A Landsat analysis of supraglacial pond variability for Langtang Valley's debris-covered glaciers, Nepal

CR4.3 Debris-covered glaciers, EGU2016-134

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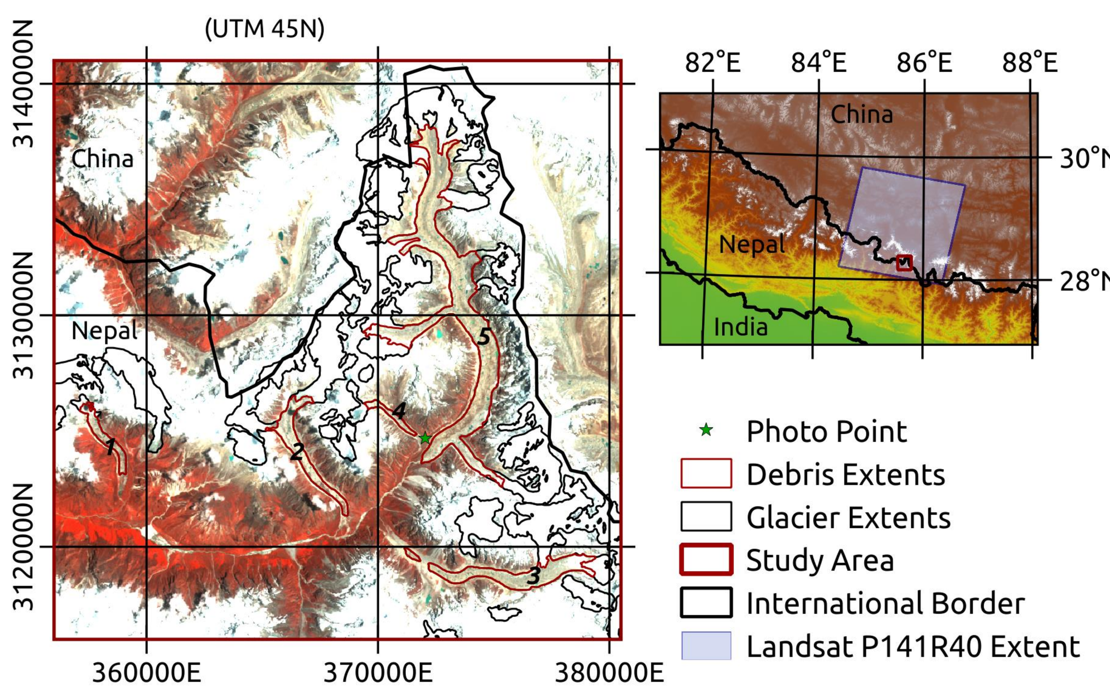
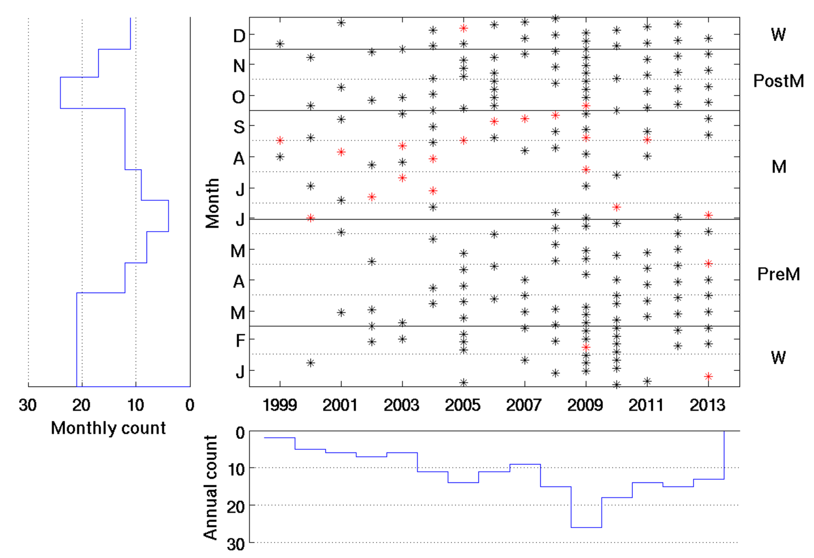
1. Motivation and Objectives



Debris-covered glaciers have received renewed interest in recent years in an attempt to improve understanding of climate-glacier interactions in High Mountain Asia. Conceptual understanding of key processes occurring in supraglacial ponds has advanced to include conduit-collapse formation, subaqueous and waterline melting, calving, and englacial filling and drainage. The behaviour of systems of ponds has received little attention, with most process observations made on individual features. Several studies have used satellite data to determine pond distributions at a single point in time or their variability across several years or decades. However, no attempt has been made to document the seasonal and inter-annual variability of ponds, even though individual ponds have been observed to fill and drain periodically.

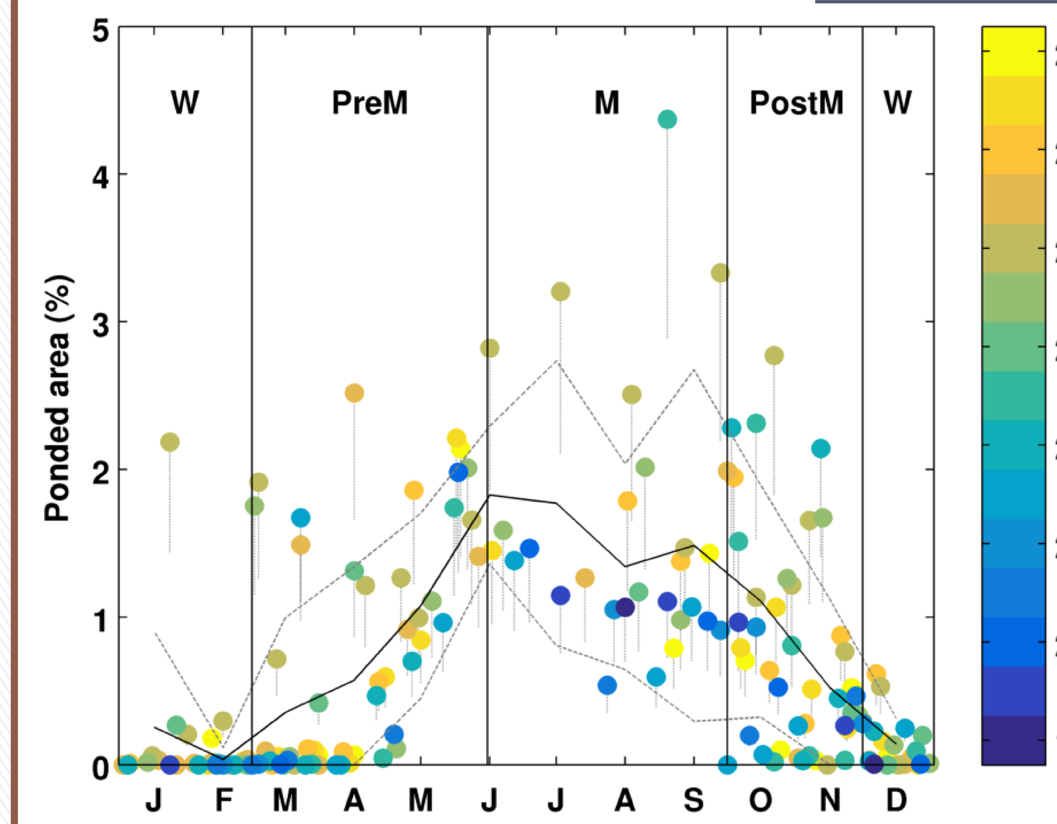
We analyse **172 Landsat TM/ETM+ scenes** for the period **1999-2013** to identify thawed supraglacial ponds for the debris-covered tongues of five glaciers in the Langtang Valley of Nepal. We apply an advanced atmospheric correction routine (*LandCor/6S*) and use band-ratio and image morphological techniques to identify ponds, then apply this database of identified ponds to:

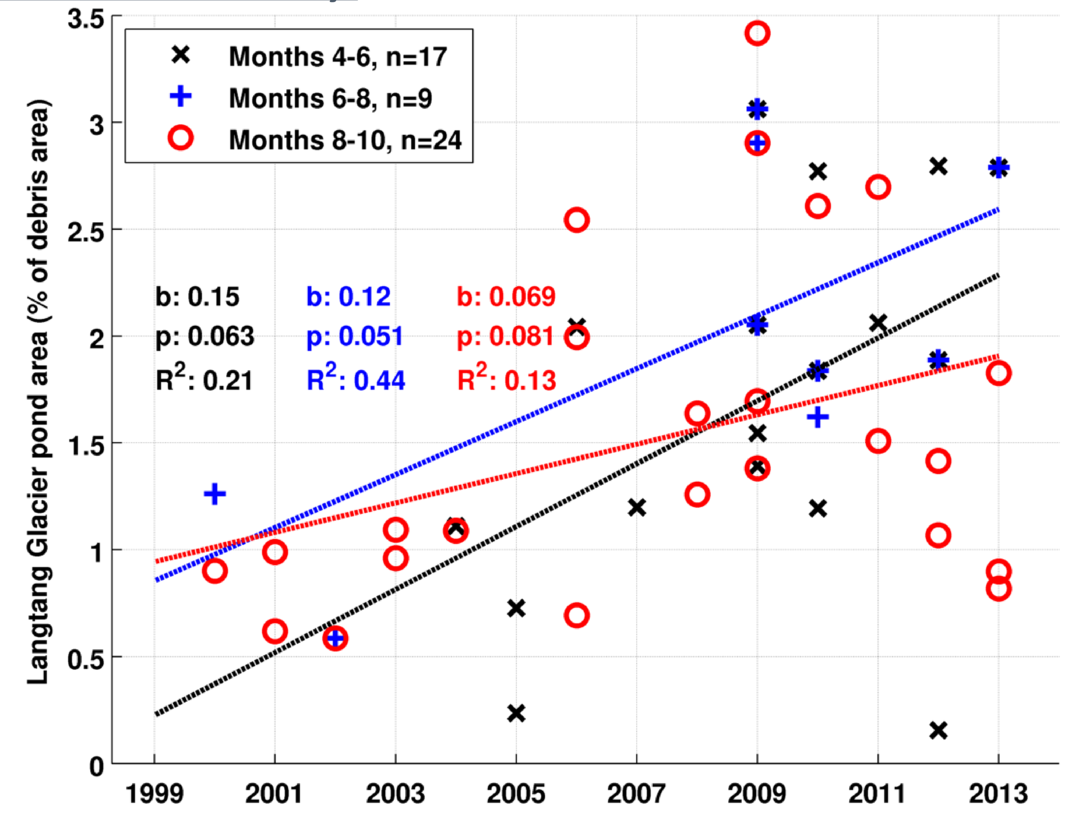
1) Measure the **density** of supraglacial ponding for five glaciers with differing characteristics;
2) Evaluate surface gradient and glacier velocity as **controls** on pond occurrence;
3) Document the **seasonal cycle** of pond occurrence and disappearance;
4) Determine if surface ponding has **increased over time** for the study glaciers.



Temporal distribution of the 172 Landsat scenes analysed

4. Results: Temporal Variability





Seasonality:

- Ponds appear in **April-May** (premonsoon)
- Peak pond area of about **2% of debris area** is in late May or early June, slightly preceding the monsoon
- Pond cover **declines slightly** during the monsoon
- A **sharp decline** occurs in the postmonsoon
- Thawed ponds are only **occasionally observed** in winter

Changes over the study period:

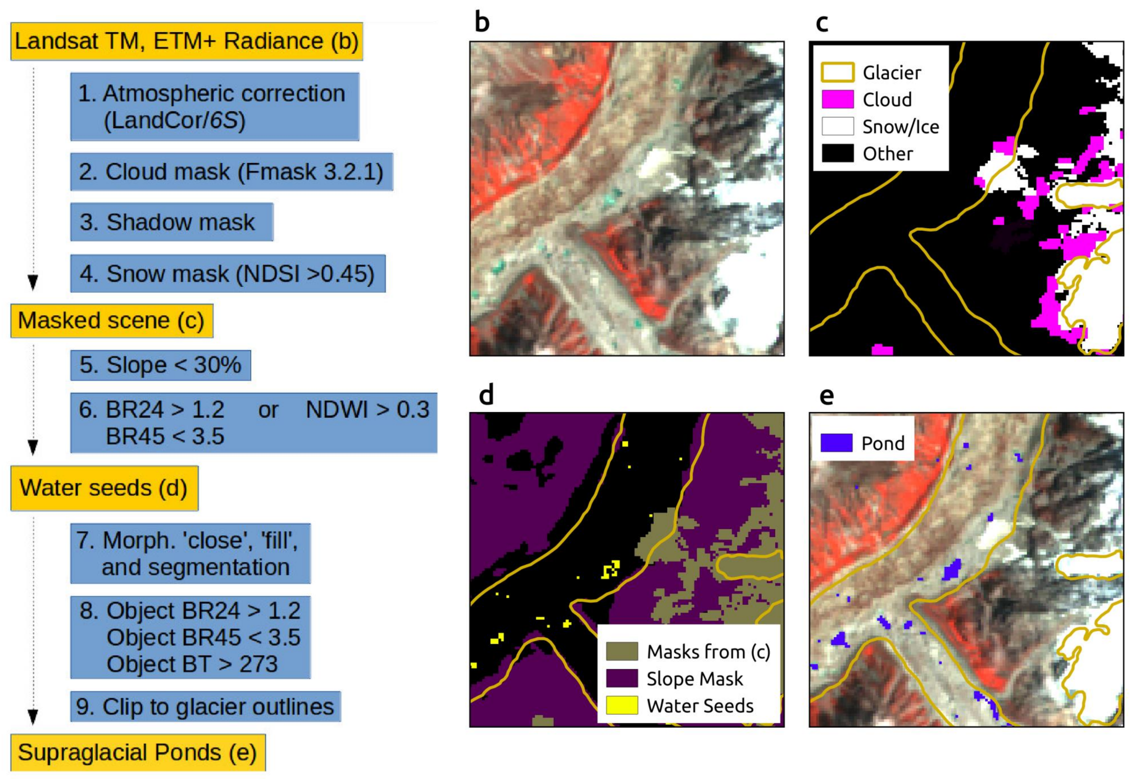
Langtang Glacier is the largest of the study glaciers, with the most ponds. Reduced seasonality in 2-month periods.

- Weak **increases** ($R^2<0.5$, $p<0.1$) in ponded area.
- Apparent postmonsoon **decline** after 2009
- High **interannual** and **seasonal** variability
- No strong relationship: T, P, PDD

2. Landsat Data Processing

Images are converted to surface reflectance using the LandCor implementation (*Zelazowski 2011*) of the 6S radiative transfer code (*Kotchenova 2006*):

- **Sun-scene-sensor geometry** accounted for across scene.
- Elevation-based parameterizations of **AOD**, **TWV**, and **ozone**
- Adapted for ASTER, **TM**, **ETM+** data (OLI soon!)



Spectral and geographic operations are used to mask **confounding factors**. Thanks to strong radiometric agreement after LandCor processing, uniform thresholds are applied:

- **Snowcover** is mapped using NDSI
- **Clouds** are mapped using *Fmask 3.2.1* routines (Zhu 2015)
- **Deep shadows** are assessed using *Fmask*, B1, B5, and slope

Last, locations of ponded water are determined:

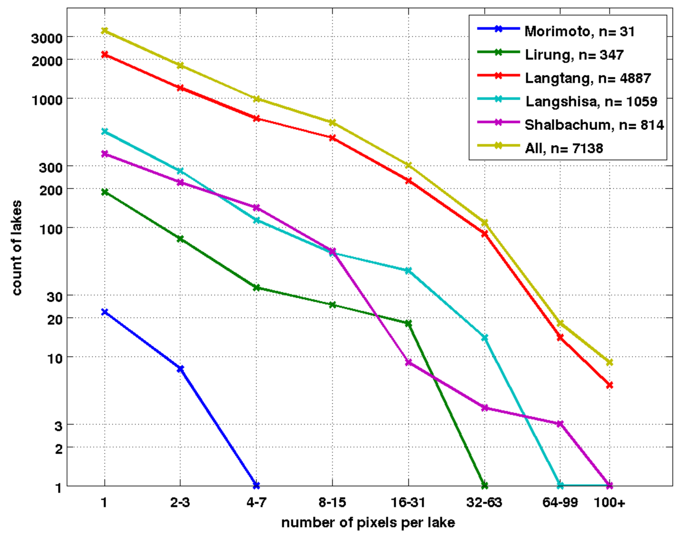
1) High-likelihood '**water seeds**' are determined using band ratios (bands 2&4, bands 4&5) and the NDWI
2) These are adjusted using **image morphological techniques** to define a segmentation of naturally-associated objects
3) Each object's mean spectral properties are reevaluated with band ratios and brightness temperature => **thawed ponds**

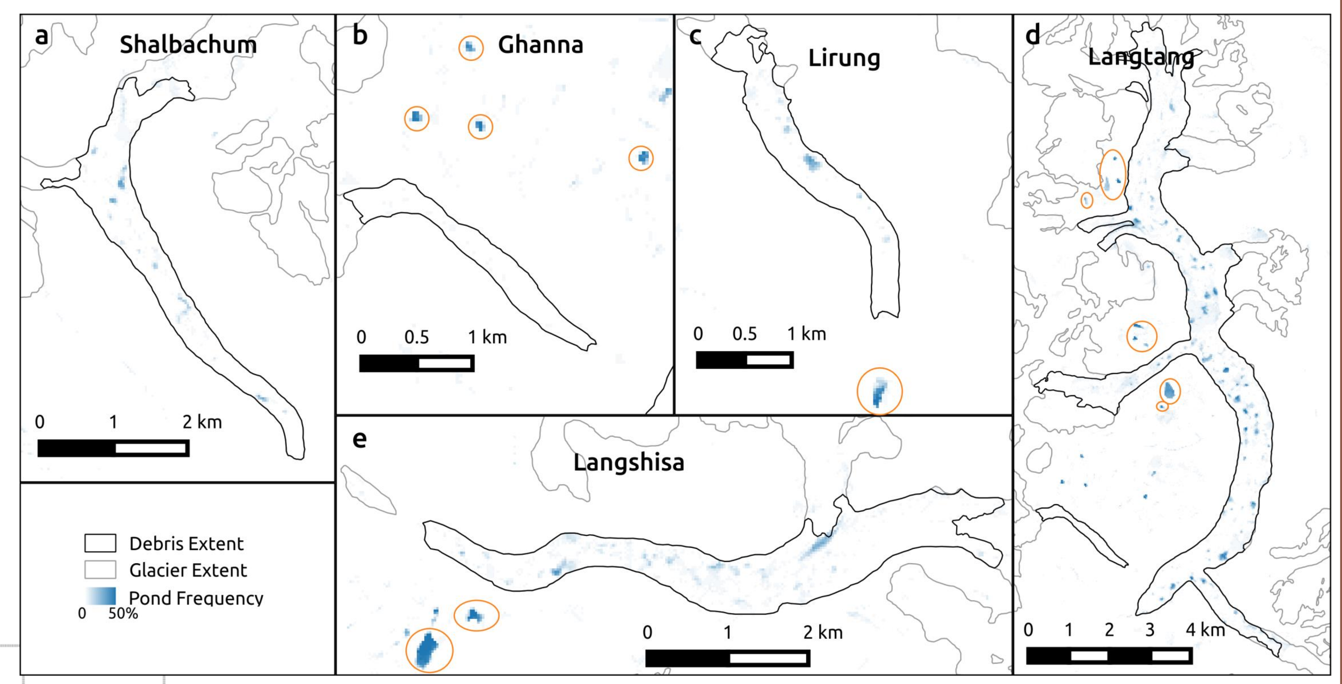
3. Results: Spatial Variability

- **7138 individual ponds** observed over the 15-year period (4887 on Langtang Glacier alone)
- Ponds show a logarithmic size distribution
- On average, **1.26% of debris area** May-October, high variability between glaciers (0.08-1.69%)
- Glacier pond density correlates to **glacier area**, **debris area**, **width**, and **surface gradient**
- No relationship with cumulative historical downwasting (**DGM**) or **velocity** at glacier scale

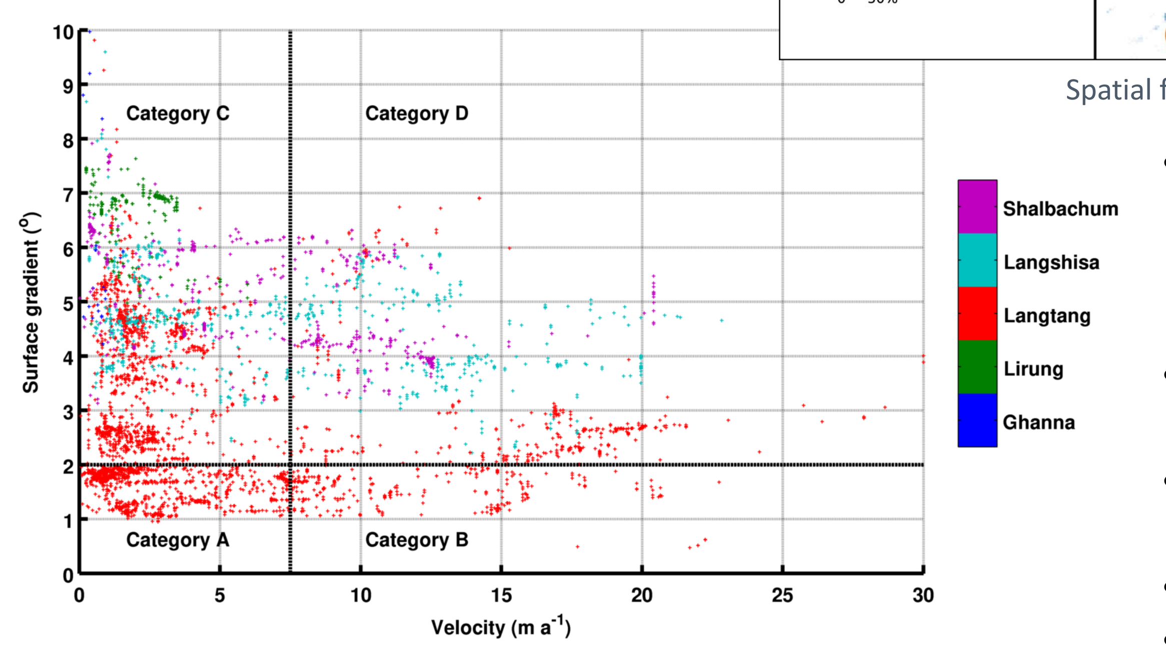
	Area (km^2)		Elevation (m.a.s.l.)		Descriptive Ratios (%)		Width	DGM	Slope	Velocity	Pond Cover
	Glacier	Debris	Min	Mean	AAR	DRAA	(m)	(m)	(°)	($m\ a^{-1}$)	(%)
R^2	[0.93]	[0.86]	[0.01]	[0.10]	[0.01]	[0.56]	[0.85]	[0.04]	[0.77]	[0.26]	[-]
p-value	[0.008]	[0.022]	[0.87]	[0.61]	[0.86]	[0.15]	[0.025]	[0.75]	[0.051]	[0.38]	[-]
Lirung	6.1	1.2	4025	4287	52%	50%	590	65	10.2	1.5	0.57
Shalbachum	11.7	2.8	4218	4607	15%	53%	430	30	7.1	5.5	0.73
Langshisa	21.7	4.4	4526	4884	49%	40%	760	125	4.9	9.0	0.88
Ghanna	1.3	0.6	4718	4879	52%	70%	295	32	9.5	0.9	0.06
Langtang	52.8	17.8	4468	4944	55%	45%	970	50	3.1	4.9	1.69
Total	93.7	26.8									1.40

AAR – accumulation area ratio
DRAA – debris ratio in the ablation area (below ELA)
DGM – difference between glacier surface and moraine crest elevations





Spatial frequency of pond observation for the five debris-covered glaciers



Glacier velocity and surface gradient at each observed pond location

- Individual pond locations are **highly recurrent** over 15 years: 40.5% of pond locations occur in 2+ years, many locations span 15 years
- Analysis has a **high success** in identifying other glacial lakes in the study area
- Ponds are most common and largest in zones of low surface gradient and velocity
- Surface gradient controls pond density
- Velocity appears to control pond size.

5. Conclusions and Outlook

1. Pond seasonality has strong implications for **surface energy balance**, as ponds inject atmospheric energy directly to the glacier interior, bypassing the thick debris mantle:
   - Whole-glacier estimates of pond-associated ablation need to account for variable pond coverage in space and time.
   - Pond density is highest early in the ablation season, when surface energy receipts are close to peak values.
2. Pond seasonality is important to account for in **change assessments** (e.g. Gardelle et al 2011), as seasonal signals have high magnitude, and distinct changes may occur in each season.
3. Ponds at the study site are **highly recurrent and persistent**, possibly suggesting that controls of surface-internal hydrologic connections experience seasonal closure and opening.
4. Individual pond locations show **expansion** and **disappearance** as well as complex of **coalescence** and **separation**; detailed study of pond and ice-cliff coevolution is needed to assess behaviour of these systems.
5. Ponding on Langtang Glacier appears to be slightly **increasing over time**, but **uncertainties** on this increase are high.

6. Select Literature

- Bolch et al. The State and Fate of Himalayan Glaciers. *Science*. 20 April 2012
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- Zelazowski et al (2011) Reconciling satellite-derived atmospheric properties with fine-resolution land imagery: Insights for atmospheric correction. *JGR*, 116
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