# Analysis of satellite-derived debris covered glacier surface temperatures for determining debris thickness on a Himalayan glacier

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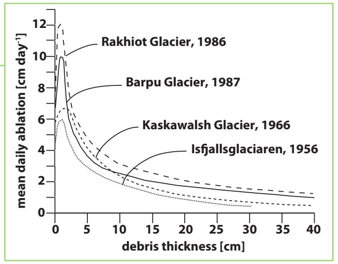
## BACKGROUND:

Debris thickness is a primary control on sub-debris ice melt.

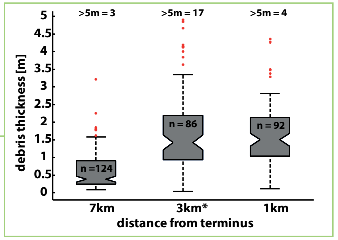



As it is impractical to measure debris thickness in most cases, it is desire able to compute this from satellite imagery on the basis that surface temperature is proportional to debris thickness.

To what extent are satellite surface temperatures, and thus inferred debris thickness, and calculated glacier melt, affected by other factors?

## FIELD DATA OF DEBRIS SURFACE PROPERTIES:

**Debris thickness** was measured by surveying exposed debris sections shows that debris thickness generally increases downglacier, but **varies widely within any zone of the glacier**. The distribution of the variability appears to evolve from skewed to more normal downglacier.

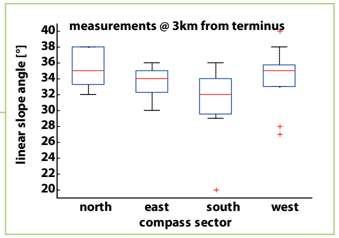



**samples at 3km are less accurate than at 1 and 7 km as they were surveyed by triangulation rather than laser distomat*

**Local relief** sampled at 1, 3 and 7km from the terminus can be **up to 56m** within a single peak to trough slope, and linear slope angles tend to show:

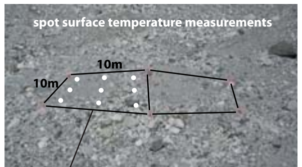
(i) **decreasing slope angle downglacier** from samples at 7, 3 and 1 km from the terminus

(ii) **slope angle varies with aspect**




Within 1km$^2$ **surface albedos** measured over variously inclined and orientated slopes with a handheld CM3 pyranometer have a median value of 0.22, with an **interquartile range of 0.13 - 0.28**.

**Surface temperature** measured at point locations with a Fluke 561 HVACPro within a 1 hour time window and a 200m$^2$ sample area @ ~3km from the terminus **varies widely** and is influenced by the surface properties.




| data from 18 points | |
|---|---|
| mean | 13.6°C |
| st.dev. | 6.0°C |
| min. | 0.2°C |
| max. | 30.1°C |

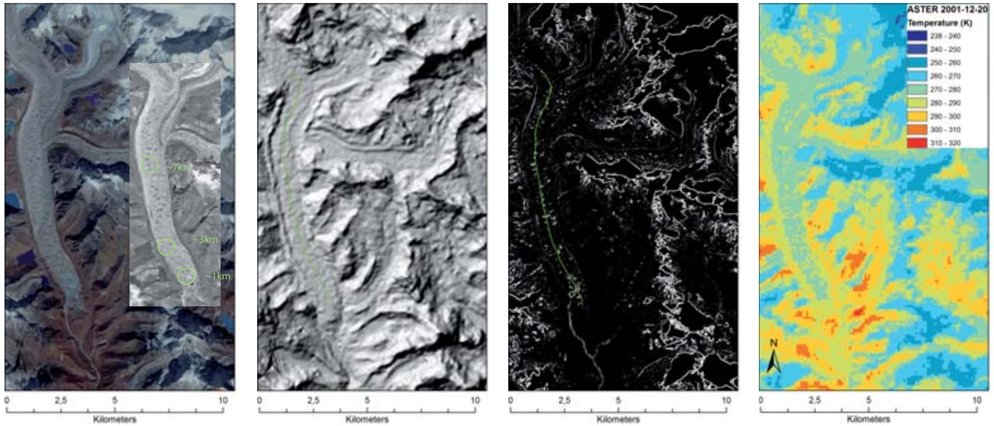
| surface | mean | +/- | st. dev. |
|---|---|---|---|
| gravel | 17.2 | +/- | 3.9 |
| cobbles | 18.5 | +/- | 4.2 |
| boulders | 8.3 | +/- | 5.8 |

Influence on satellite temperature?

What about ice faces? Surface waters? Shadowing effects? Local variability?

How to account for these in inverting satellite surface temperature for mean debris thickness?

## SATELLITE DATA FROM NGOZUMPA GLACIER:

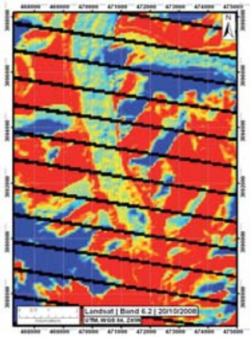



GEOEYE SPOT ASTER DEM ASTER surface variance ASTER surface temp.

The visible image shows many of the complex features of the debris covered area of the Ngozumpa glacier, including the 'Spillway lake' at about 1km from the terminus that has expanded rapidly during the 2000s (Thompson et al., 2012). ASTER images were used to generate a surface DEM and surface variance and thermal maps for 20th December 2001.

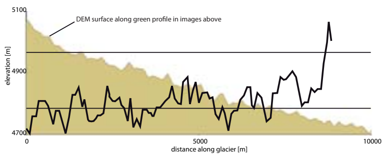
The ASTER surface temperature for this date was compared to field measurements of surface temperature at a single location ~3km from the terminus. The satellite temperature was 6.5°C and thermistor measurement of surface temperature for the same time as image capture was 9.8°C.

The LANDSAT surface temperature from 2008 on the right shows the impact of the growth of the Spillway Lake on the temperature field in the lower glacier, where the expanding lake is a cold temperature anomaly.

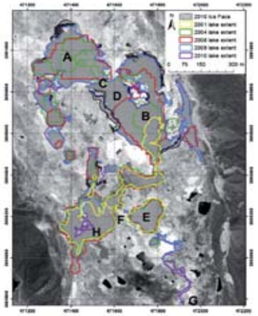



LANDSAT surface temp.

## DOWNGLACIER RELATIONSHIPS:




The elevation of the Ngozumpa debris covered terminus in 2001 generally decreases at a shallow gradient downglacier. Local surface elevation variability is evident in the long profile shown below. Surface temperature along the same profile shows a general increase towards the glacier terminus, but large variability.




Satellite pixels that contain significant proportions of lake surfaces, exposed ice of shadowed portions of the glacier will result in computed debris thickness estimates that underestimate the characteristic debris thickness for that region of the glacier.

## ANATOMY OF A DEBRIS-COVERED GLACIER


Ngozumpa glacier, Nepal. Mature debris-covered glacier with a rapidly expanding lake behind its terminal moraine

Steep headwalls with frequent avalanches deliver snow and rock debris to high elevation snowfields or to avalanche cones, within which lies the glacier mass equilibrium line

Former tributary glaciers are disconnected in terms of ice dynamics, but may have hydrological connections.

Variable topography studded with supraglacial ponds and flanked by upstanding moraine crests in the middle section of the debris-covered portion of the glacier


Englacial meltwater channels throughout the debris covered portion play a crucial role in both surface and hydrological evolution

Coalescence of lakes near the terminus where supraglacial lakes intersect the englacial water table

Terminal moraine is ice cored and shows stable and geomorphologically active areas