a pertinent feature of the Himalaya and they generate a substantial amount of this melt water [*Scherler et al.*, 2011; *Immerzeel et al.*, 2013]. However, debris-covered glaciers remain relatively unstudied for several reasons, but mainly because they are difficult to access and the field work is complicated due to the thick debris mantle. Satellite remote sensing may overcome these difficulties, but the resolution is often too coarse (30 m/pixel) for detailed investigations and the fixed time of image acquisition may not provide the best images or frequency. The use of Unmanned Aerial Vehicles (UAVs) can bridge the gap between cumbersome field work and coarse resolution satellite imagery, and provide critical, detailed information about glacier change.

In 2013 Utrecht University, ICIMOD and HiView (a spinoff of FutureWater dedicated to scientific applications of UAVs) conducted a ground-breaking pilot project on the debris-covered Himalayan Lirung Glacier using a UAV [*Immerzeel et al.*, 2014].The high resolution imagery and digital elevation model (DEM) that were acquiredfor the glacier in this project could be used for flow and mass balance analyses in unmatched detail. Besides the scientific output this generated, an important conclusion could be drawn from the project: the technology and methods thus generated related to UAVs are now at a stage that they can be used for routine monitoring of debris-covered glaciers. This may revolutionize research on debris covered glaciers as it bridges the gap between field based studies (hampered by accessibility problems) and satellite remote sensing (hampered by coarse resolution and clouds).

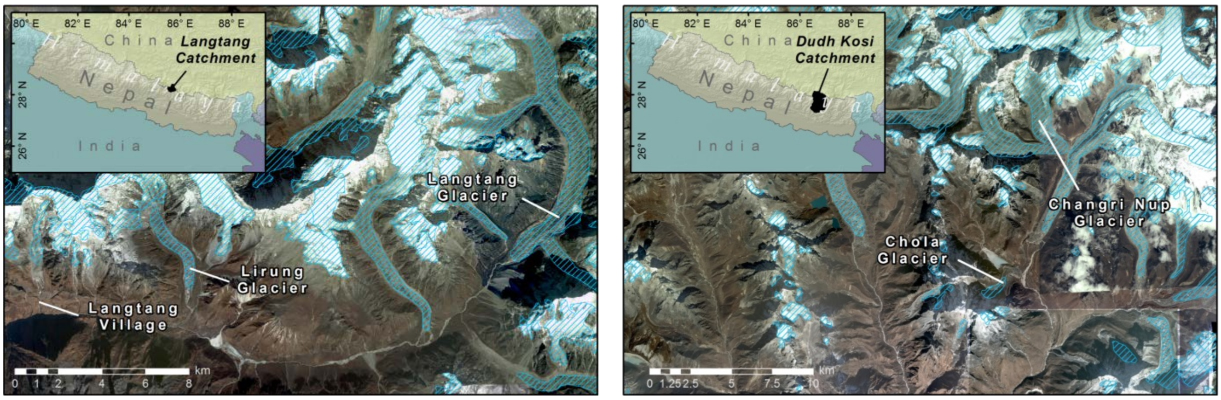

Figure1: Overview map of theLangtang and Everest regions

Ice cliffs and supra-glacial lakes present on debris-covered glaciers are believed to play an important role in the melt of such glaciers [*Sakai et al.*, 2009; *Haidong et al.*, 2010; *Benn et al.*, 2012; *Immerzeel et al.*, 2014]. Their dynamics are, however, not fully understood yet and to further improve our understanding of their role in glacier melt it is important to use both qualitative and quantitative methods. The high resolution UAV-acquired imagery can support both as it can be used for multitemporal visual inspections and automated mappings of the surface features, and as an input for energy balance models at a cliff scale in the form of DEMs.

In this project we build on this experience and we address the following research questions

- How fast do the debris-covered glaciers move?
- Do the debris-covered glaciers retreat?
- How quickly and where specifically do debris covered glacier tongues melt?
- How dynamic are ice cliffs and supra-glacial lakes and what is their role in glacier melt?

UAV flights are performed for two regions in Nepal: the Langtang region and the Everest region (Figure 1).

For the Langtang the focus is on the Lirung and Langtang glaciers. The Lirung Glacier, as mentioned, has been monitored before in 2013 with success. The Langtang Glacier was monitored for this first time in the framework of this project. A comparative study between those two glaciers can help understand the differences and agreements between the surface processes that occur at both glaciers, which are in different conditions [*Pellicciotti et al.*, 2015].

For the Everest region the focus is on the Changrinup Glacier where the UAV data can be combined with field datasets of glacier ice thickness, glacier melt and surface profiles. These data are provided through an informal collaboration with Dr. Patrick Wagnon (IRD France/ICIMOD), Dr. Christian Vincent (LTHE France), Dr. Dibas Shrestha (Nepal Academy of Science and Technology) and Ms. Alexandra Giese (PhD student, Dartmouth).

2.2 Achievements

Three successful missions have been conducted during the course of the project: (i) Langtang in May 2014 where the Lirung and L glaciers were monitored, (ii) Langtang in October 2015 where the Lirung and Langtang glaciers were monitored plus the location of Langtang village after the earthquake that struck on 25 April 2015 and (iii) Everest in November 2015 where the Chola and Changrinup glaciers have been monitored.

Figure 2: Launching the eBee (left) and acquiring ground control points (right).

Data were acquired using the eBee UAV (https://www.sensefly.com/drones/ebee.html), which is professional mapping drone. The eBee takes overlapping pictures from the glacier including its location based on GPS measurements. In combination with accurate ground control points the images are converted to high resolution elevation models and ortho-mosaics of the surface of the glacier using dedicated software (Figure 2). The high resolution (~ 10 – 20 cm / pixel) is the largest advantage of this technology and this level of detail allows the investigation of key processes that occur on the surface of the glacier.

2.2.1 High resolution mapping of glacier surfaces

For all flights surface elevation models are derived. These elevation datasets are then used to generate orthomosaics of the entire glacier surface (Figure 3). The orthomosaics reveal a very heterogeneous pattern on the glacier surface including ponds and ice cliffs. An earlier study [*Immerzeel et al., 2014*] revealed that these ponds and cliffs accelerate the melt of this type of glaciers and climate change may cause an increase in these features. It is therefore important to automatically map the ice cliffs and ponds on the surface of glaciers and to investigate their formation mechanisms.

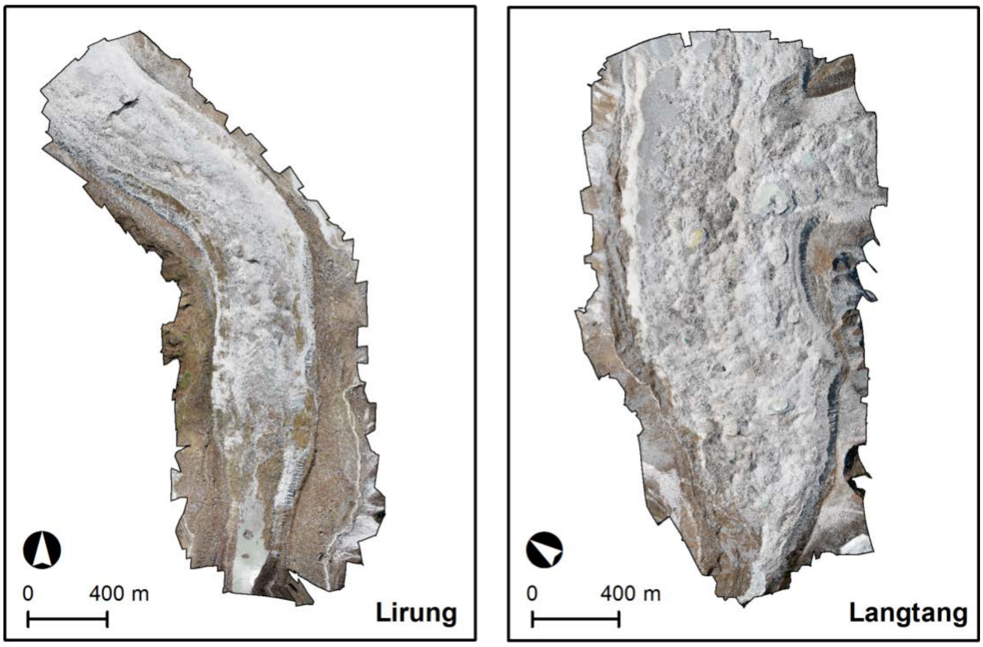

Figure 3: The stitched and georeferenced orthomosaics for both the Lirung Glacier (l) and the Langtang Glacier (r).

In the project a new semi-automated object based approach was developed to automatically classify ice cliffs and ponds with a very high accuracy for the Langtang glacier (Figure 4). The overall identification accuracy was equal to 0.978 for the number of features, and 0.988 for the total area (a perfect score would be equal to 1). This technique has also a wider field of application and it could potentially also be used for larger areas using high resolution satellite imagery. For each of the identified cliffs and lakes a number of statistical parameters such as slope, aspect and flow velocity were derived and it was found that ice cliffs and ponds generally develop on low sloping glacier tongues and nearly stagnant areas [*Kraaijenbrink et al.*, 2016b].

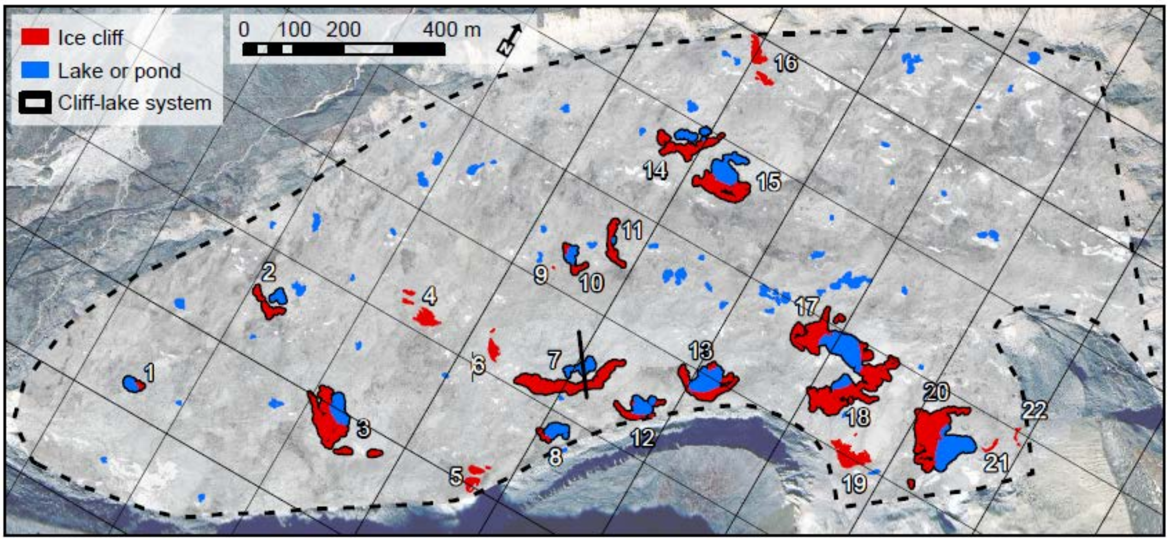

Figure 4: Ice cliffs and supraglacial ponds on Langtang Glacier as classified on the May 2014 UAV imagery by object-based classification.

2.2.2 Understanding changes in Himalayan glaciers

Understanding the change in Himalayan glaciers over time is one of the main objectives of the project and we focused on differences in the surface elevation and the seasonal flow velocities between survey flights. By subtracting the elevation models of October 2015 from May 2014 the changes in elevation can be quantified (Figure 5). The results show that overall the glaciers have a lost a significant amount of ice over this period. For Lirung the overall decrease in surface elevation is 0.52 m and for Langtang 0.53 m. The results also show that the spatial pattern is highly variable. The red areas are hotspots where the loss in surface elevation can be up to a factor 10 higher than the average value. The blue areas are region where the surface elevation has increased. The increase in surface elevation on the top left part of the Langtang map is most likely caused by an earthquake induced avalanche, which dropped large amounts of snow, ice and debris on top of the glacier.

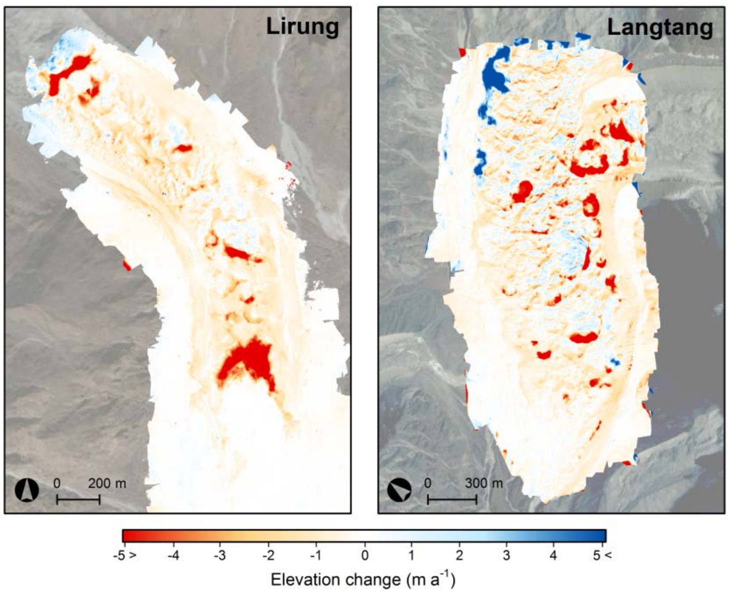

Figure 5: Differences in surface elevation in meter per year (m a^{-1}) between May 2014 and October 2015 for the Lirung and Langtang glaciers

As ice and mass are transferred from higher to lower parts of a glacier, the actual mass balance (incoming minus outgoing mass) of the glacier tongue is greater than the observed change in surface elevation. By estimating the influx of ice at the upper boundary (emergence velocity) a true estimate of the glacier mass balance can be made. For the Changrinup glacier in the Everest region this influx of ice was estimate using ground penetrating radar and flow velocity measurements. It was found that over the debris-covered terminus, the area-weighted thickness change between 2011 and 2015 is -0.95 m ice/year or -0.86 m water equivalent / year. The emergence velocity in this region, estimated from the total ice flux through a cross-section immediately above the debris-covered zone, is +0.42 m water equivalent / year. The debris-covered portion of the glacier thus has a negative mass balance of -1.3m water equivalent / year. This rate of mass loss is comparable to surface mass balance observations at nearby debris-free locations, which has important implications for glacier mass loss throughout the region [*Vincent et al.*, 2016].

A reinforcing mechanism that enhances mass loss of glacier tongues is the fact that glaciers slow down due to climate change. Using a novel cross-correlation technique an approach was developed to quantify the seasonal flow velocity of glaciers. This was tested for the Lirung glacier and the results show that the glacier significantly slow down during the winter season when the glacier remain frozen and there is limited water within the glacier Figure 6, which is important for the flow mechanism [*Kraaijenbrink et al.*, 2016a].

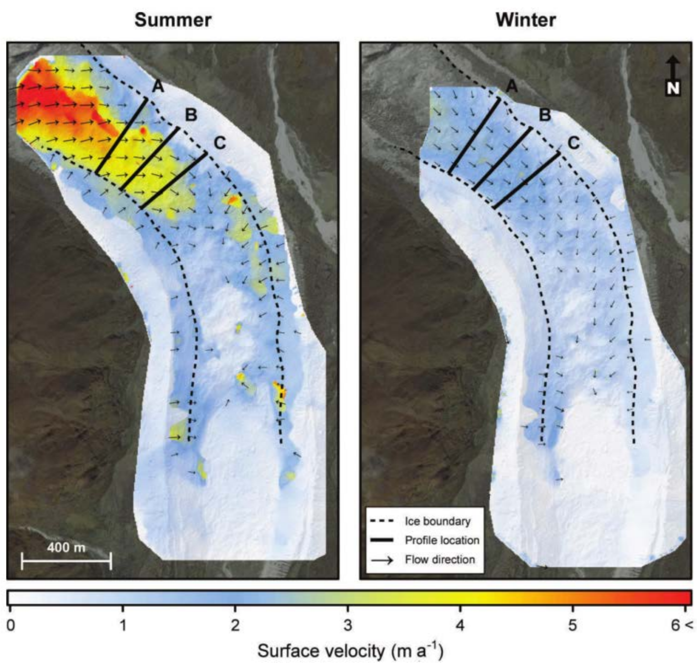

Figure 6: Differences in seasonal flow velocity for the Lirung glacier.

2.2.3 Impact of the earthquake

On 25 April 2015 a 7.8 magnitude earthquake struck Nepal and in particular the Langtang catchment was very badly affected [*Kargel et al.*, 2016]. Langtang village, which is the main village in the valley, was hit by a very large avalanche that completely destroyed the village and over 300 people were killed (Figure 7).

Figure 7: Langtang village before and after the April 2015 earthquake (credit: D. Breashears/GlacierWorks).

As a result of the earthquake, the entire valley was shifted and our dGPS measurements revealed that the catchment moved southwards by 1.2 m and lowered by 0.7 m. Together with a Japanese group of scientists, we have also used the UAV in October 2015 over the Langtang village area to map the extent of the damage and to try and reconstruct the causes and the volume of ice and debris that was deposited on the village (Figures 7 and 8). This was an informal collaboration, but since we were in the field with access to the UAV it was considered very beneficial by both teams to collaborate. We have shared the data with the Japanese team and they are working on a scientific paper investigating the causes and background of the avalanche that destroyed Langtang village.

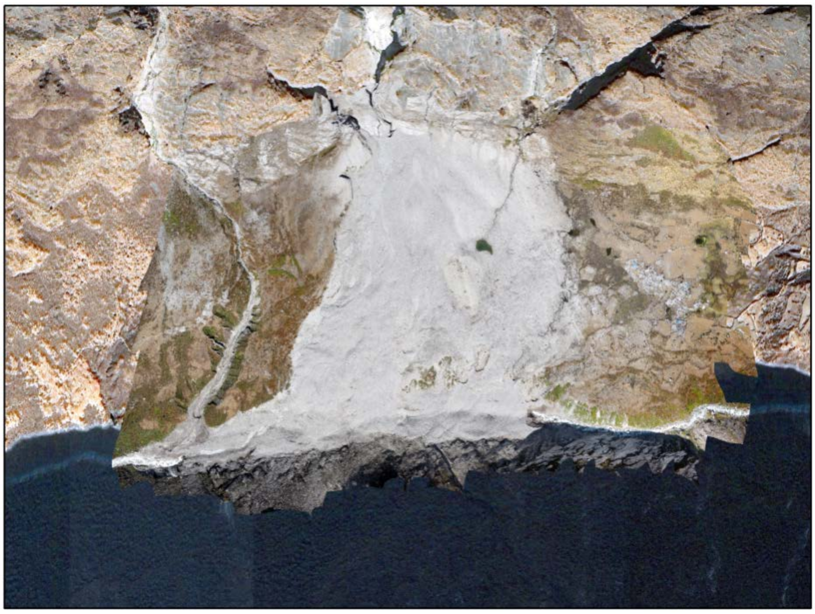

Figure 8: Langtang village after the April 2015 earthquake based on UAV imagery.

2.3 Conclusions

It is concluded that the project was very successful and the application of UAVs has tremendous potential for climate change impact research. UAVs change the current practice of investigating debris covered glaciers:

- Direct glaciological methods: this approach requires access to the glaciers and normally bamboo stakes are drilled into the ice before the melt season with a steam drill and the location is measured accurately with a differential GPS. After the melt season, the melt and horizontal movement is measured at the stake location.
- Satellite remote sensing methods: using optical or radar imagery elevation and area changes of glacier are mapped using imagery of different time period.

In the table below we compare the two classical approaches with the UAV approach. The UAV can be applied for an entire glacier or at least a significant part of a debris covered tongue, whereas for the direct method point measurements are conducted and many are required to get a comprehensive picture of an entire glacier. Satellite remote sensing obviously covers larger regions than a UAV can handle, however the resolution is much poorer, satellites are hampered by clouds and the accuracy is much less. Surface properties, like ice cliffs and lakes, which play a major role in the melt of debris covered glaciers cannot be accurately resolved using satellite imagery. The risks of UAV research are also smaller compared with direct measurements as the scientists do not need to be on the glacier for prolonged periods of time. The costs for a high density set of direct measurements are also much higher as it takes much more time to collect the required data. Another clear advantage of UAVs is the fact that they can be deployed on demand, e.g. at the same time when other measurements are conducted, under cloud-free and good weather conditions and/or at the same time as a satellite overpass. Finally the technology also has clear potential for knowledge transfer and ownership. Our experience taught us that regional scientists are very keen to use UAVs as it is an exciting new way of conducting research. However, it also requires the tough and physically challenging work on debris covered glaciers.

Table 1 Comparison of different techniques to study glaciers.

	Direct method	Satellite remote sensing	UAV
Scale	point scale	entire glacier	entire glacier
Resolution	Several points	~ 30 meter	~ 20 cm
Accuracy	~ 2 cm	~ 10 meter	~ 10 cm
Risks	High	Low	Medium
Costs	High	Low	Low
On demand	Yes	No	Yes
Knowledge transfer	Medium	Low	High
Ownership	Low	Very low	High

For glaciology it is concluded that UAVs can be successfully applied:

- To the surface and its features of glaciers
- To quantify changes in surface elevation of glacier tongues and to link that to melt processes
- To quantify the (seasonal) flow velocities of glaciers accurately

We have focused in particular on debris covered glacier tongues and our results show that these types of glacier are losing mass at similar rates as clean ice glaciers at the same altitude. Theoretically it was always assumed that debris covered glaciers melt at lower rates because of the insulating effect of the debris; however our results show that surface features like the lakes and cliffs may be responsible for this accelerated melt. This key finding was only possible due to the use of UAVs which provide the high level of detail required to show these spatial difference in melt rates. The warming climate may also be a positive feedback as more and more lakes and cliffs may form and further accelerate the melt of the glacier tongues, which are the main ice reserves in the Himalaya. Overall we conclude that the Himalayan glaciers in this region are in a poor shape, they are consistently losing mass, move very slowly and many supra-glacial ponds and ice cliffs have formed in their surface.

2.4 Challenges

UAV technology has shown great progress over the last years but the development of the rules and regulations regarding their use are lacking behind the technological advances. In Nepal, as elsewhere in the world, a permit is required to use a UAV. The fact that our research area is located in a National park posed an additional challenge to get a permit for the research. To overcome this challenge we organized a workshop in January 2015 with all stakeholders (Nepal police, Army, Department of National Parks and Wildlife Conservation, Civil Aviation Authority) to illustrate the scientific potential of UAV and this was very beneficial to the project and in securing support for our project. A report of the UAV workshop is given in Annex 6.

Through this DFID funded project, we pioneered in the use of UAVs at high altitude. Under these circumstances the air is very thin and this has implications for the performance of the UAV; it flies much faster, it is less stable and it is sometime challenging to get enough lift during take-off. The highest flights were conducted in the Everest region at an altitude of 5900 meters above sea level. This seems to be the upper limit of what is technically feasible. To overcome this challenge we are in touch with the manufacturers and we are discussing whether it is possible to make special high-altitude adaptation such as larger wings or a stronger engine.

2.5 Future directions

The application of UAVs has tremendous future potential and we recommend the following:

- To establish several benchmark glaciers throughout the Himalaya where long-term monitoring of debris covered glaciers will take place to understand the multi-year impact on debris covered glaciers.
- To test whether the UAV technology also works on debris-free snow and ice surfaces. A first test in Norway in September 2015 revealed that the software also works for snow and ice surfaces which are not covered by debris. Earlier it was assumed that the contrast over snow surface was too small to accurately derive the surface elevation, but this does not seem to be the case and this provides a lot of opportunities to also monitor the accumulation zones of glaciers or snow fields.
- Thermal cameras are now available for the eBee. Using thermal cameras will allow for detailed mapping of surface temperatures, which will be used to better quantify the melt processes and to estimate the debris thickness. A test of the thermal camera is proposed for the spring 2016 field campaign to Langtang Valley.
- We showed that even under very extreme applications UAVs can be successfully applied for glaciological research. There are also many other applications that have a direct bearing on the livelihoods of people. Some examples are given below:
    - The UAV was used after the earthquake to map the damage at both a village in Kathmandu valley (Sankhu) and at Langtang village. It provides fast, reliable and detailed information that can help planning the response when natural disasters occur.
    - Thermal infrared cameras can be used to study evaporation and water use of crops, and this may be very useful for precision agriculture, irrigation scheduling and identification of crop diseases.
    - Many cities in Asia are developing rapidly and UAVs can be a useful tool to map, control and plan urban development.

2.6 Policy implications

Glacier research has received an enormous boost after an error was discovered in the fourth IPCC assessment report published in 2009. In the second working group, it was speculated that all Himalayan glaciers will disappear by the year 2035, which is obviously not correct. The Himalayas are tremendously diverse and so are its glaciers and we are only at the beginning of understanding the interaction between climate, climate changes and the response of glaciers. However, it is clear that the future will see large changes in glacier area, volume and water supplied to downstream regions.

Since 2009, many glaciological studies have been initiated and contributed to the understanding of Himalayan glaciers and their role for the millions of people downstream. These studies also revealed that a large amount of ice is stored in debris-covered glacier tongues, yet methods to accurately study those glaciers were not available. With the rapid development of UAV technology this has now changed and this project has contributed to the understanding of the interaction between the climate and those vast ice reserves of the glacier tongues.

This project has shown that debris covered tongues melt more rapidly than previously thought and that the debris covered glaciers in the central Himalaya are in a poor state; they move slow, they lose mass and many lakes and ice cliffs form on their surface, which further accelerate the melt.

We offer the following policy recommendations for governments in the region:

1) A reasonable approach to facilitate the applications of UAV technology for scientific purposes such as glaciological research. With responsible operators the technology is completely harmless and it provides a vast knowledge resource which was unthinkable until a few years ago.
2) To implement an international benchmark glacier monitoring program at representative sites in the Himalayas where UAV mapping is conducted annually to generate long-term time series of changes in glaciers. Only then we can understand the impacts of climate change and formulate proper adaptation measures downstream.

3 PROJECT DELIVERABLES

3.1 Field studies

During the course of the project a total of three field campaigns were successfully conducted in both the Langtang and Everest region in Nepal. In the Langtang two campaigns were conducted in May 2014 and in October 2015 on the Langtang and Lirung glaciers and in the Everest region one campaign was conducted on the Changrinup and Chola glaciers.

During these trips, the unmanned aerial vehicle (UAV) that was used is the *eBee* from the Swiss company *SenseFly*. The UAV includes a GPS, a camera and several other sensors and each flight took approximately 30 minutes during which overlapping pictures of the glacier surface are taken. In addition highly accurate GPS measurements (dGPS) of Ground Control Points (GCPs) are collected to geometrically correct the image locations during processing. These images are all processed using the software package *Agisoft Photoscan Professional* [*Agisoft*, 2013]. To georeference the imagery the GCPs were then marked within the software on all the images that included them. The photogrammetrical algorithms of the software were subsequently used to generate digital elevation models of the glaciers. Using the elevation information the software processed the images into a 10 cm/pixel stitched and georeferenced image, known as an *orthomosaic*.

In Annex 1 and 2 the progress reports are included that describe all field trips in detail including the results of the processing.

3.2 Scientific open access papers

The data acquired during the project resulted in three high quality **open access** scientific papers:

- A paper where novel techniques are used on assessing seasonal differences in glacier flow in the Langtang catchment. This paper was published in the special issue of the Annals of Glaciology that resulted from the International Symposium on Glaciology in High-Mountain Asia in March 2015. Philip Kraaijenbrink who presented the paper at the symposium also won the best student presentation award. The paper is attached as Annex 3 and can be downloaded at http://dx.doi.org/10.3189/2016AoG71A072.
- A paper where a novel classification technique is used to identify supra-glacial ice cliffs and lakes, which are known to play a major role in catalyzing melt of debris covered glaciers. The final draft of paper is currently being reviewed by the co-authors and will be submitted to Remote Sensing of Environment in February 2016. The draft paper is attached as Annex 4.
- A paper where the UAV data is combined with field measurements of ice flow, thickness and melt on the Changrinup glacier in the Everest region. The paper is also nearly complete and will be submitted to The Cryosphere in February 2016. The draft paper is attached as Annex 5.

3.3 Content for the dedicated webpages and media outreach material

- A 9-minute professional outreach documentary was developed together with the Dutch company ScienceMedia. The documentary is aimed at a broad audience to show how novel measurement techniques can be used to understand the response of Himalayan glaciers to climate change. It also zooms in on the devastating effects of earthquake that hit Nepal on 25 April 2015.

  The documentary will also be screen during the CRISSA final workshop in April 2016 in Delhi and it can be viewed via this link: https://youtu.be/JJ_ZtoC90Jo.

- Interactive 3D models were developed based on the UAV datasets, which can be easily embedded on websites. These models were developed using the software package SketchFab and they can also be viewed on smartphones using virtual reality glasses. This will be demonstrated during the CRISSA workshop in April 2016 in Delhi.

  The following 3D models were developed:

  - Part of the Langtang glacier at high resolution - https://skfb.ly/K6LE
  - The landslide over Langtang village - https://skfb.ly/KoM7
  - The Changrinup glacier in the Everest region - https://skfb.ly/KpEA
  - The camp on Changrinup glacier in the Everest region - https://skfb.ly/Kpuy

  A screenshot of the 3D model of Langtang glacier 3D model is shown below.

Figure9: 3D model constructed in SketchFab of the Langtang glacier based on UAV data.

3.4 Datasets

The project has resulted in unique datasets at an unprecedented level of details, which have a very large scope for future studies and publications. These datasets will be made publicly accessible on the regional database system of ICIMOD and via www.mountainhydrology.org.

The following datasets have been generated during the course of the project:

- Lirung Glacier: digital elevation models (20 cm resolution) and orthomosaics (10 cm resolution) for May 2014 and October 2015
- Langtang Glacier: digital elevation models (20 cm resolution) and orthomosaics (10 cm resolution) for May 2014 and October 2015
- Langtang Village: digital elevation model (20 cm resolution) and orthomosaic (10 cm) for October 2015
- Chola Glacier: digital elevation model (20 cm resolution) and orthomosaic (10 cm resolution) for November 2015
- Changrinup Glacier: digital elevation model (20 cm resolution) and orthomosaic (10 cm resolution) for November 2015

Several scientific publications have been submitted or are currently under preparation based on these datasets. Once these publications have been published in their final form the datasets will be assigned a digital object identifier (DOI) and made publically accessible **by 1 February 2017**. Once the datasets have been published online, Utrecht University will confirm this in writing with project officer of DFID.

4 UPTAKE AND ENGAGEMENT WITH BENEFICIARIES

On 27 January 2015 a workshop was organized at ICIMOD in the use of UAVs in different fields. The workshop was attended by representatives from DFID, The Nepali army, the Civil Aviation Authority, the police, ICIMOD, Utrecht University, Nepal Academy of Science and Technology, The Department of Hydrology and Meteorology, Kathmandu University and Tribhuvan University. During the morning several presentations were given by experts from ICIMOD, Utrecht University and Kathmandu University. During the afternoon a demonstration was given using one of the UAVs on the Kirtipur cricket pitch in Kathmandu. The workshop was a great success and people showed keen interest in the application possibilities of this technology. A full report of the workshop including a list of participants, schedule, and presentations is included in Annex 6.

Figure 10: Workshop participants for the UAV workshop on 27 January 2015

Students from Kathmandu University, Tribuvahn University, and researchers from the Nepal Academy of Science and Technology (NAST) have assisted with the UAV research. A group of students from the region (India, Pakistan, Nepal, and Bhutan) also assisted during the 2014 survey in Langtang Valley as part of the Training on Glaciohydrological Monitoring and Modelling hosted by ICIMOD and sponsored by the American Embassy in Kathmandu (http://www.icimod.org/?q=12074).

5 CHALLENGES, DISAPPOINTMENTS AND LEARNINGS

The 25 April 2015 earthquake affected the project considerably. The second field campaign could not take place as it was planned the week after the earthquake had occurred. This resulted in a delay of the project and in additional costs. However these circumstances were beyond our control and the project officer of the South Asia Research Hub of the UK Department for International Development has been very supportive to ensure a successful completion of the project.

While UAV technology has shown great progress over the last years, the regulations regarding their application develops only slowly. In Nepal, as elsewhere in the world, a permit is required to use a UAV. The fact that our research area is located in a National park posed an additional challenge to get a permit for the research. To overcome this challenge we organized a workshop in January 2015 with all stakeholders (Nepal police, army, Department of National Parks and Wildlife Conservation, Civil Aviation Authority) to illustrate the scientific potential of UAV and this was very beneficial to the project and in securing support for our project.

We pioneered in the use of UAVs at high altitude. Under these circumstances the air is very thin and this has implications for the performance of the UAV; it flies much faster, it is less stable and it is sometime challenging to get enough lift during take-off. The highest flights were conducted in the Everest region at an altitude of 5700 meters above sea level. This seemed to be the upper limit of what is technically feasible. To overcome this challenge we are in touch with the manufacturers and we are discussing whether it is possible to make special high-altitude adaptation such as larger wings or a stronger engine.

6 REFERENCES

Agisoft (2013), *PhotoScan Professional 0.9.1 User Manual*, St. Petersburg.

Benn, D. I., T. Bolch, K. Hands, J. Gulley, A. Luckman, L. I. Nicholson, D. J. Quincey, S. Thompson, R. Toumi, and S. Wiseman (2012), Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, *Earth-Science Rev.*, *114*(1-2), 156–174.

Haidong, H. A. N., W. Jian, W. E. I. Junfeng, and L. I. U. Shiyin (2010), Backwasting rate on debris-covered Koxkar glacier , Tuomuer mountain , China, *J. Glaciol.*, *56*(196), 287–296.

Immerzeel, W. W., F. Pellicciotti, and M. F. P. Bierkens (2013), Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds, *Nat. Geosci.*, *6*, 742–745.

Immerzeel, W. W., P. D. A. Kraaijenbrink, J. M. Shea, A. B. Shrestha, F. Pellicciotti, M. F. P. Bierkens, and S. M. de Jong (2014), High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles, *Remote Sens. Environ.*, *150*, 93–103.

Kargel, J. S. et al. (2016), Geomorphic and geologic controls of geohazards induced by Nepals 2015 Gorkha earthquake, *Science (80-.).*, *351*(6269), 140, doi:10.1126/science.aac8353.

Kraaijenbrink, P., S. W. Meijer, J. M. Shea, S. M. D. E. Jong, and W. W. Immerzeel (2016a), Seasonal surface velocities of a Himalayan glacier derived by automated correlation of unmanned aerial vehicle imagery, *Ann. Glaciol.*, *57*, 103–113.

Kraaijenbrink, P. D. A., W. W. Immerzeel, F. Pellicciotti, and J. M. Shea (2016b), Distribution and characteristics of surface features on a debris-covered glacier, an object-based analysis, *Remote Sens. Environ. (in Prep.*

Pellicciotti, F., C. Stephan, E. Miles, W. W. Immerzeel, and T. Bolch (2015), Mass balance changes of the debris-covered glaciers in the Langtang Himal in Nepal between 1974 and 1999, *J. Glaciol.*, *61*, 373 – 386.

Sakai, A., K. Nishimura, T. Kadota, and N. Takeuchi (2009), Onset of calving at supraglacial lakes on debris-covered glaciers of the Nepal Himalaya, *J. Glaciol.*, *55*(193), 909–917.

Scherler, D., B. Bookhagen, and M. R. Strecker (2011), Spatially variable response of Himalayan glaciers to climate change affected by debris cover, *Nat. Geosci.*, *4*(1), 156–159.

Vincent, C., P. Wagnon, J. M. Shea, W. W. Immerzeel, P. D. A. Kraaijenbrink, D. Shrestha, A. Soruco, Y. Arnaud, and E. Berthier (2016), Surface mass balance of the debris-covered area of Changrinup Glacier (Nepal) assessed from an ice flux method, *Cryosph. (in Prep.*

Viviroli, D. (2004), The hydrological significance of mountains: from regional to global scale, *Hydrol. Earth Syst. Sci.*, *8*(6), 1016–1029.