http://www.glims.org

Satellite-era glacier changes in High Asia

Jeffrey S. Kargel*, Richard Armstrong, Yves Arnaud, Etienne Berthier, Michael P. Bishop, Tobias Bolch, Andy Bush, Graham Cogley, Koji Fujita, Alan Gillespie, Umesh Haritashya, Georg Kaser, Siri Jodha Singh Khalsa, Greg Leonard, Adina Racoviteanu, Bruce Raup, and Cornelis Van der Veen.

- * Lead author: University of Arizona (Email: jeffreyskargel@hotmail.com)

Background support presentation for NASA "Black Carbon and Aerosols" press conference associated with Fall AGU, Dec. 14, 2009

For further information, please contact any author

Dec. 14, 2009 JSK
Updated Jan. 14, 2010

Why this presentation was produced.

Dec. 14, 2009 JSK
Updated Jan. 14, 2010

-- A series of media and science errors has produced confusion about the actual state of Himalayan glaciers (slides 40-42).

-- Some errors exaggerate the rate of melting, and others go the other way and errantly claim climatic insensitivity of glaciers.

-- A planned NASA press conference (which occurred Dec. 14*) appeared likely to reproduce and reinforce some of those errors, and this had to be avoided.

*www.nasa.gov/topics/earth/features/himalayan-warming.html

-- The lead author of this presentation was asked to join the press conference as a guest panelist (not part of the team whose work was to be featured).

-- A nuanced perspective on Himalayan glaciers, and the effects of glacier changes on water resources and other matters, is necessary; reality is complex. Oversimplification, exaggeration, or ignoring serious matters can be consequential.

-- An expert team has been assembled to build the case and buttress statements by Kargel that the glaciers will not disappear by 2035, but that they are melting rapidly in some areas and responding differently to climate change in other areas of the Himalaya/Hindu Kush (including some glacier advances).

-- This effort has expanded now to present a more complete view for the benefit of scientists as well as the media and public.

Presentation Summary

-- We will show examples of:
- Wasting, disintegrating glacier tongues
- Stagnating tongues that are thinning but have stably positioned termini
- A surging glacier

-- Total Himalayan mass balance is distinctly negative; some anomalies may exist.

-- There is complexity in glacier parameters, e.g., glacier area, types, and debris-cover, and in how they relate to the integrated Earth system.

-- Glacier responses and response times depend on climate, topographic characteristics, and unique aspects of each glacier, e.g., debris cover and types and sizes of lakes.

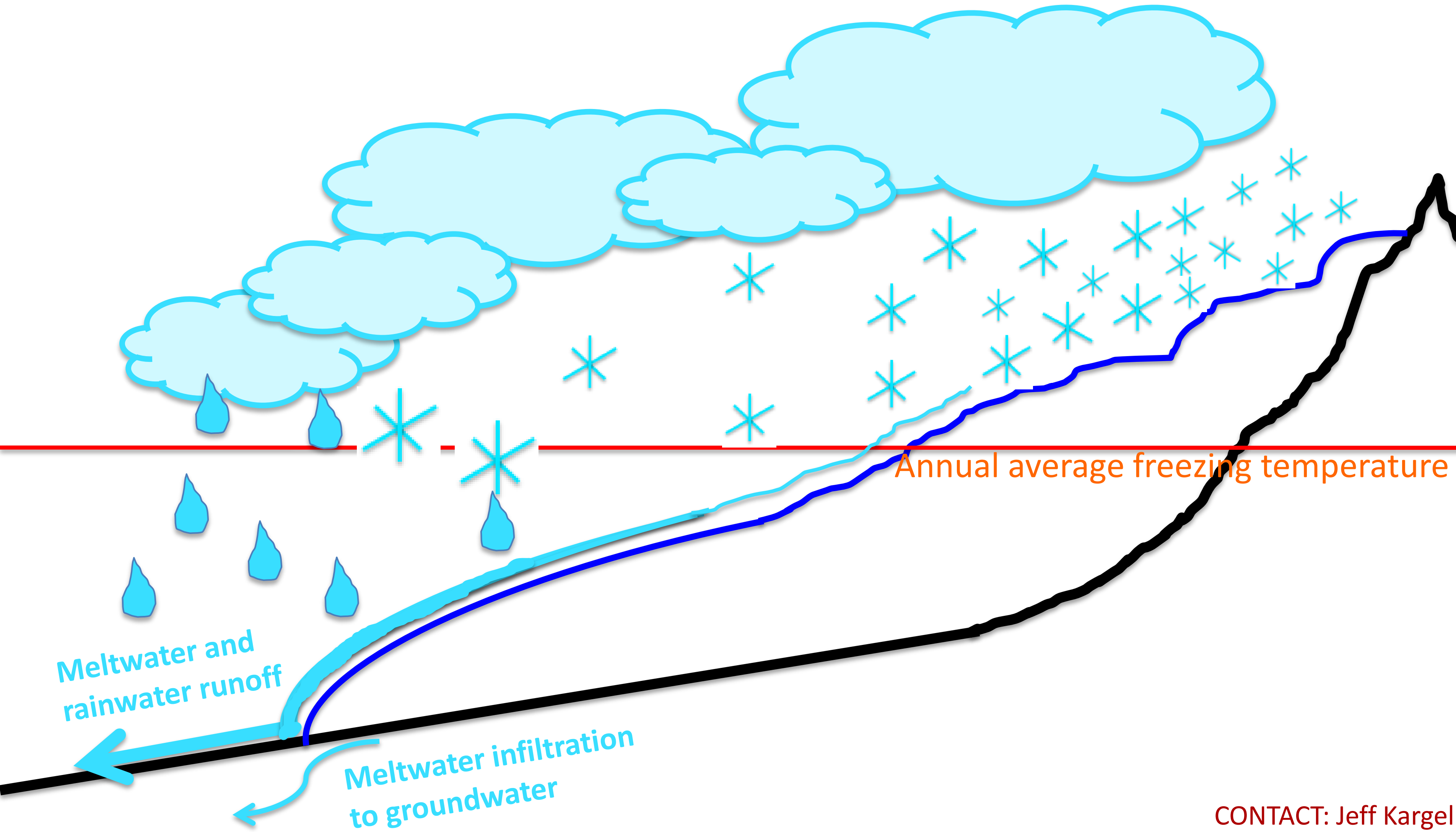
-- There may be a geographic pattern to aspects of the glacier dynamical complexity.

-- Glaciologists and climatologists have partial explanations for what is happening (but much is still not known or understood):
- Anthropogenic emissions (gases and aerosols) affect the global climate system and regional transport/precipitation of moisture.
- Regional variation in Elevated Heat Pump (EHP), Monsoons, and Westerlies.

-- We attempt to correct recent media and space agency errors and summarize and quantify some more realistic rates of glacier retreat and impacts on water resources.

Generalized glacier

Glaciers try to achieve a balance between snow accumulation and melting. When climate or any environmental condition shifts even a little, the balance is thrown off, so glaciers continually readjust.

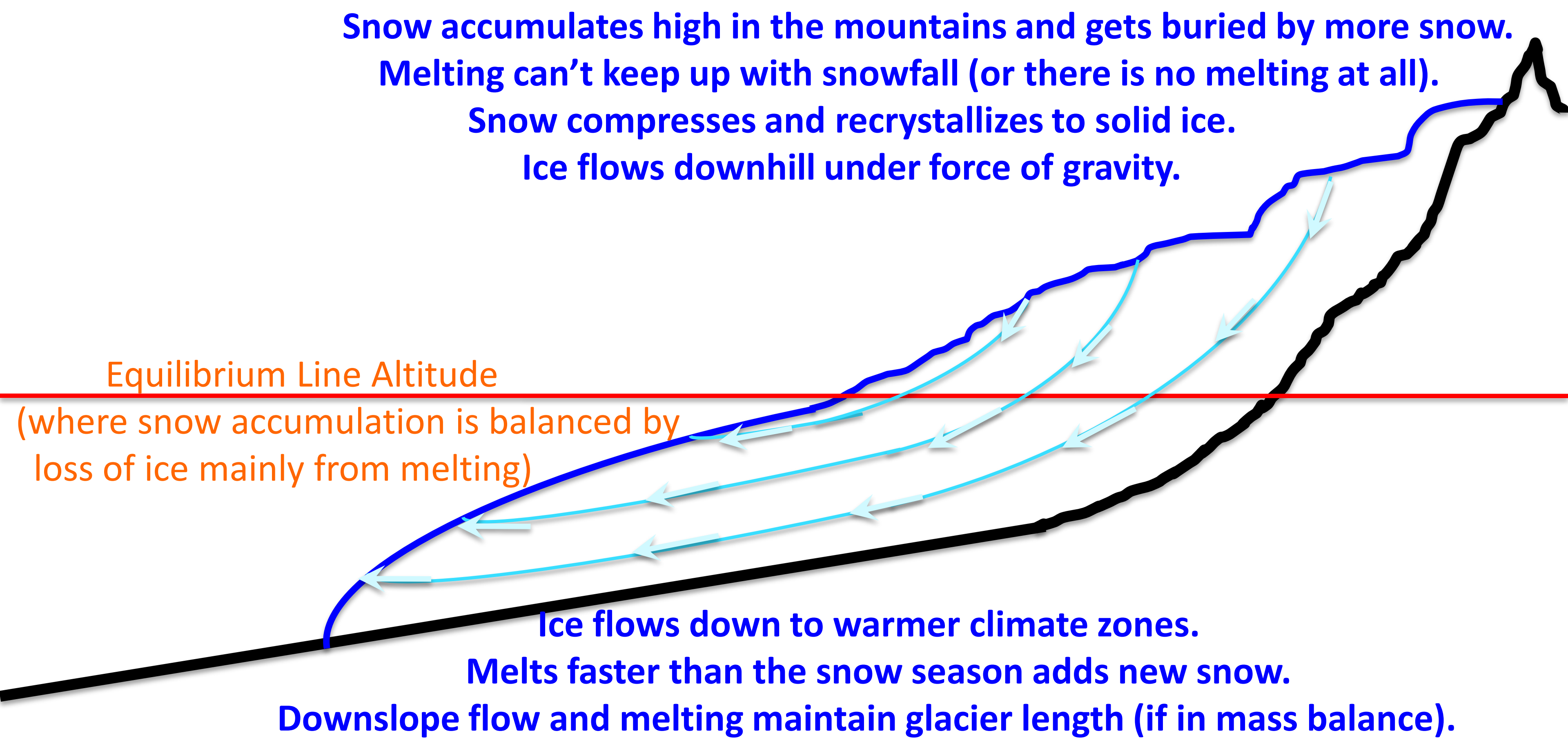


CONTACT: Jeff Kargel

CONTACT: Jeff Kargel

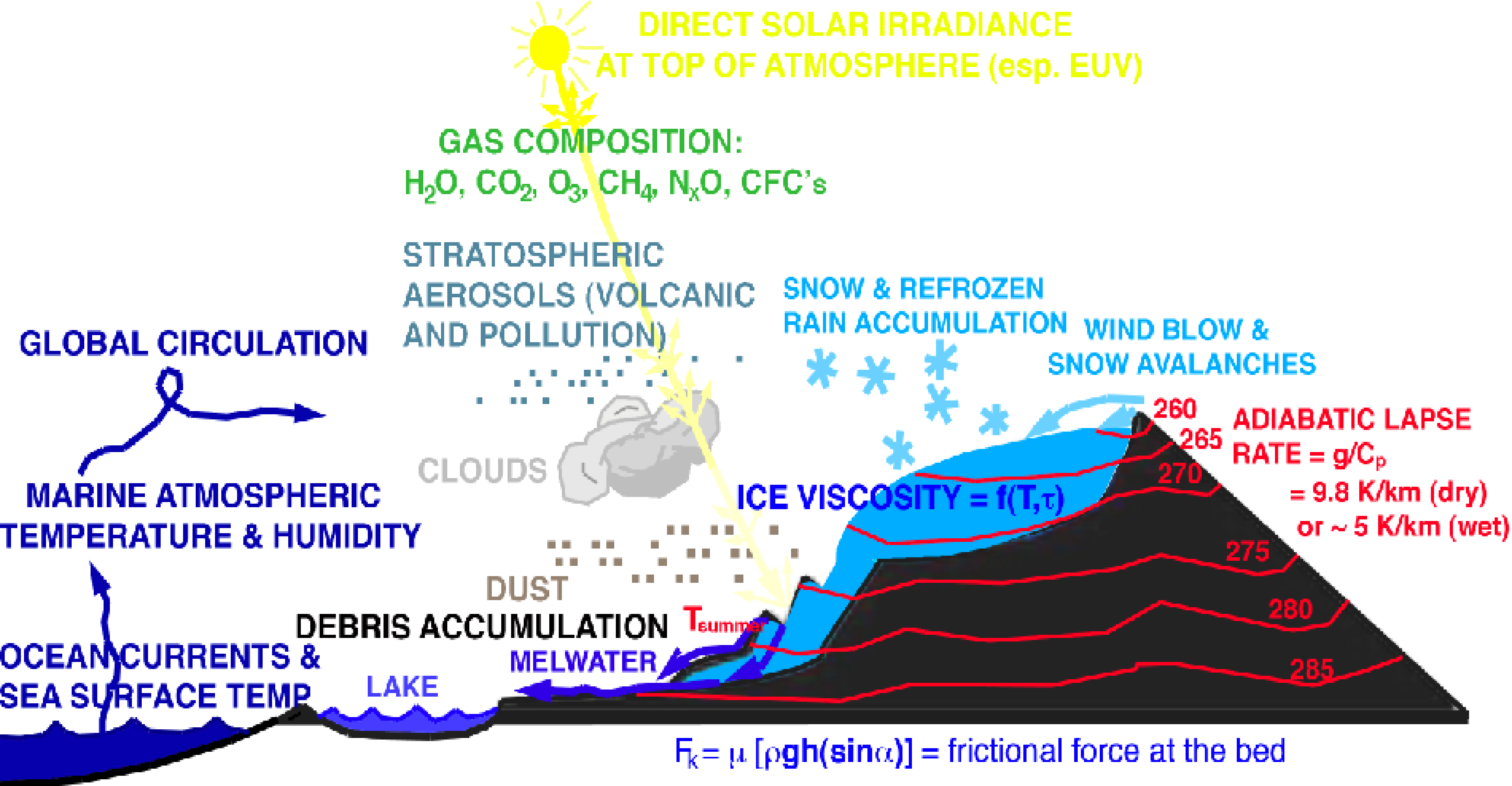
Generalized glacier

The Equilibrium Line Altitude is where snow accumulation (snowfall and any added snow avalanches) is balanced by melting and sublimation losses. It is not the same as the elevation where annual average temperature is at the melting point (but there is a relationship).

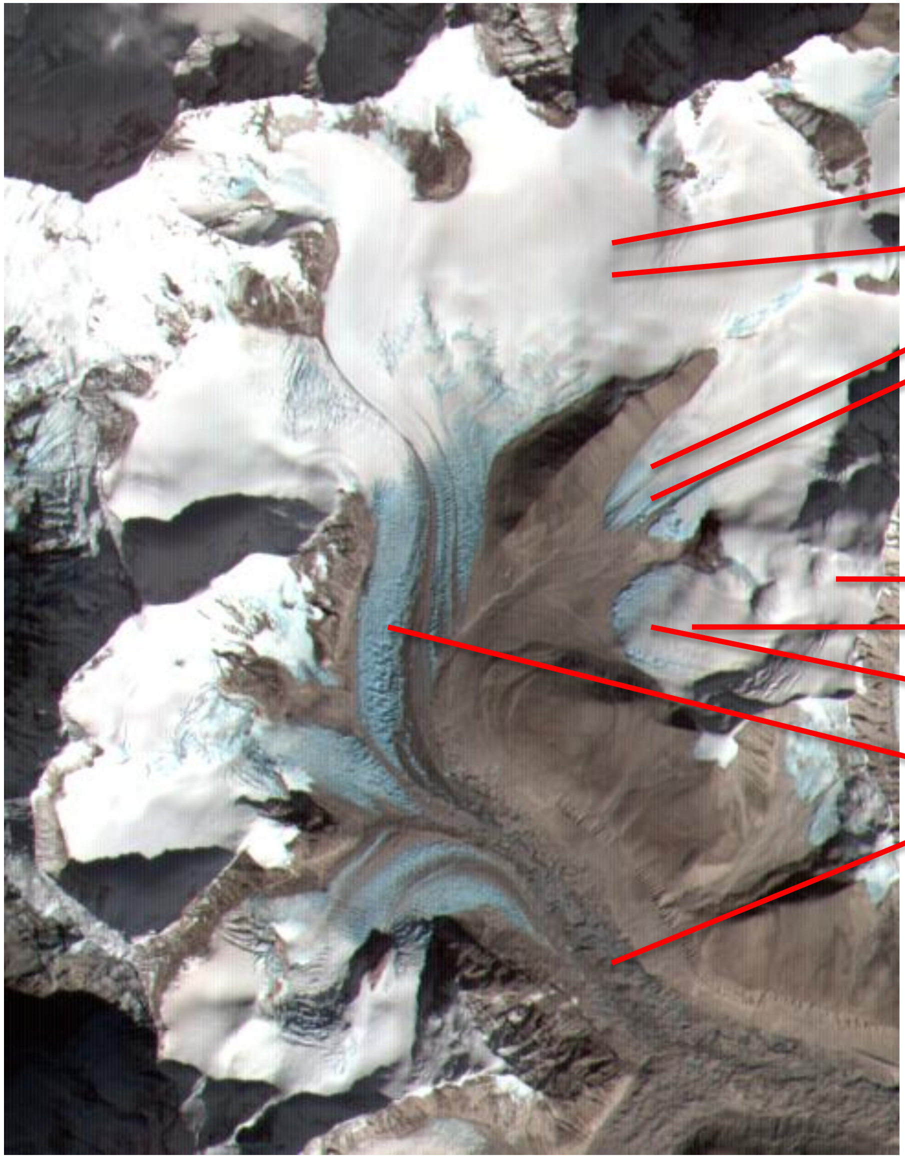


CONTACT: Jeff Kargel

Climate and environmental change related to glaciers is more than about rising temperatures



The melting influence of atmospheric aerosols and deposited soot and dust vary across the glacier



Atmospheric aerosols and Elevated Heat Pump:
Atmospheric thermal structure, H_2O transport, clouds and precipitation

- Reduced sunlight reaching glacier surface (+)
- Snow and rain precipitation (+)
- Melt line evolution through the year (-)
- Surface temperature and melting (-)

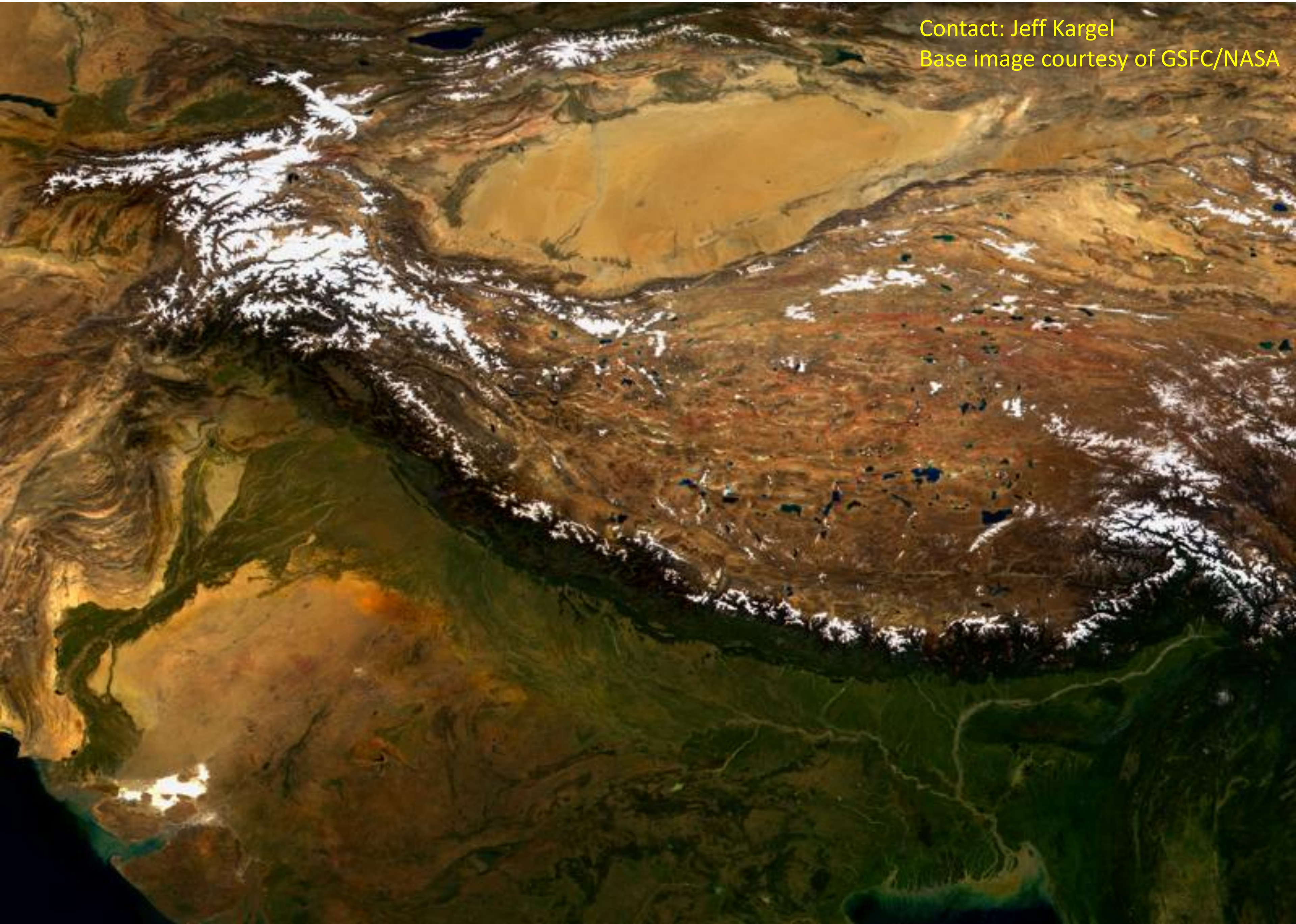
Deposited black carbon and dust:

- Albedo, melting above dry snow zone (0)
- Albedo, melting in snowmelt zones (-)
- Albedo, seasonal melt line evolution (-)
- Albedo, melting in exposed ice areas (-)
- Albedo, melting in debris covered zones (0)

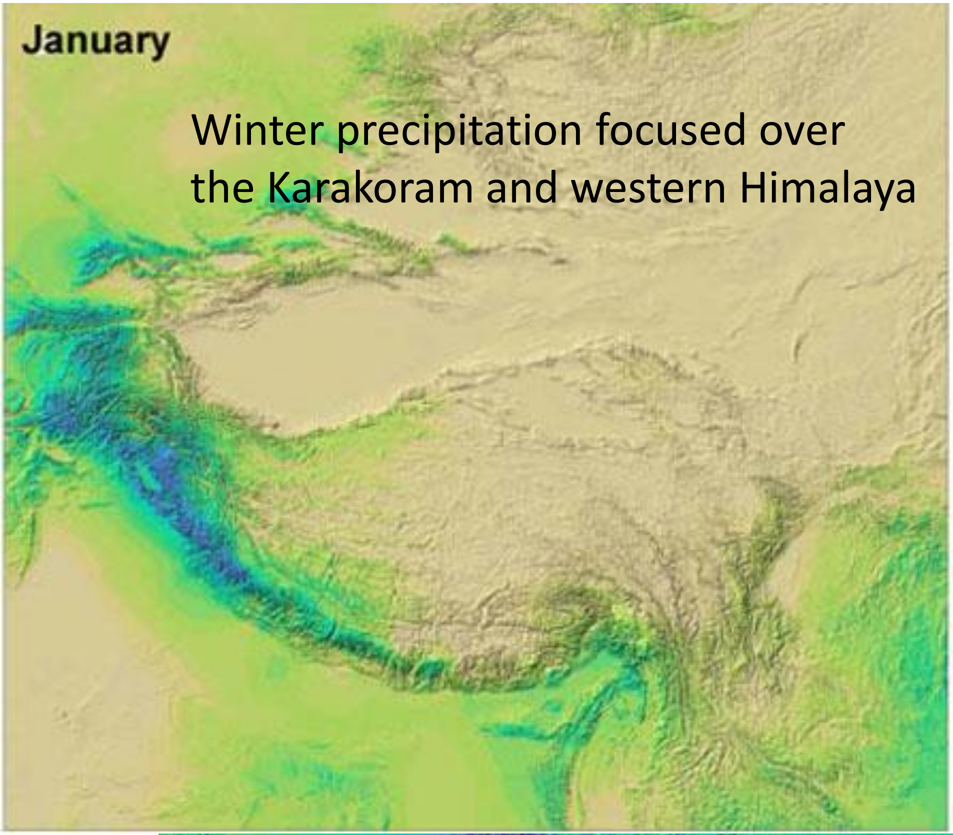
0 no significant influence
\+ influence tending toward positive balance
\- influence tending toward negative balance

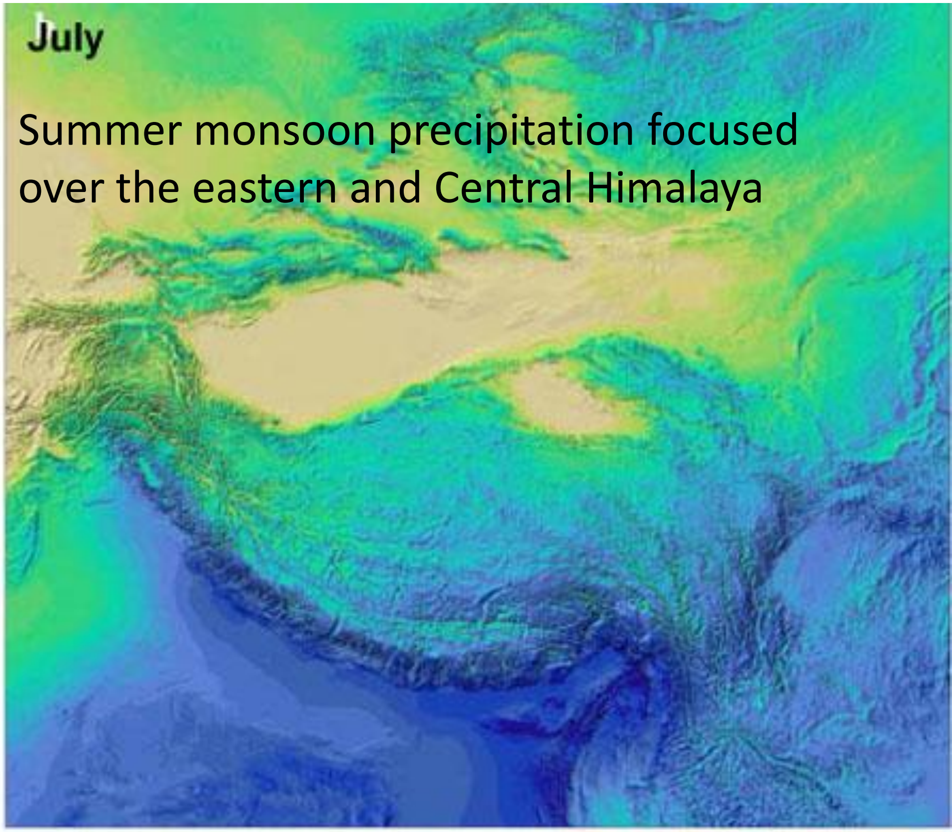
CONTACT: Yves Arnaud and Jeff Kargel

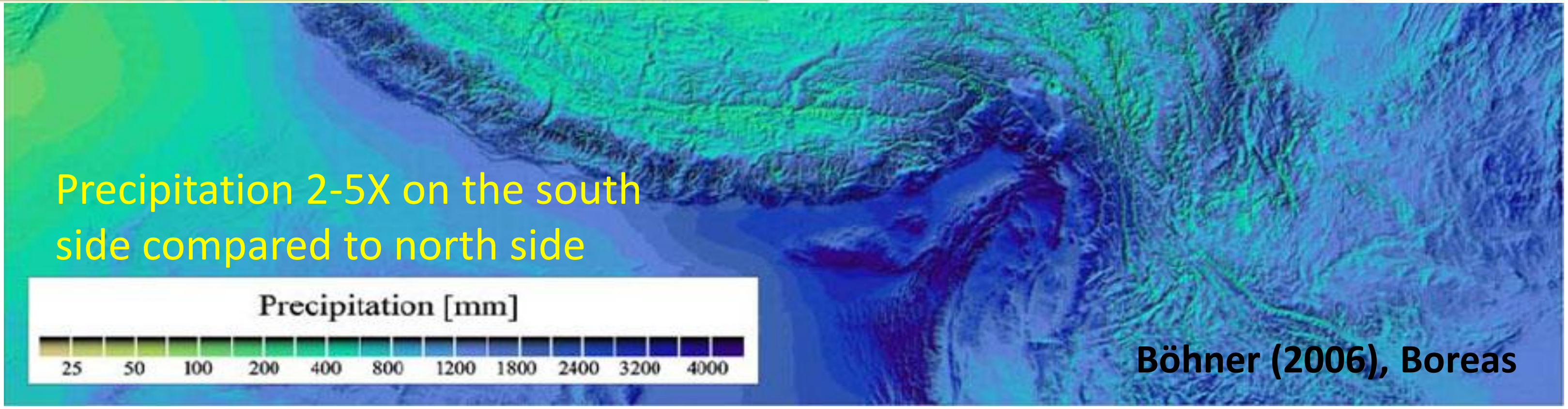
MODIS summer and autumn composite base image.



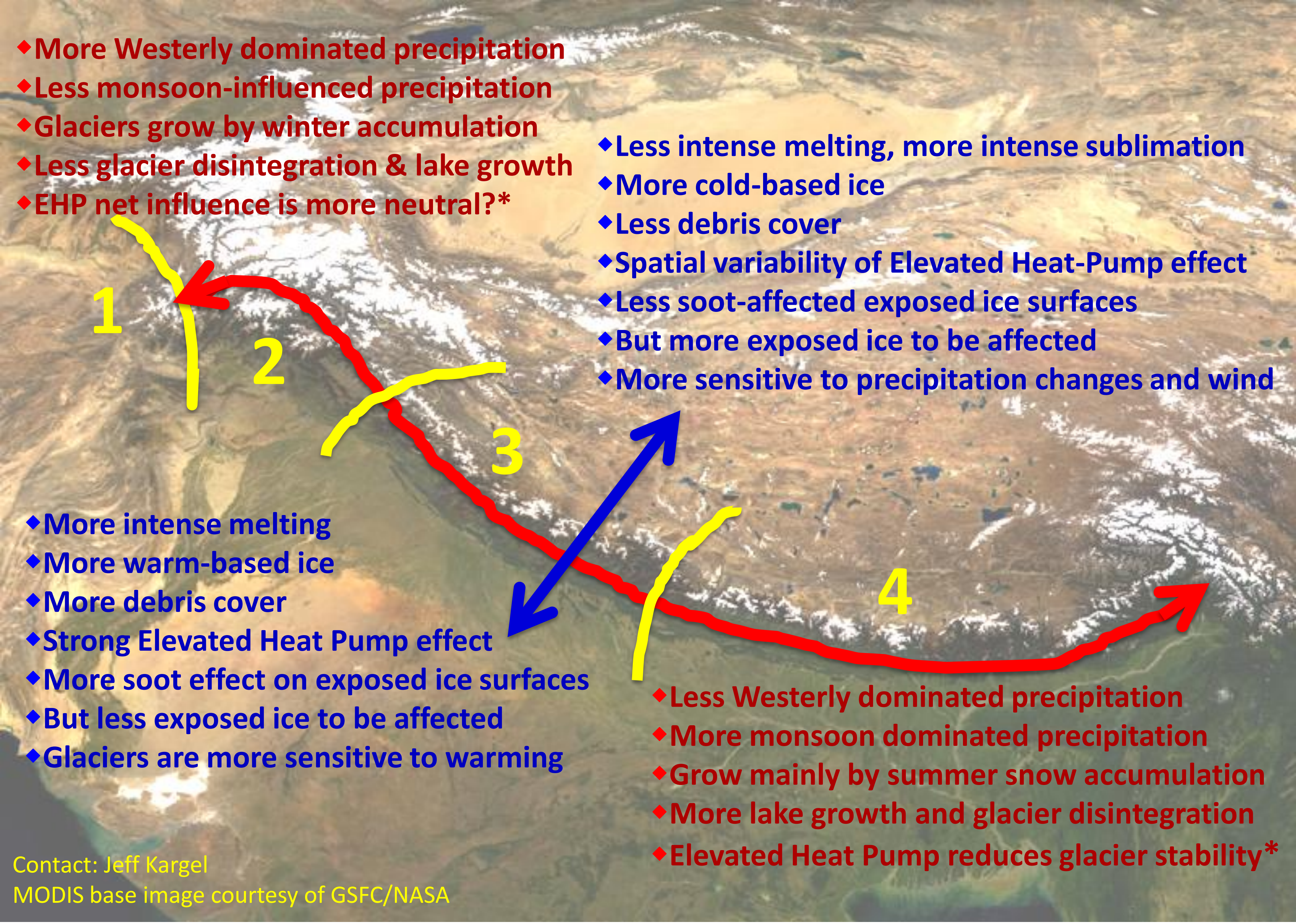
Precipitation seasonality and E-W/N-S gradients over the mountains of Central Asia







ADDITIONAL CONTACT: Tobias Bolch

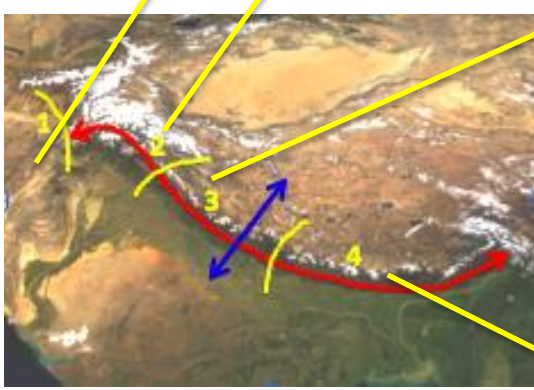


•Glacier behavior varies across the region, with faster retreat in the east. Possibly glaciers in northwest pick up more snow precipitation due to Elevated Heat Pump (EHP) and other climate mechanisms thus partly offsetting heating/melting. Glaciers in the eastern Himalaya may be more sensitive to EHP heating and are melting more quickly.

Brief summaries of gradational "zones" in previous slide

Zoned responses have happened before.

Zonation of Himalayan glacier responses to Holocene climate changes were crudely similar to zones 1-2 and 3-4 outlined in the previous slides, and key drivers and direction of the responses are similar. Of course, that is without the aerosols and soot. (Rupper et al. 2009)



CONTACT: Jeff Kargel

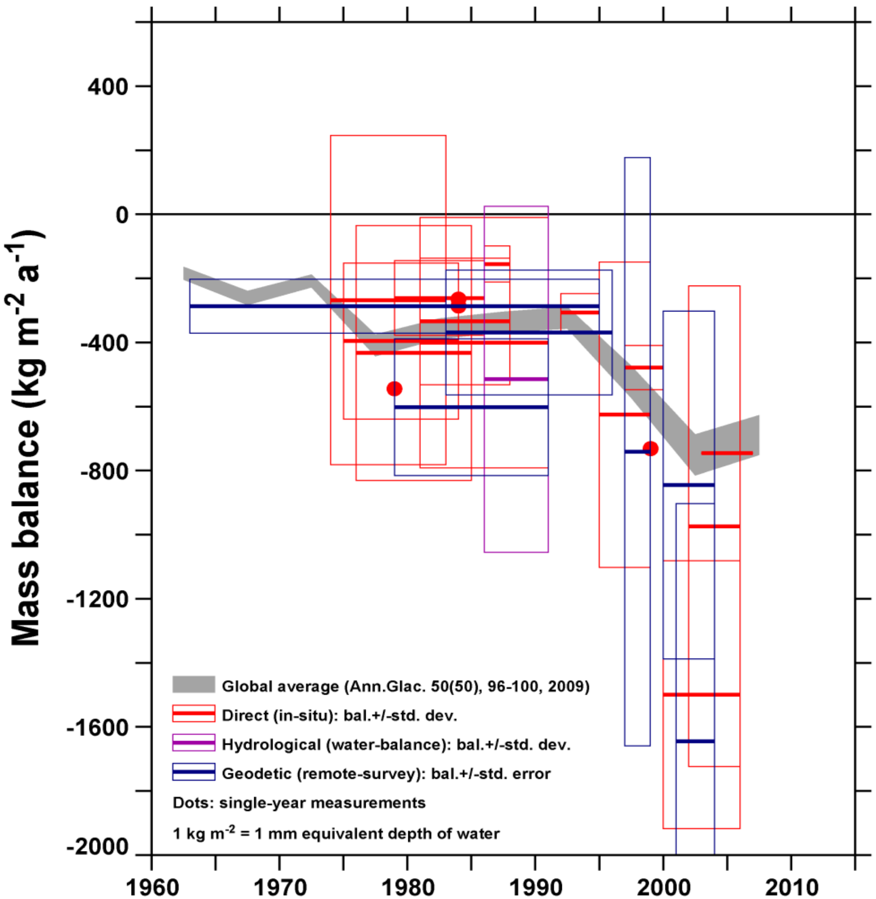
- **Zone 1: Mainly Afghanistan. Relatively stable or very slowly retreating; mostly cirque glaciers.**
- **Zone 2: Mainly Northwestern Himalaya and Karakoram. Rapidly changing dynamics and heterogeneity of response. Many surge glaciers, many advancing, stable, and retreating snouts; comparatively few large lakes. Retreat dominating in Pamir, complexity in Karakoram, but lacking wholesale, rapid disintegration of glacier tongues and rampant lake growth.**
- **Zone 3: Mainly India, southwestern Tibet, western Nepal: Mainly stagnating, retreating snouts (e.g., Bhambri and Bolch 2009), but time variable, with periods of slower retreat of some glaciers during some decades of 20th-21st Centuries. Fewer lakes than in eastern Himalaya.**
- **Zone 4: Mainly Nepal, Bhutan, Sikkim, SE Tibet. Many large glacier lakes especially since 1960's, rapid disintegration of many glaciers, stagnation (stable snouts but thinning) of others. More debris cover on south side than north side.**

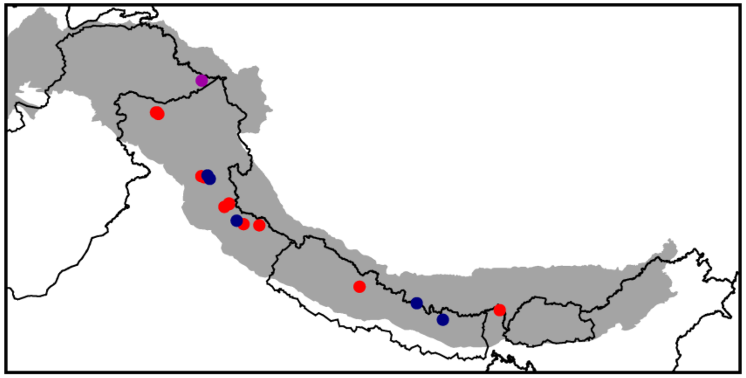
Glacier Measurements

- **Determination of rate of change in glacier mass (mass balance) is one of the cornerstones of glaciology, and aids in projections of future state.**
- **Changes in glacier length can be either related to or unrelated to changes in glacier volume or mass.**
  - **-- Some glaciers change length in a mathematical relationship to area and thickness/mass.**
  - **-- Some glaciers change length with little or no change in mass.**
  - **-- Some glaciers change thickness and mass, but not length.**
- **Four parameters are measured to indicate changes of glacier size: length, area, volume, and mass. Length variations alone do not signify mass balance sign or change of balance.**
- **Length and area discernible by satellite, thickness with more difficulty, reported commonly, as some of these examples show.**

Mass balance of Himalayan glaciers

CONTACT: Graham Cogley
Additional expert reference: Koji Fujita





The graph shows all published Himalaya-Karakoram (HK) measurements; they are more negative after 1995 than before. The map shows where the measurement sites are.

Mass balance varies greatly year to year; these are series averages. Boxes suggest estimated uncertainty. The apparent trend is less uncertain than any one measurement. The data indicate either accelerating loss or stepwise increase in mass loss rate. This need not be true of every part of the region. For example there are suggestions of recent mass gain in the Karakoram.

Mass loss rate here is consistent with the global average.

The mass-balance rate required to remove all H-K ice during 2000-2035 would be about -11,000 kg m^{-2} a^{-1}. The oft-quoted 2035 disappearance date of Himalayan glaciers is not accurate (see slides 39-41).

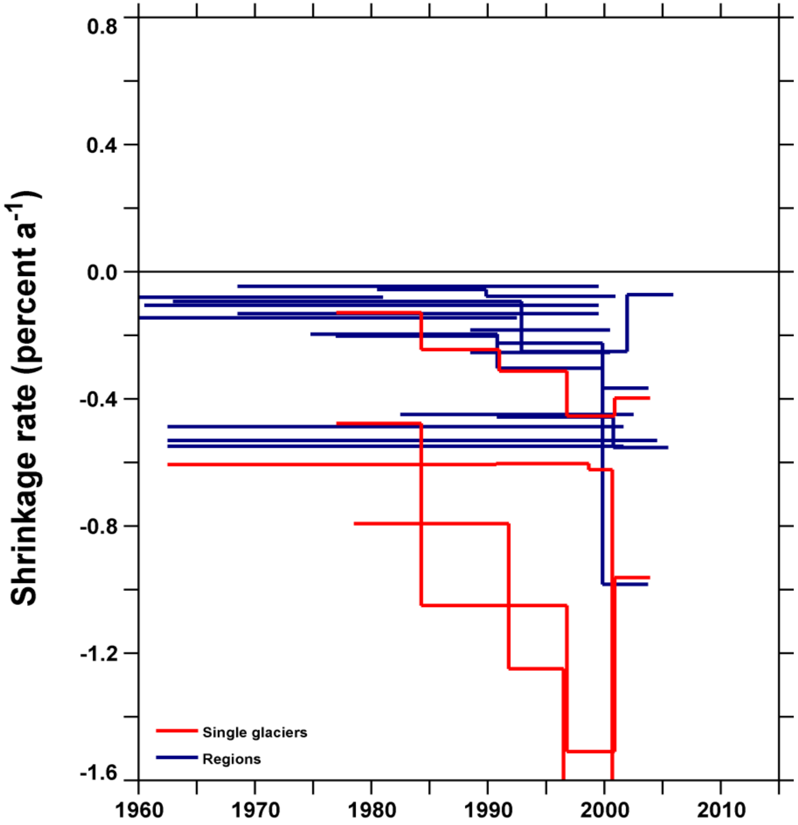
Negative mass balance is loss of a non-renewable water resource. We can only get it back from the ocean by desalination. In the meantime, it will raise the level of the sea, and the glaciers themselves (and thawed mountain slopes) in some cases become more hazardous as they shed mass.

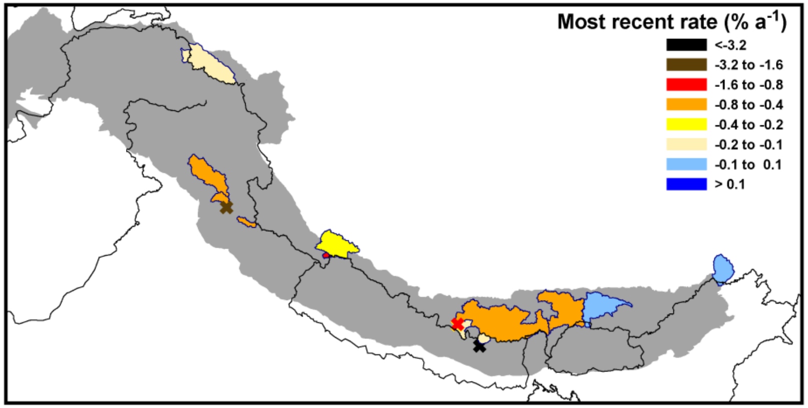
The data are insufficient to make strong intraregional comparisons, and so inferences about regional transitions of behavior are drawn from other types of information, such as the pattern of glacier breakup into lakes and other morphological indicators of behavior.

More benchmark glacier data and satellite observations are needed.

CONTACT: Graham Cogley.
Additional expert reference:
Koji Fujita

Area shrinkage rates of Himalayan glaciers





Graph shows all(?) published rates of glacier shrinkage (area reduction) in the Himalaya and Karakoram; there are no measurements from the Hindu Kush.

Uncertainties are substantial, but hard to display.

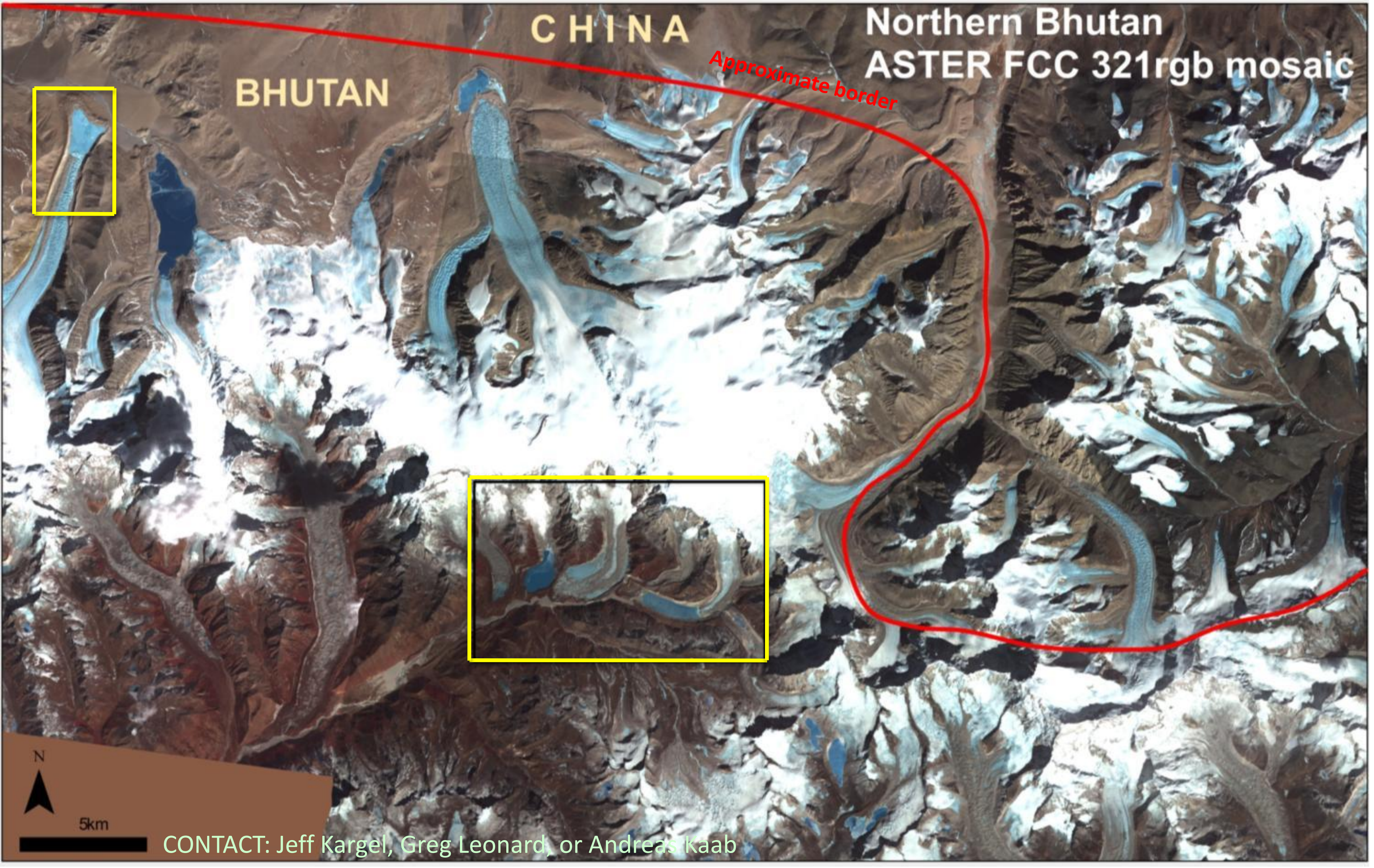
Map shows spatial distribution; most regions are drainage basins, with variable, usually small, coverage by glaciers; there is some spatial overlap between measured regions.

It is not obvious how to proceed with analysis of the data. Comparisons are impossible without conversion to rates of fractional change (as here), and also interpolation to common start and end dates (a step not taken here).

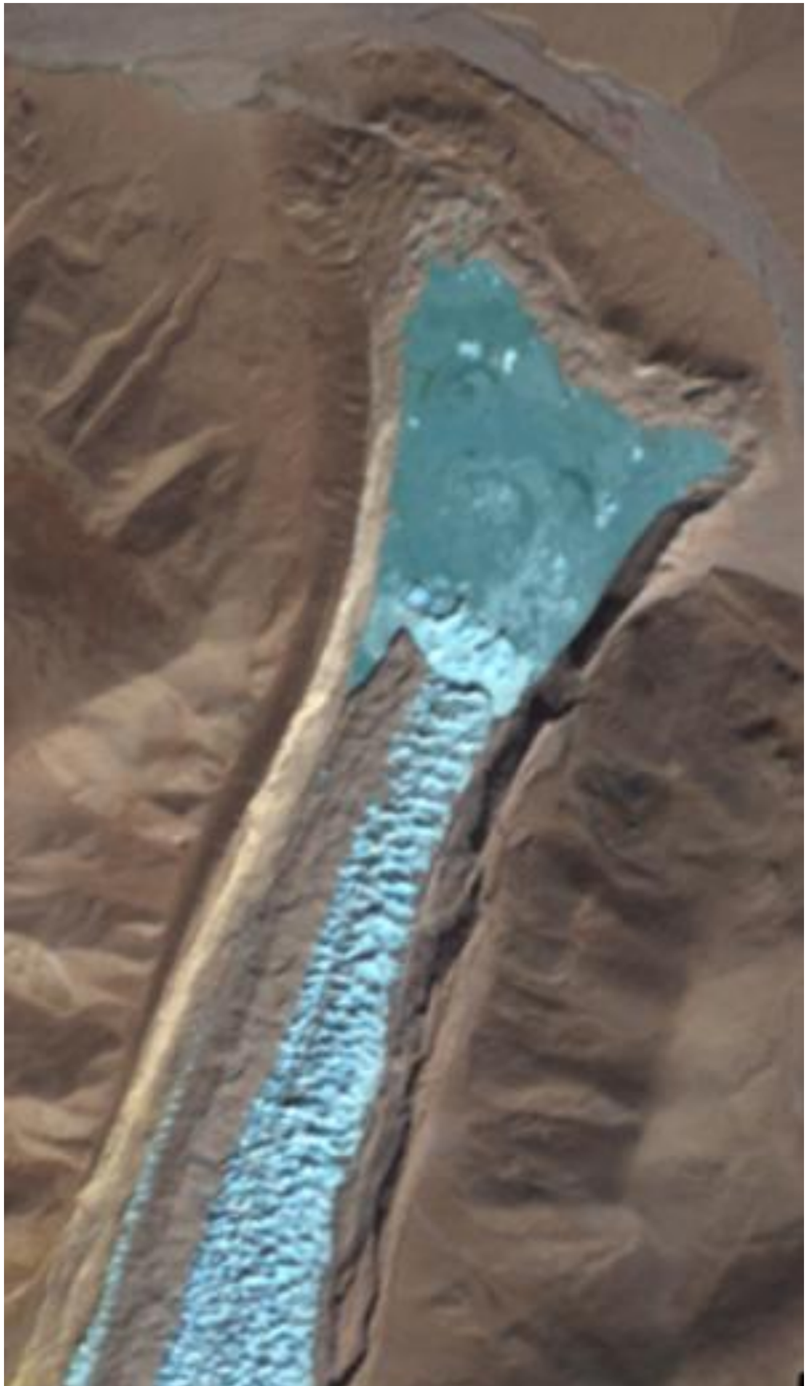
Excluded from our analysis here, the influences of initial glacier size (smaller glaciers usually shrink faster) and elevation range (the highest elevations are probably less vulnerable to warming) should be assessed.

The region-wide average is probably bracketed somewhere between –0.50% a^{-1} (-20%/40 years, often quoted), and –0.10% a^{-1}, as some measurements suggest.

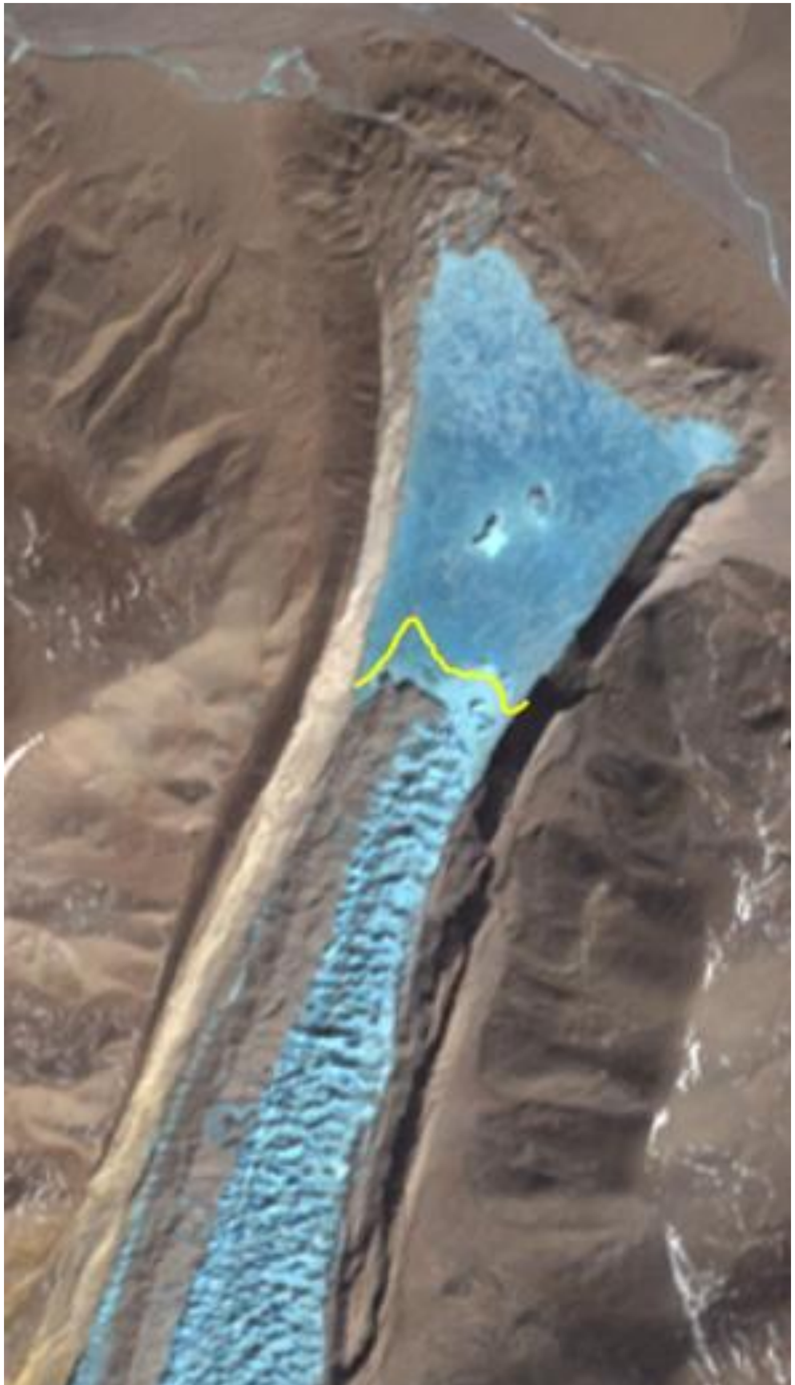
"Zone 4" Eastern Himalaya, dominated by disintegration of debris-covered glacier tongues



Northern Bhutan, glacier lake growth and retreating north-flowing glacier

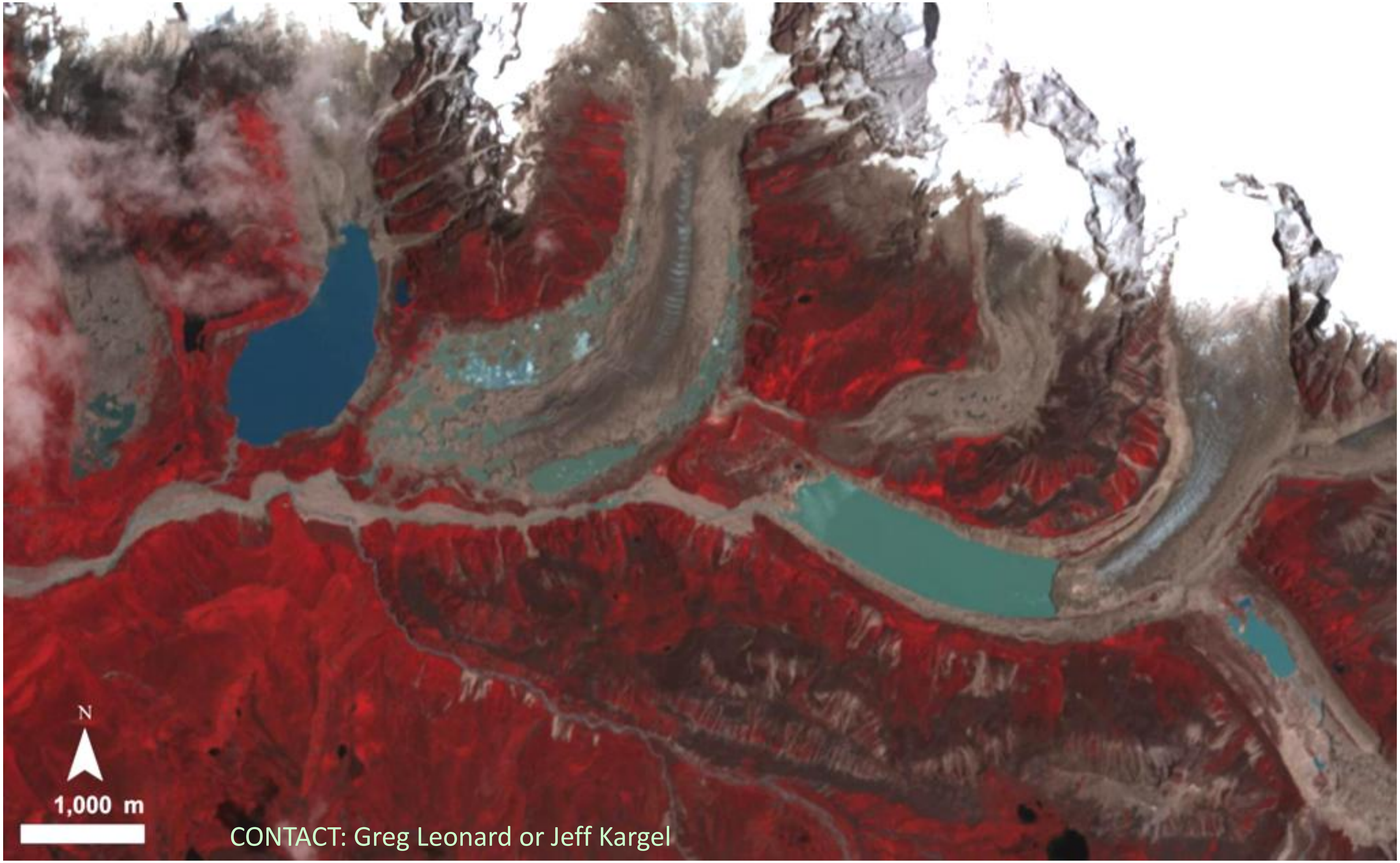


Northern Bhutan, glacier lake growth and retreating north-flowing glacier



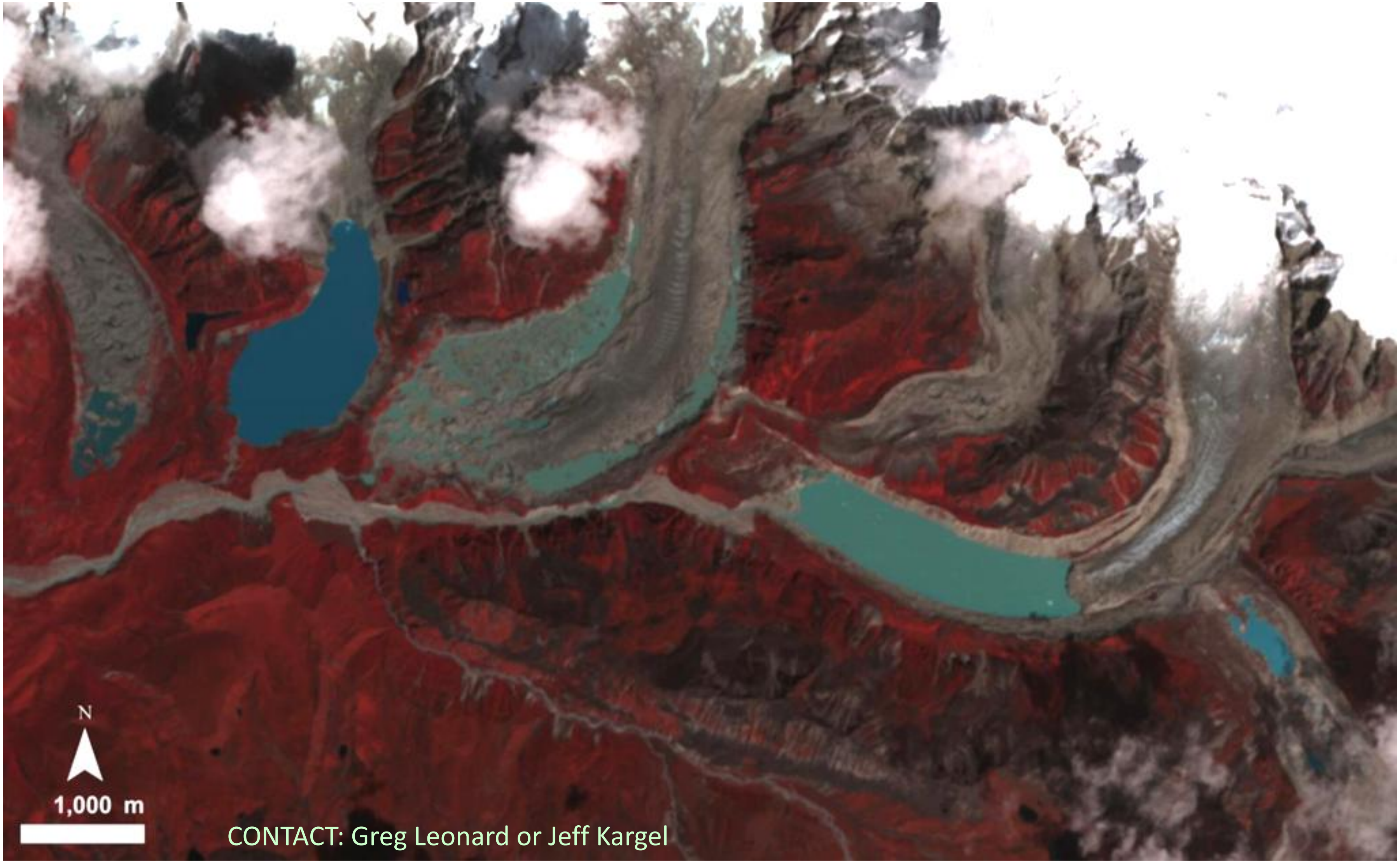
This 4-slide sequence shows a continuation during the 2000's of lake initiation, growth, and coalescence, and rapid glacier disintegration, that began here in the early 1950's and 1960's.

North Bhutan – ASTER Imagery (321rgb) **21 July 2003**

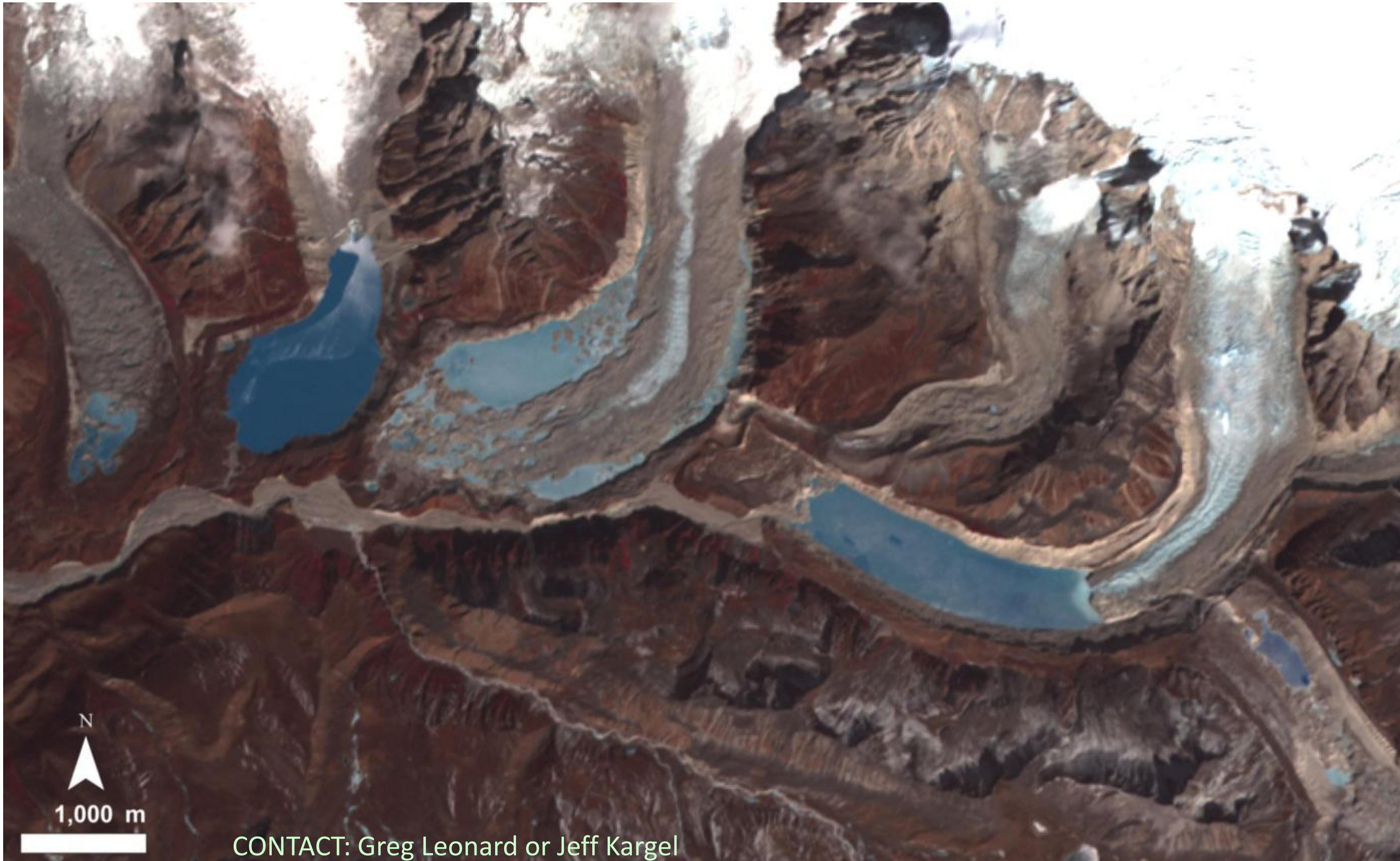


North Bhutan – ASTER Imagery (321rgb)

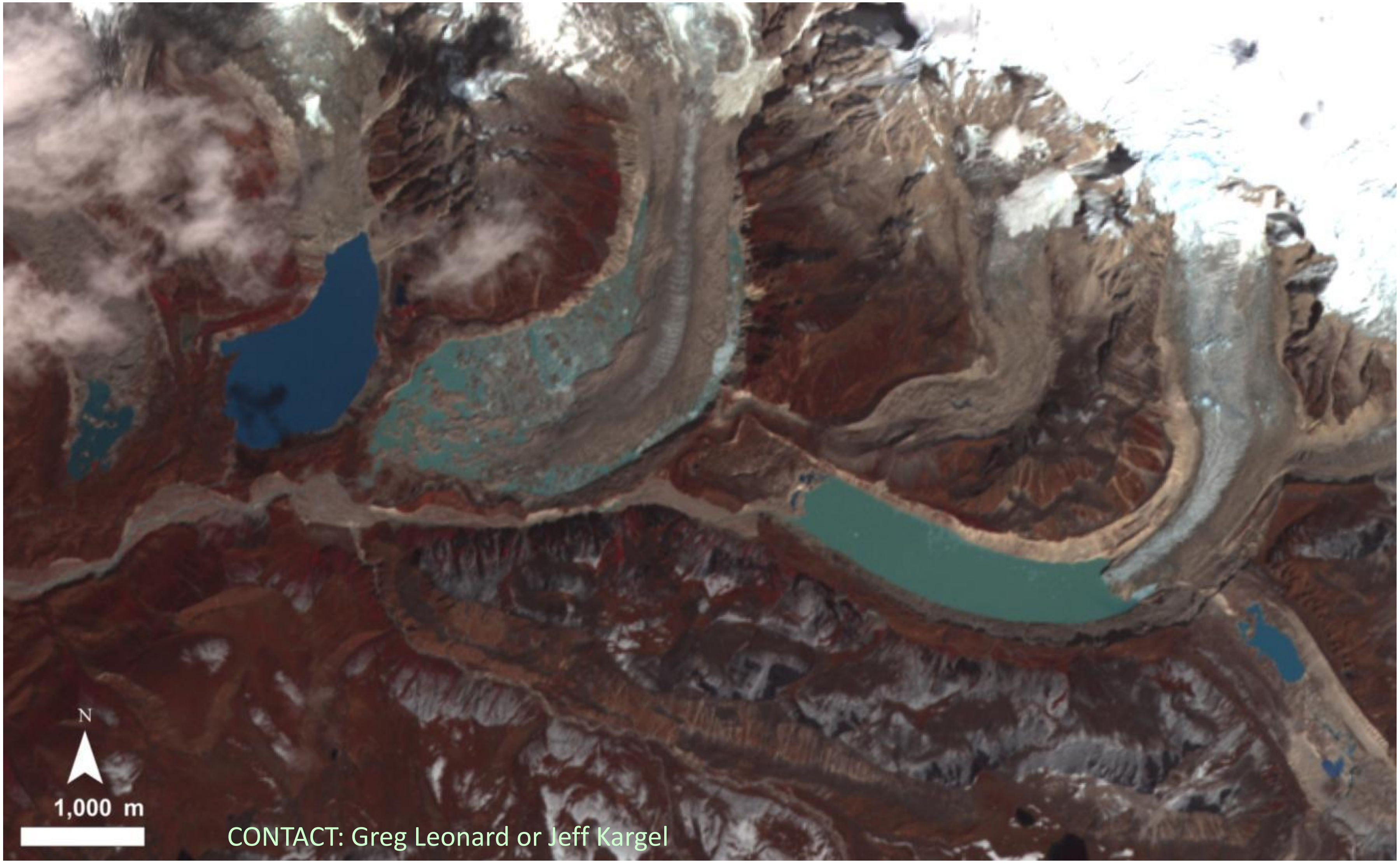
28 Sept 2005

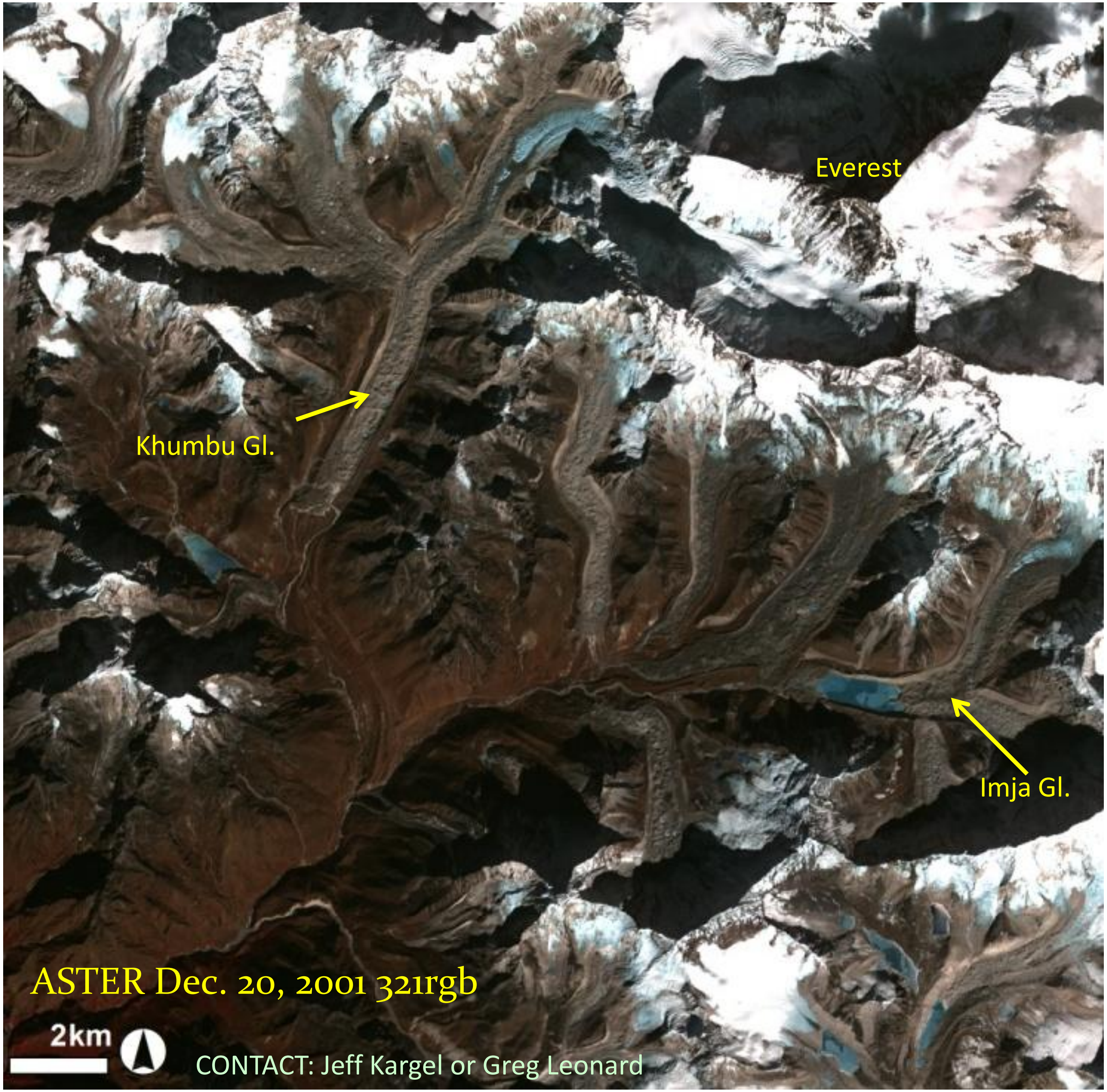


North Bhutan – ASTER Imagery (321rgb) **30 Jan 2007**



North Bhutan – ASTER Imagery (321rgb) 03 Nov 2009

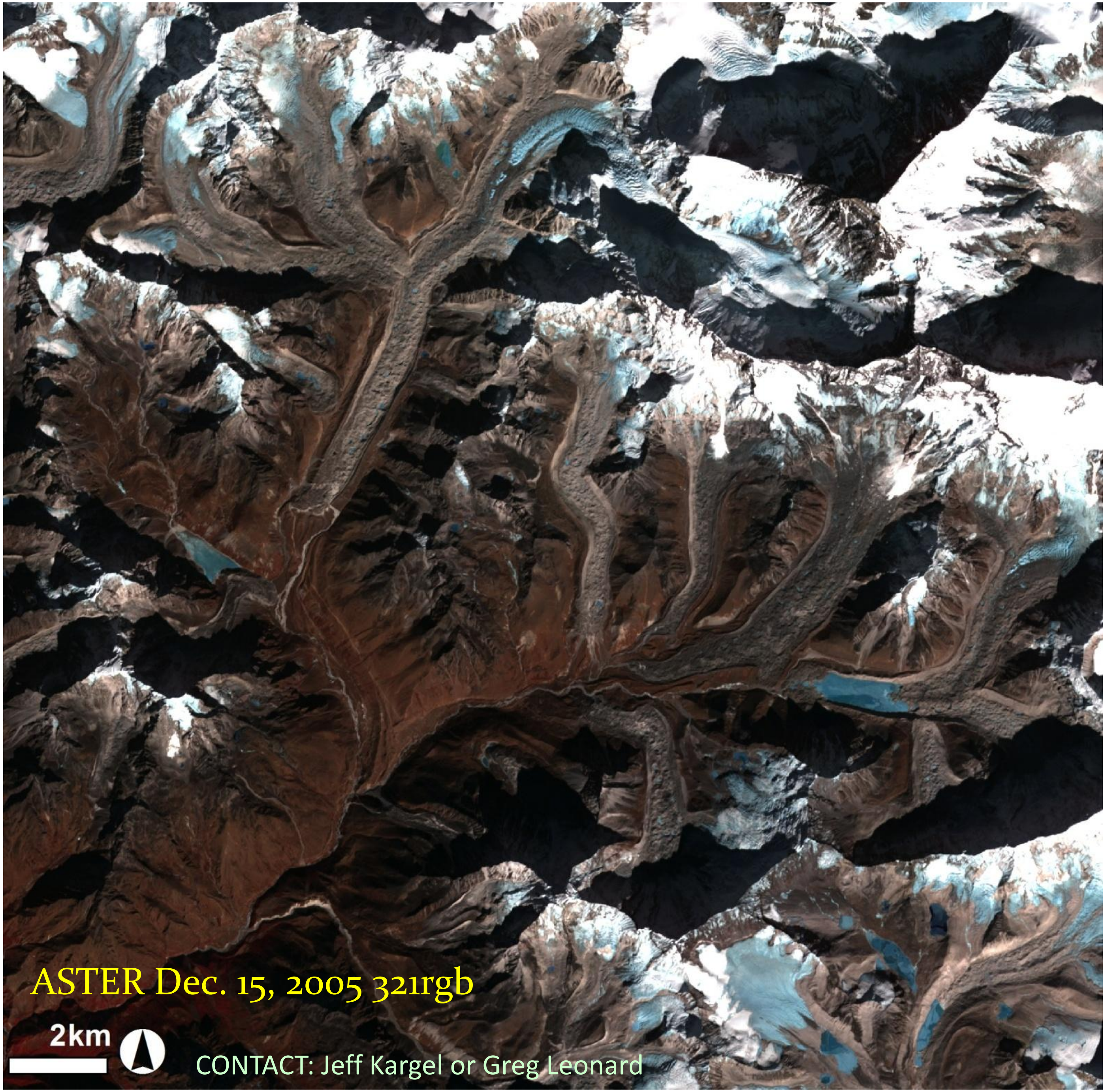




Typical in-place wasting (thinning) of glaciers in "Zone 4" as it grades toward Zone 3.

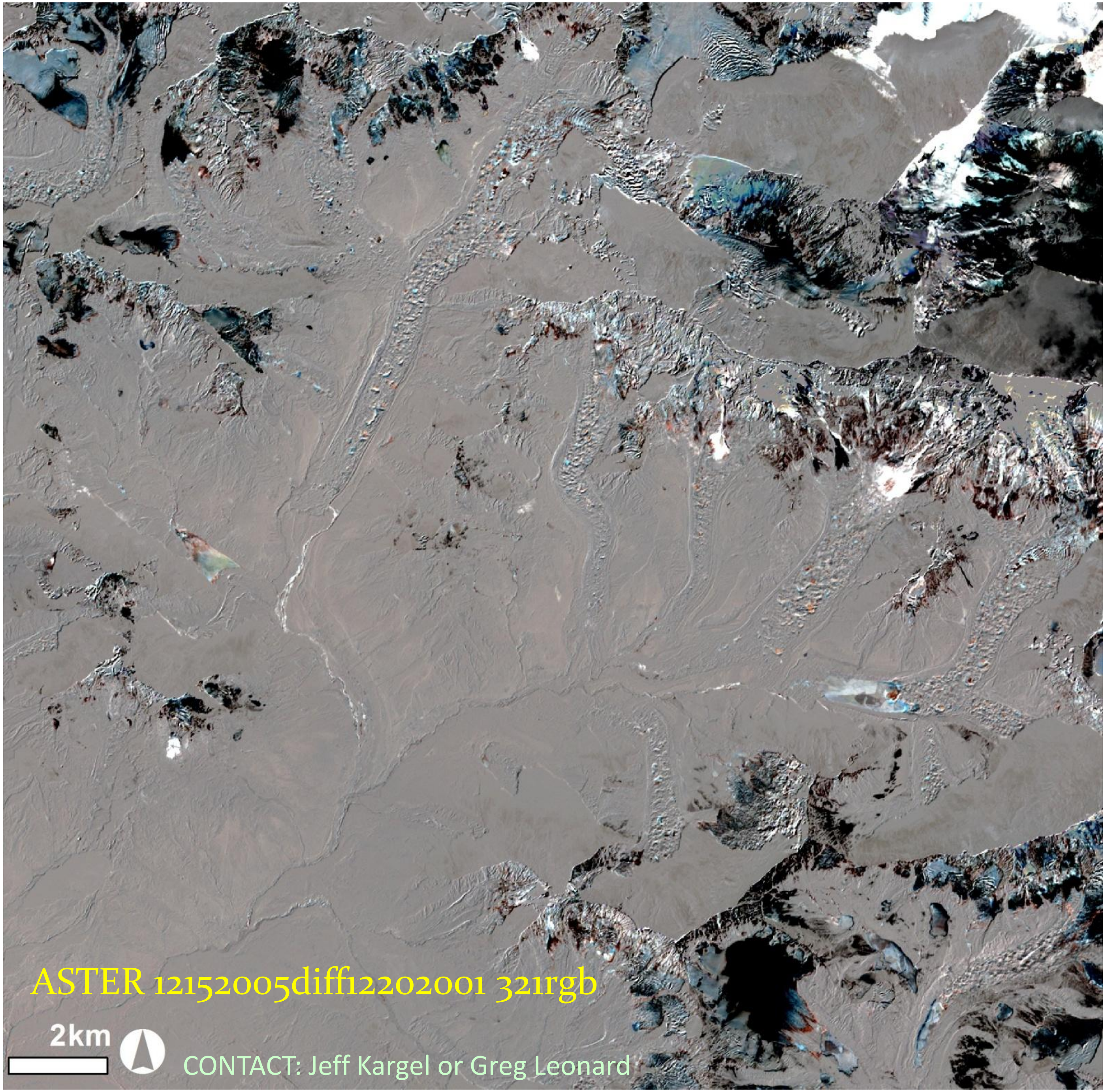
2-slide sequence shows 4 years of change in the Mt. Everest area: Khumbu Glacier, Imja Glacier and others.

These are examples of stable glacier termini with stagnating debris-covered toes. In some cases glaciers are known to be thinning and slowly losing mass along their debris-covered-tongues, e.g., Khumbu Glacier (stagnant terminus). Imja Glacier is in rapid retreat due to lake thermal influences.



2-slide sequence showing 4 years of change in the Mt. Everest area: Khumbu Glacier, Imja Glacier and others

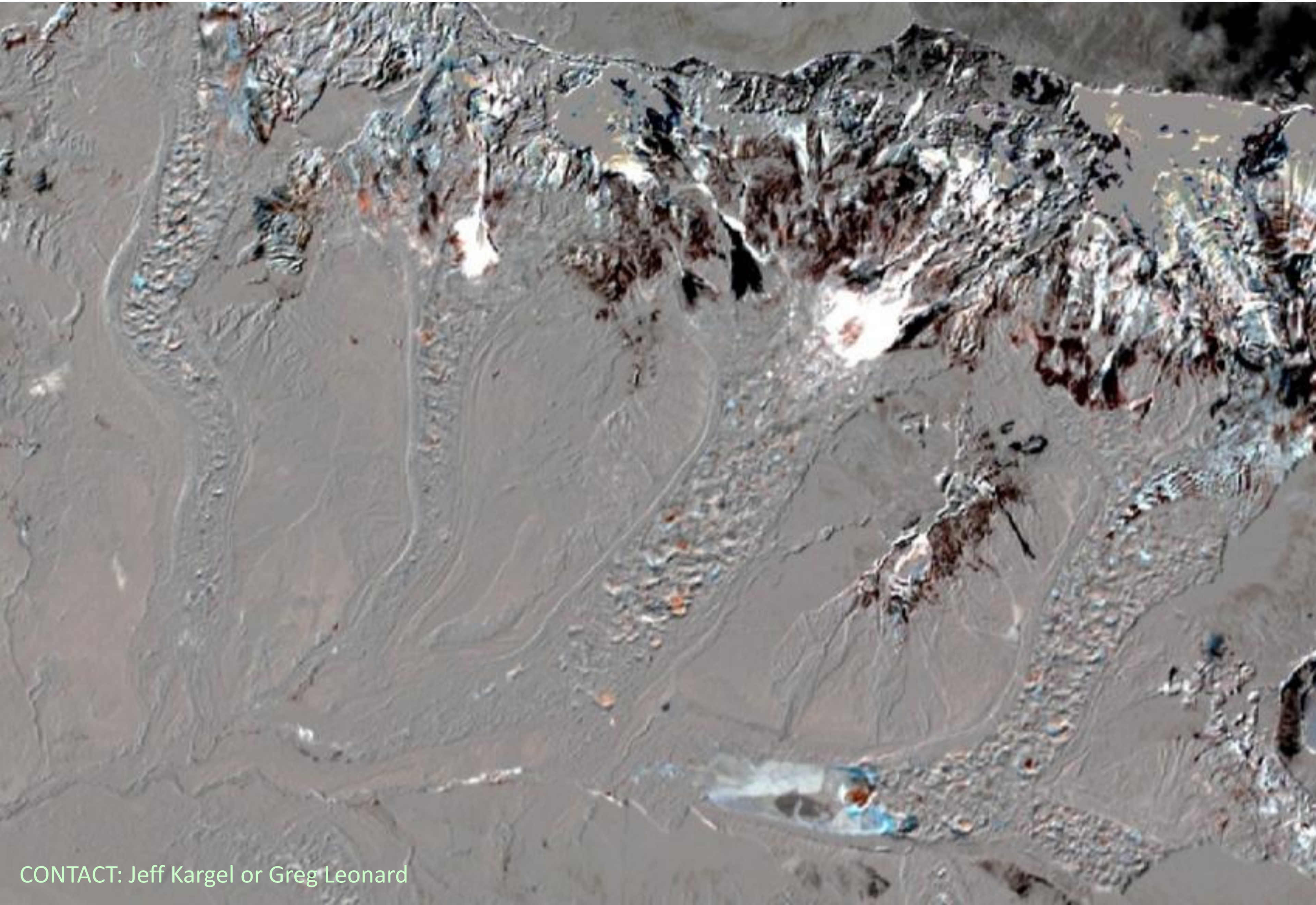
See also Tartari et al. 2008, Fujita et al. 2009.



Differencing image, Dec 15, 2001 to Dec 20, 2005. (ASTER)

(Some details are shown in the next slides; then the color scheme is explained following that.)

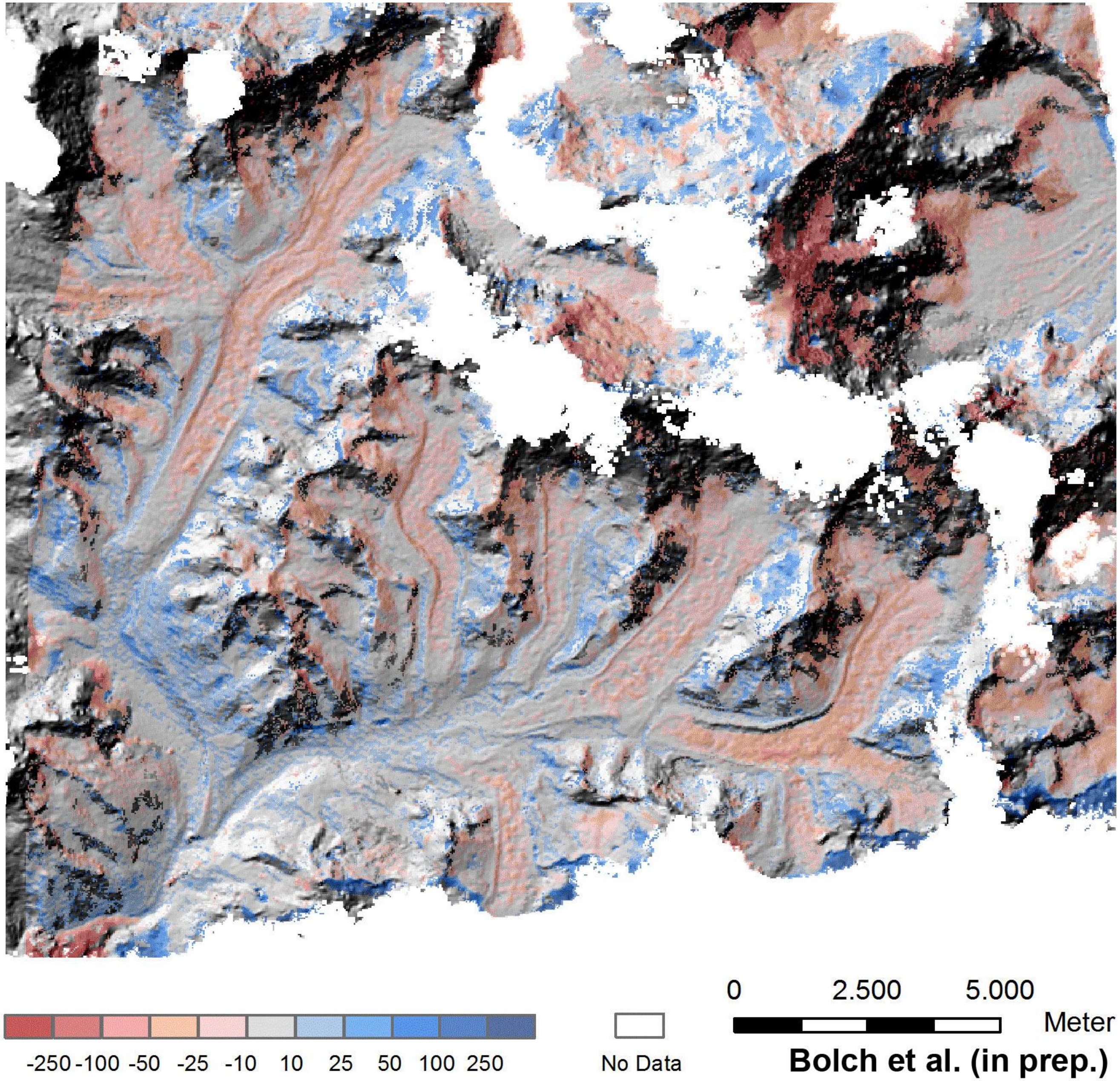
ASTER multispectral differencing image of the Imja Lake region south of Mt. Everest.



CONTACT: Jeff Kargel or Greg Leonard

Color scheme (interpretation) for Himalaya multispectral differencing image (previous two slides)

- Red = water in 2001 that disappeared or moved elsewhere by 2005.
- Blue = new water, or water appearing downglacier in 2005 from where it was in 2001 due to flow, or freshly exposed blue glacier ice.
- White = new snow or ice (including avalanches).
- Black = snow that has disappeared or has been darkened by soot or dust.
- Textured pattern of shades of gray: uniformly debris-covered hummocky areas of glacier that have been displaced by flow, uniform hummocky or crevassed exposed ice displaced by flow, or slumped stagnant glacier masses.
- Neutral untextured gray: Areas that have undergone little or no change from 2001 to 2005.

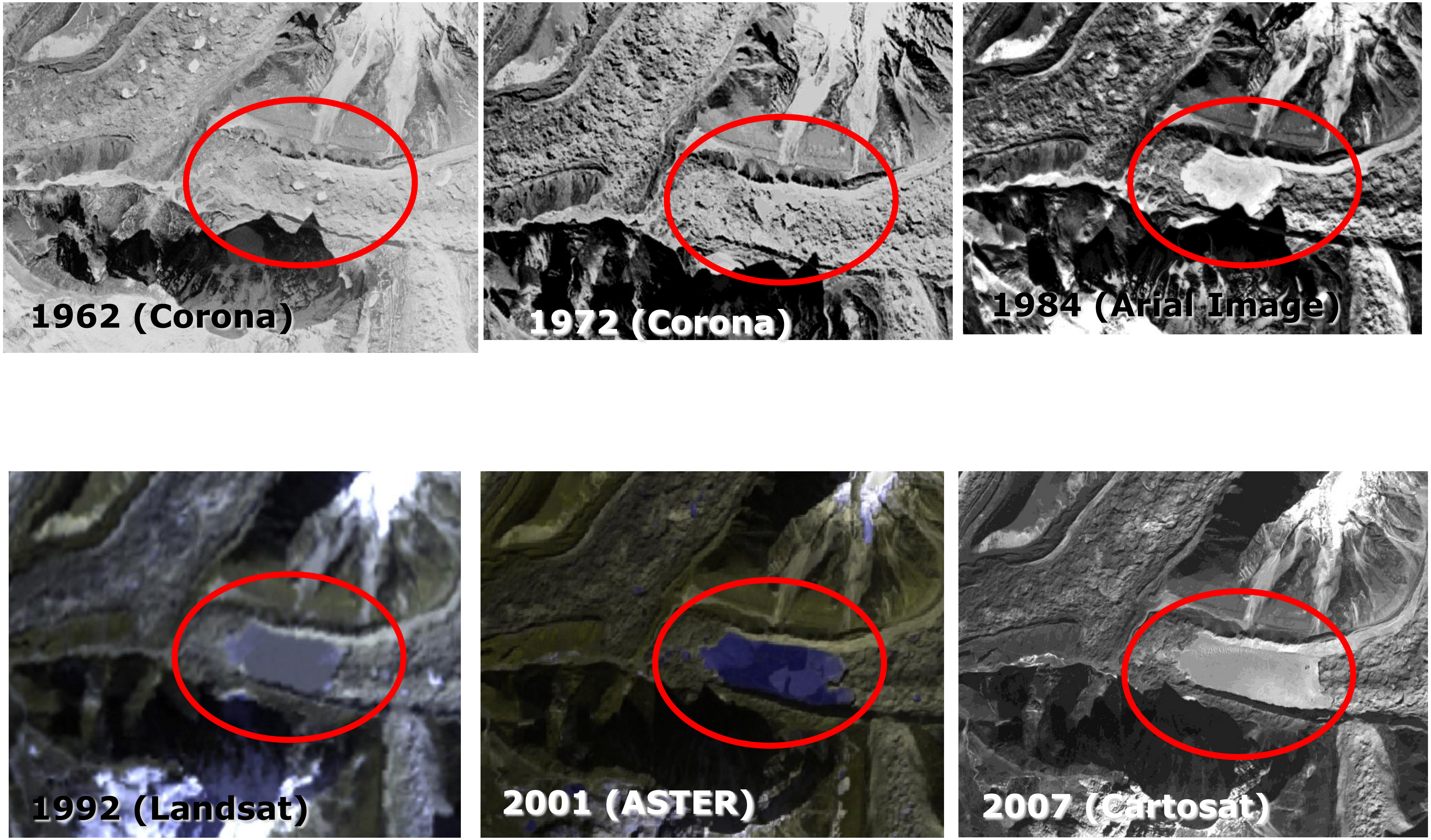


Mount Everest/Khumbu /Imja DEM differencing.

Red means that the terrain surface has lost elevation between the 1972 Corona image and 2007 Cartosat data. Blue means the terrain has gained elevation according to the analysis. Glaciers have lost an average ~40 cm/year.

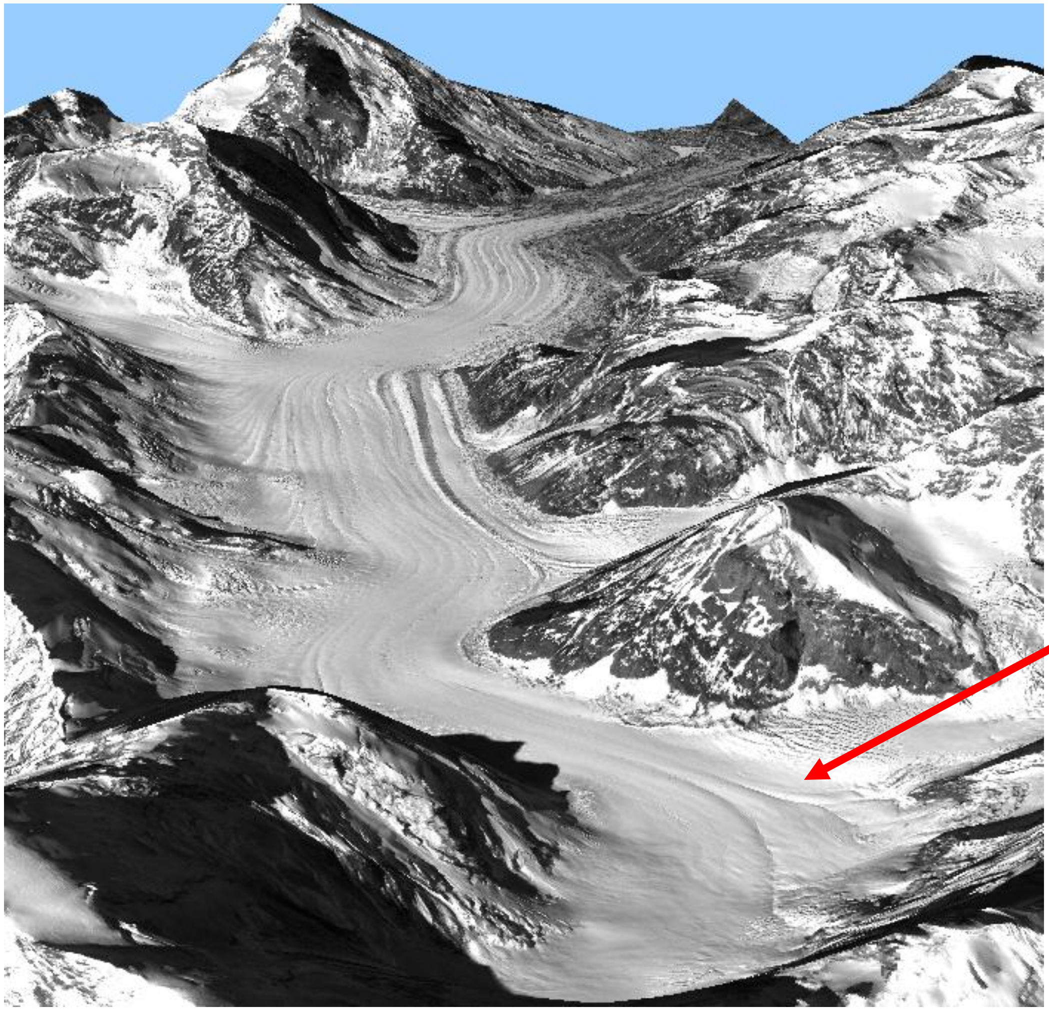
Contact: Tobias Bolch
See also Bolch et al. 2008

Formation and growth of Imja Lake (south of Mt. Everest), 1962-2007

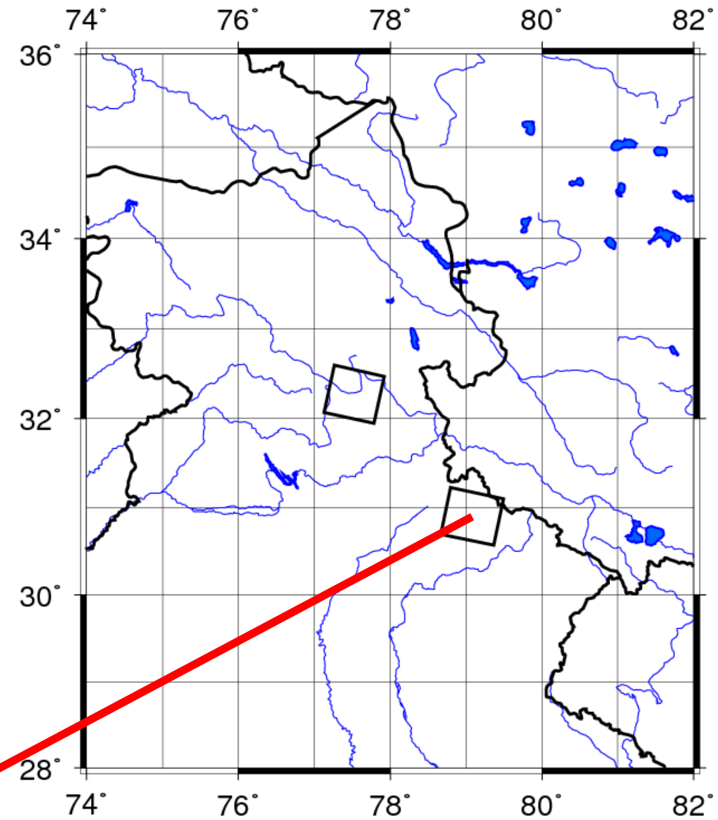


Realized by Tobias Bolch **(1984-image courtesy of D. Benn)**
Bolch et al. 2008, NHESS

Gangotri Glacier, "Zone 3"



3D perspective view of Gangotri glacier SPOT5 image November 2004 *(copyright CNES 2004, Distribution Spot Image)*



Location map

- **Area average mass balance 1999-2004: -1.05 m/yr w.e.**
- **2001-2009 time series shows an indistinct terminus, little clearly evident retreat.**
- **Mass loss up through 2004 indicates recent slowing of terminus retreat (Raina 2009, and next 3 slides). The longer record suggests that retreat likely will resume.**

Gangotri Glacier, India (ASTER 321rgb)

ASTER 09 Sept 2001

CONTACT: Greg Leonard

Gangotri Glacier, India (ASTER 321rgb)

ASTER 23 Sept 2006

CONTACT: Greg Leonard

Gangotri Glacier, India (ASTER 321rgb)

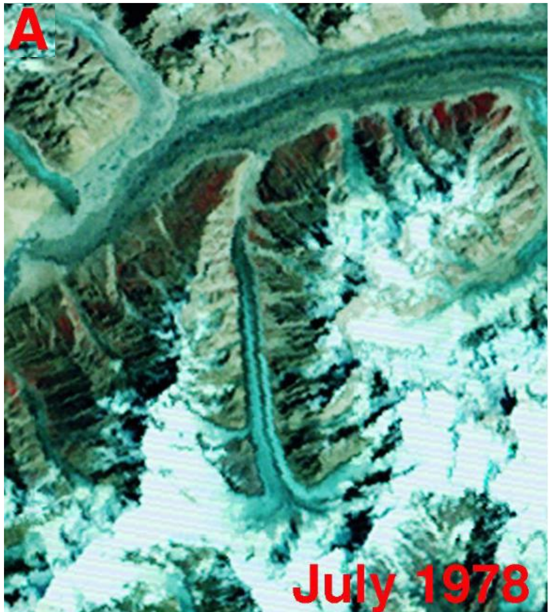
ASTER 20 June 2009

CONTACT: Greg Leonard

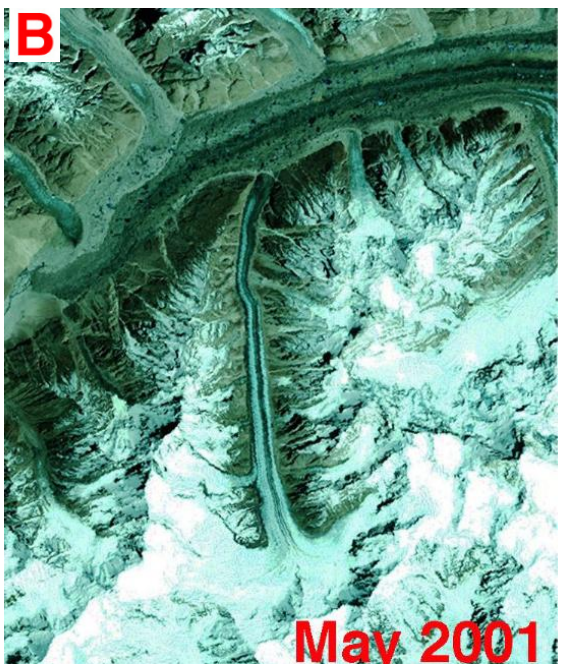
Example of an advancing glacier, “Zone 2”

Liligo Glacier advance into Baltoro Glacier, 1978-2001 (Karakoram, Pakistan)

Surge-type behavior well documented in this region (K. Hewitt 1969, Canadian Jour. Earth Sci.; and Bishop).
This 2-km advance is a surge.
Surge/waste cycle is important in the Karakoram.
Surges generally do not signify positive balance.
Some other non-surge glaciers are also advancing near here.

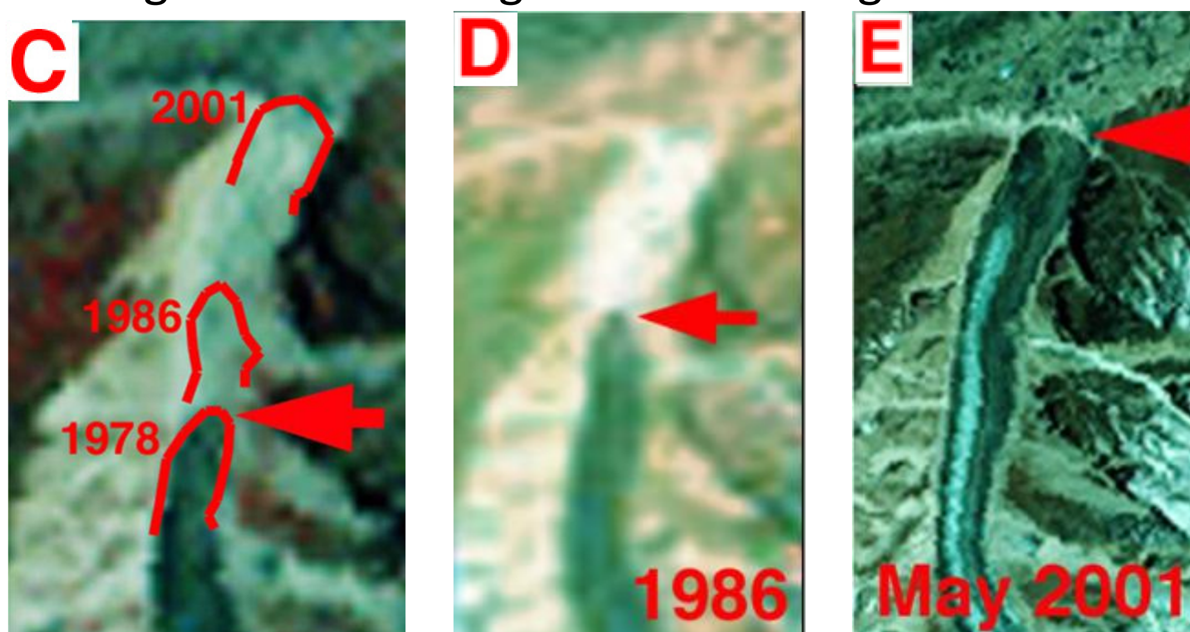


Landsat MSS false-color composite



ASTER 321 RGB

Region of advancing terminus of Liligo Glacier:

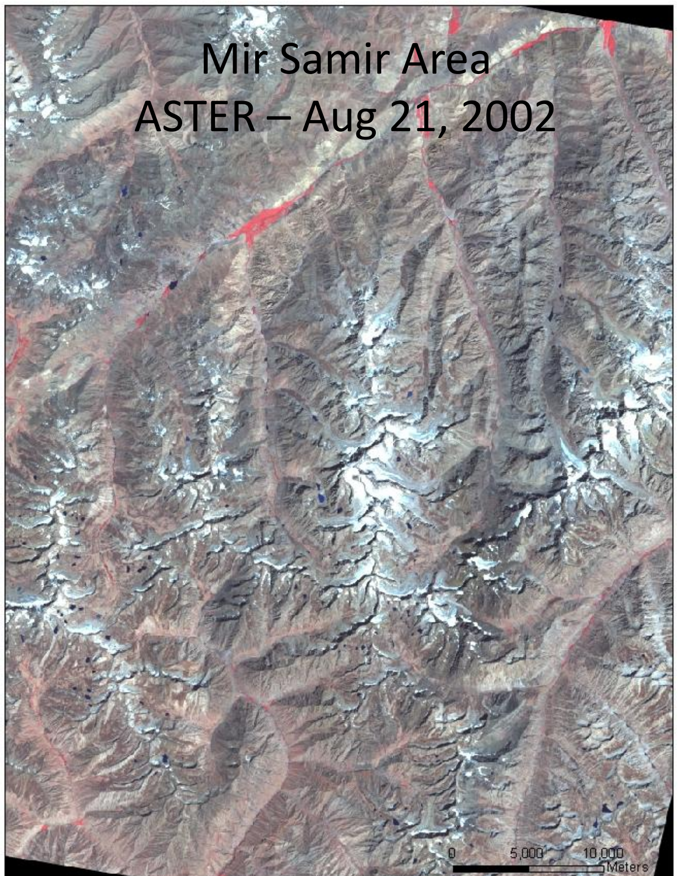


Contact: Michael Bishop. Contributed by M. Bishop to J.S. Kargel et al. 2005, Rem. Sens. Env.

Contact:
Umesh Haritashya.
Reference: 2009 Fall AGU

Afghanistan glaciers ("Zone 1"):

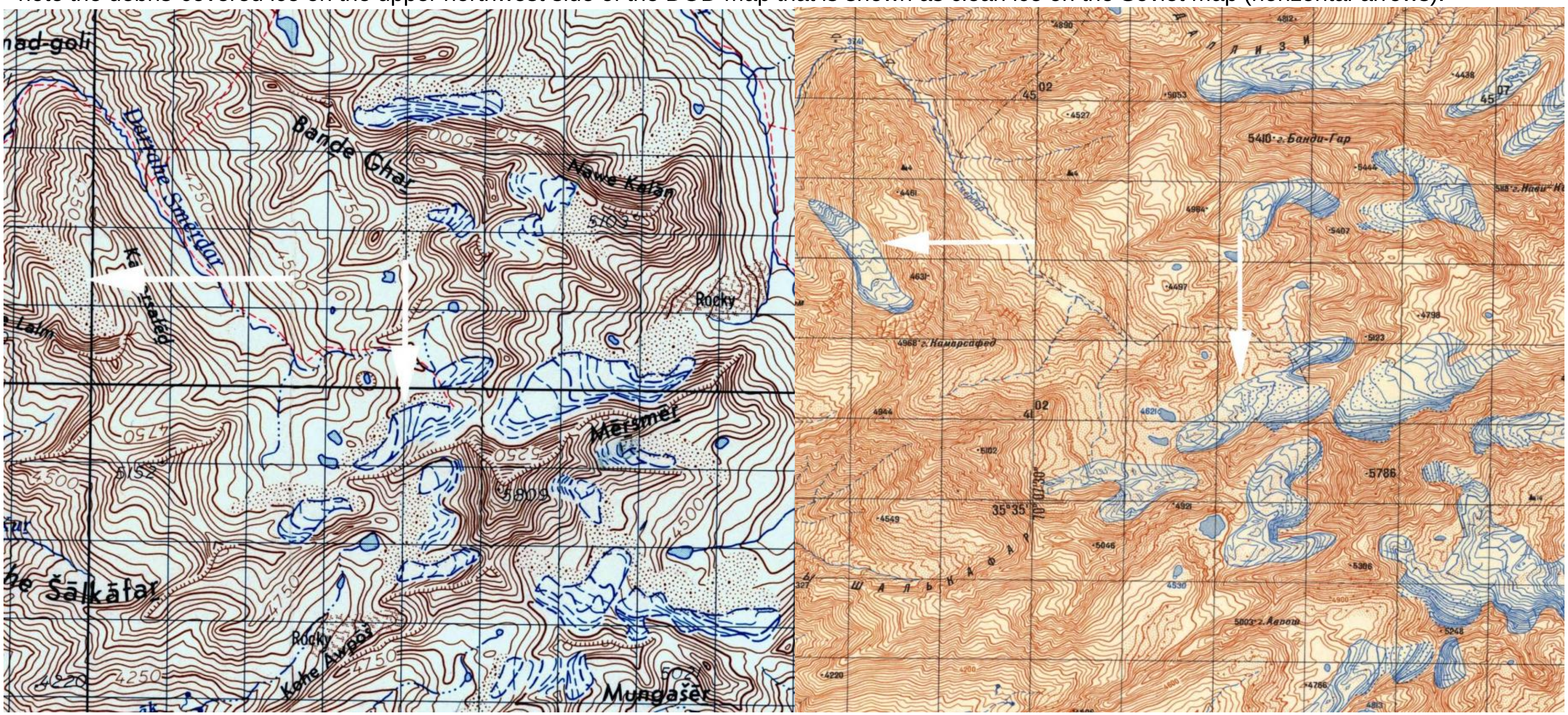
Most glaciers in the region are relatively small



Contact:
Umesh Haritashya

Afghanistan glaciers: Problem with old topo maps

Comparison of US DOD (left) and Soviet (right) topographic maps of Mir Samir glacierized area showing varying quality and quantity of mapping of glaciers. The DOD map shows glacier ice as white ground with dashed blue outline and contours, as well as debris- covered ice and moraine. The Soviet map has several areas that are treated as rock but that are actually ice, as well as areas of debris that are treated as clean ice. For example, note the debris-covered ice on the upper northwest side of the DOD map that is shown as clean ice on the Soviet map (horizontal arrows).



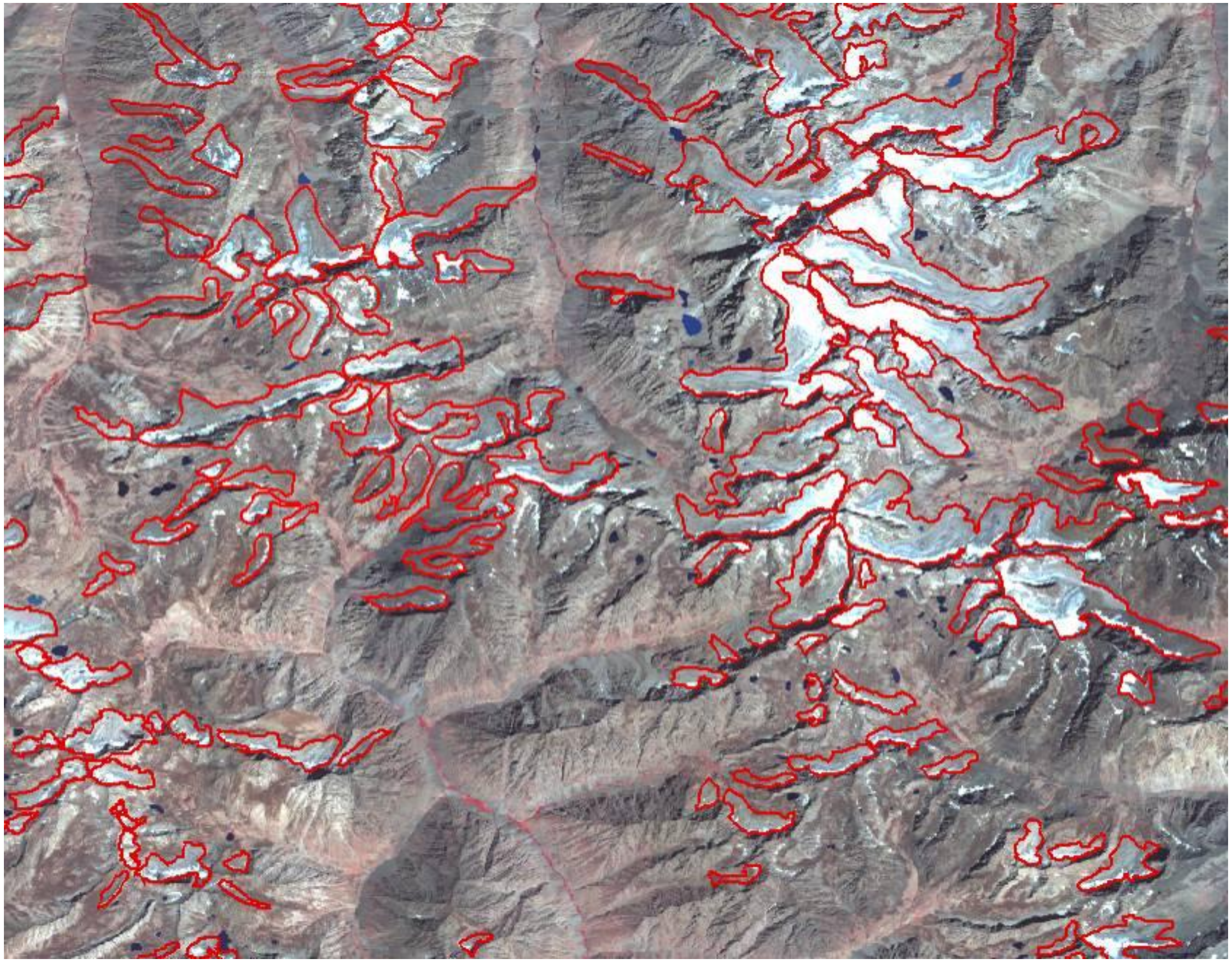
(Reference John F. Shroder Jr., Michael P. Bishop, Henry N. N. Bulley, Umesh K. Haritashya and Jeffery A. Olsenholler (2007) Global Land Ice Measurements from Space (GLIMS) project regional center for Southwest Asia (Afghanistan and Pakistan). In: R. Baudo, G. Tartari and E. Vuillermoz (Eds.) *Mountains, Witnesses of Global Change Research in the Himalaya and Karakoram*, Developments in Earth Surface Processes Book Series, Elsevier Publishing, Amsterdam, The Netherlands, Vol. 10, pp 187 – 208.

Contact:
Umesh Haritashya

Afghanistan glaciers: Outlines available in GLIMS database

See www.glims.org

Note: Discernment of glacier outlines is always a challenge where the termini are debris covered. Some Afghan glaciers have debris covered toes. Where glaciers are small, such as in this area, this is a special problem.



How long might Khumbu Glacier last?

CONTACT: Jeff Kargel

Radio echo-soundings of Khumbu Glacier (Gades et al. 2000) indicate:
-- Maximum measured thickness 450 m, mean of all measurements ~ 196m
-- Estimated mean thickness of entire glacier ~175 m (accounts for thinning at edges)

Thinning rate over most of Khumbu surface ~0.4m/year (Bolch et al. 2008); it could increase to 1 m/year.

If 1 m/year prevails, most of the ice would be gone in 175 years, but this would leave some stagnant ice in the thickest valley segments and active ice in the highest areas (reduced glacier remnant)

If massive runaway lake formation occurs, likely at some point this century, the average melt rate could accelerate, and most of the long glacier tongue could disappear sooner.

If the Bhutan Himalaya is used as a guide, disappearance of most of the glacier tongue could take 50 years once lakes start undergoing growth, so a much-reduced remnant of Khumbu might exist by 2060.

But this assessment does not imply that the high-altitude parts of the Khumbu will or even can disappear under any climate warming scenario. The Khumbu will retreat to a new quasi-equilibrium length and thickness as climate warming levels off. Ice at highest elevations might even thicken as monsoonal precipitation increases due to warming sea surface and enhanced Elevated Heat Pump.

The fact is we don't know how long the ice will last, but Khumbu Glacier is out of equilibrium with the present climate and this condition is apt to get worse. This glacier is going to change substantially this century, and it will probably be a bare remnant of what it is now by century's end. However, Khumbu Glacier, and other large Himalayan glaciers, will clearly *NOT* disappear entirely or even mostly by 2035.

Water resources represented by Himalayan glaciers

CONTACT: Jeff Kargel
and Georg Kaser

Radio echo-soundings of Lirung and Khumbu Glaciers (Gades et al. 2000) indicate:
- -- Maximum measured thicknesses 160 m (Lirung) and 450 m (Khumbu), mean ~125 m
- -- Lower 30% of Zuoqiupu Glacier, Tibet, also averages about 125 m thick (Aizen 2002)
- -- Assume mean Himalayan ice thickness is 125 m.

Area 30,000 km^2; volume of Himalayan glaciers = 3750 km^3 of ice = 3375 km^3 of water.

~1263 km^3 per annum combined water discharge of Indus, Ganges & Brahmaputra R.

Himalayan glaciers store about 2.7 years X annual water flow of these rivers.

If glaciers thin by 0.5 m per year averaged over their area, negative mass balance contributes 15 km^3 of water annually, or about 1.2% of the current river flow.

Glacier contributions in semi-arid valleys is locally much greater. Seasonal influence of glacier melt also strong locally, but is not very significant basin-wide (Kaser et al. 2009)

Increased melting may further increase water discharge by 1-2% in next few decades.

Within 50-100 years discharge would decrease several % as current negative balance contribution decreases. Other climate change effects exceed those of glacier changes.

Summary of recent changes of Himalayan glaciers

Many glaciers are rapidly retreating and in eastern Himalaya many glaciers will be much diminished in the next few decades, regardless of carbon emissions, aerosol emissions, and global warming trajectory. These glaciers are already out of equilibrium with existing climate due to late 20th Century emissions. Further emissions increase disequilibrium.

Himalaya are so high that few hundred meters ELA[1] change will not kill the glaciers, but will just establish new equilibrium lengths, areas, and AAR[2]; thus, retreating glaciers generally will leave shortened valley glacier and cirque glacier remnants. Glacier response times to climatic and other changes are mainly <100 yr (<1 year possible for basal sliding).

[1]Equilibrium Line Altitude = elevation where accumulation and melting balance. [2]Accumulation Area Ratio is a measure of glacier stability.

Some glaciers may undergo periods of comparative stabilization of length or even growth in mass. Long-term overall trends across South Asia indicate glacier retreat. Some may simultaneously retreat at low elevation and thicken at high elevation as more precipitation falls due to (1) increased evaporation of the warming sea, (2) shifting convergence of Indian monsoon and Westerlies, and (3) the Elevated Heat Pump. The EHP might shrink some glaciers, but might grow others in special topographic circum-stances. Influences of deposited soot/dust also appear important in shrinking glaciers.

Too few observations of recent fluctuations constrain models of such a complex system, but the past 100 years suggests that the next 100 years will involve mainly retreat.

Confusion about the future of Himalayan glaciers: 1

Two recent conjectures about Himalayan glaciers have caused much confusion. A letter submitted (by Cogley, Kargel, Kaser and Van der Veen) to the editor of *Science*, summarized here with some further elaboration, attempts to clear up the confusion.

First, in the IPCC Fourth Assessment of 2007, Working Group II stated[a]:

Glaciers in the Himalaya are receding faster than in any other part of the world ... the likelihood of them disappearing by the year 2035 and perhaps sooner is very high if the Earth keeps warming at the current rate. Its total area will likely shrink from the present 500,000 to 100,000 km^2 by the year 2035 (WWF, 2005).

This statement is in error. To clarify the actual situation:

1. Himalayan rates of recession are not exceptional.[b]
2. The first "2035" is from WWF 2005, which cites a news story[c] about an unpublished study[d] that does not estimate a date for disappearance of Himalayan glaciers.
3. The second "2035", an apparent typographic error, is not in WWF 2005, but can be traced circumstantially to a rough estimate[e] of the shrinkage of all extrapolar glaciers (excluding those in basins of internal drainage) between the present and ***2350***.
4. In conflict with knowledge of glacier-climate relationships, disappearance by 2035 would require a 25-fold acceleration during 1999–2035 from the loss rate estimated[f] for 1960–1999.
5. This was a bad error. It was a really bad paragraph, and poses a legitimate question about how to improve IPCC's review process. It was not a conspiracy. The error does not compromise the IPCC Fourth Assessment, which for the most part was well reviewed and is highly accurate.

a. IPCC, 2007, *Climate Change 2007: Impacts, Adaptation and Vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm, (p. 393-394).
b. World Glacier Monitoring Service, various dates, *Fluctuations of Glaciers,* http://www.geo.unizh.ch/wgms/fog.html.
c. *New Scientist*, **162**(2189), 18, 5 June 1999.
d. Now available at http://www.cryosphericsciences.org/docs.html#ICSI1999 .
e. Kotlyakov, V.M., 1996, *Technical Documents in Hydrology*, **1**, 61-66, http://unesdoc.unesco.org/images/0010/001065/106523e.pdf.
f. Dyurgerov, M.B. and M.F. Meier, 2005, *Occasional Paper 58*, http://instaar.colorado.edu/other/occ_papers.html.

Confusion about the future of Himalayan glaciers: 2

A discussion paper of the Indian Ministry of Environment and Forests[a] speculates that observed fluctuations of large Himalayan glaciers may be in response to the climate of as long as 6,000-15,000 years ago. Glacier response times are obtained in the discussion paper by dividing the length of the glacier by a typical ice velocity. For example, for Siachen Glacier, about 74 km long, an ice velocity of about 5 m a^{-1} leads to a response time of 15,000 years.

Although some observations in the paper appear to be reasonable and accurate, this speculation about response time is in error and could seriously confuse the media, the general population, and policy makers if not corrected.

1. The source for the ice velocity is not clear. It seems improbably low. Other similar, large debris-covered South Asian glaciers typically flow at average speeds that are factors of 2 to 20 times faster[b], the only exceptions being clearly stagnant and thinning or disintegrating glacier tongues.
2. This is a legitimate way to calculate the maximum travel time of ice through the body of the glacier, but it gives a grossly excessive estimate of the response time of the glacier to climatic changes.
3. A well-accepted method[c] uses a measure of thickness (for example, near the equilibrium line) divided by the ablation rate close to the terminus, which yields response times of several decades to a century or two for very large alpine glaciers.
4. This method, or suitable modifications to account for different mountain relief characteristics[d], gives reasonable response times that accord well with some glacier response and climate histories.
5. Many glaciers clearly respond much more rapidly to changes in environment, according to direct measurements, including some that change flow speed on a seasonal or even on a daily basis as a response to meltwater that penetrates to the glacier bed and affects slip along that boundary[e].
6. Other processes can speed glacier responses to climate[f].
7. Debris-covered stagnant (non-flowing) ice can melt extremely slowly due to thermal insulation by the rock cover, and such bodies may persist for decades or even a couple centuries after the climate and glacier events first emplaced the ice. For stagnant glaciers, disappearance times are consistent with reference c.

a. Raina, V.K., 2009, *Himalayan Glaciers*. Ministry of Environment and Forests, New Delhi, http://moef.nic.in/downloads/public-information/MoEF%20Discussion%20Paper%20_him.pdf.
b. Quincey, D.J., et al. 2009, Ice velocity and climate variations for Baltoro Glacier, Pakistan, J. Glaciol. 55, 1061-1071. Bolch, T. et al. 2008, Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery, Nat. Hazards Earth Systems Sci. 8, 1329-1340. Kaab, A., 2005, Combination of SRTM3 and repeat ASTER data forderiving alpine glacier flow velocities in the Bhutan Himalaya,Rem. Sens. Environ. 94(4), 463–474.
c. Jóhannesson, T., et al., 1989, *Journal of Glaciology*, **35**(121), 355-369.
d. Raper, S.C.B., and R.J. Braithwaite, 2009, Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry, *The Cryosphere*, **3**, 183-194.
e. Joughin, I., S.D. Das, M.A. King, B.E. Smith, I.M. Howat and T. Moon, 2008, Seasonal speedup along the western flank of the Greenland Ice Sheet, *Science*, **320**(5877), 781-783. Suiyama, S., 2006, Measurements and modelling of diurnal flow variations in a temperate valley glacier, *Glacier Science and Environmental Change*,P.G. Knight (ed.), Blackwell Science.
f. Johnson, J.N., 1968, Steady profile of a finite-amplitude kinematic wave on a glacier, *Journal of Glaciology*, **7**(49), 117-119. Van der Wal, R.S.W., and J. Oerlemans, 1995, Response of valley glaciers to climate change and kinematic waves: a study with a numerical ice-flow model, *Journal of Glaciology*, **41**(137), 142-152.

Confusion about the future of Himalayan glaciers: 3

A NASA press release and press briefing activity restated a popular refrain that exaggerates the roles of glaciers in providing water to people.
http://www.nasa.gov/topics/earth/features/himalayan-soot.html
This announcement was made in a fresh context of a newly identified climatic change mechanism affecting Himalayan and Tibetan glaciers (the Elevated Heat Pump, EHP) and new recognition of a previously known mechanism (soot influences on melting). Citing the warming due to the EHP, added to global warming from greenhouse gases, NASA stated: "This warming fuels the melting of glaciers and could threaten fresh water resources in a region that is home to more than a billion people."

The same press item stated, "But since the 1960s, the acreage covered by Himalayan glaciers has declined by more than 20 percent."

We seek some clarification and point out these matters:

1. We have not tracked a definitive source for this figure of 20% decline (which averages about -0.5%/a).

2. Individual glaciers' values for area retreat rates are not necessarily representative, because they tend to be derived from benchmark glaciers, which have been selected primarily as debris-free or low-debris glaciers.

3. Debris-free glaciers can better integrate recent climate signals, because they respond more rapidly to warming, but they do not well represent Himalayan glaciers, which are mostly debris-covered.

4. Average area retreat rates for multiple larger regions within the Himalaya probably better represent what is happening.

5. It is likely that the region-wide average area retreat rate is bracketed somewhere between −0.50% a^{-1} (-20%/40 years, often quoted), and −0.10% a^{-1}, as some measurements suggest. The -0.5%/a rate is an unlikely upper limit.

6. For climatic significance, area shrinkage is useful to integrate effects of climate change over many decades.

7. More useful for water resource assessment is volume or mass rates of change, which area change does not provide very well.

8. Accumulation area ratio (AAR) is more useful to project likely future behavior, and recent time-series changes in equilibrium line altitudes also can help to assess likely future behavior.

9. As we have calculated, melting glaciers (specifically, negative mass balance components of the melt) contribute an estimated 1.2% (perhaps factor of 2 uncertain) of total runoff of three of the most important drainages, the Indus, Ganges, and Brahmaputra combined. The seasonal flow regulation influences and the negative mass balance is more important in local drainages close to the glacier sources, wgere glaciers can dominate the hydrology in arid regions, but on the scale of the subcontinent, glaciers are secondary players in looming hydrologic problems, which stem more from population growth and inefficiency of water resource distribution and application.

10. The near future effect of a sharp increase in melting rate of glaciers is to increase water supplies. Sometime this century, as the lowest elevation parts of glaciers melt and disappear, the melt rate will decrease, and the decrease of this source of water will decrease supplies. However, that may be balanced or exceeded by increased overall precipitation related to the warming sea surface. The NASA press release's proposed "Elevated Heat Pump" effect, if validated by further research, would tend to shift precipitation from the Indian peninsula northward to the Himalaya and Tibet. It is not immediately clear whether in some areas this influence might not actually slow down the shrinkage of glaciers due to enhanced snowfall.

Conclusions

- Global climate change is a huge factor in this region.
- There are W→E and N→S transitions to wetter and warmer climate, and this shows in the pattern and complexity of glacier changes being observed.
- Soot deposition and aerosols are likely important parts of the climate-glacier system, especially in recent decades.
- The effects on glaciers of industrial and natural particulates as well as global warming should vary across the region.
- These effects must be more thoroughly documented by remote sensing and from the field with more benchmark glaciers and high-altitude meteorological stations established for long-term study.

References on glacier remote sensing and field glaciology of the Himalayan zone:

Ageta, Y., Iwata, S., Yabuki, H., Naito, N., Sakai, A., Narama, C., et al. (2000). Expansion of glacier lakes in recent decades in the Bhutan Himalayas. In M. Nakawo, C. F. Raymond, & A. Fountain (Eds.), Debris-Covered Glaciers, Vol. 264. IAHS Publications.

Aizen, V., 2002, http://www.sci.uidaho.edu/cae/projects/reports/NationalGeog_TechRep_2002.pdf

Berthier, E., Vadon, H., Baratoux, D., Arnaud, Y., Vincent, C., Feigl, K. L., et al. (2005). Mountain glacier surface motion derived from satellite optical imagery. Rem Sens Environ, 95(1), 14 ␣ 28.

Berthier, E., Arnaud, Y., Vincent, C., & Remy, F. (2006). Biases of SRTM in high-mountain areas: Implications for the monitoring of glacier volume changes. Geophysical Research Letters, 33(8), L08502. doi:10.1029/ 2006GL025862.

Berthier, E., Y. Arnaud, R. Kumar, S. Ahmad, P. Wagnon, P. Chevallier, 2007, Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India), Rem. Sens. Of Environment, 108, 327-338.

Bhambri, R. & T. Bolch (2009). Glacier Mapping: A Review with special reference to the Indian Himalayas. Progress in Physical Geography, 33(5): 672-704.

Bishop, M. P., Kargel, J. S., Kieffer, H. H., MacKinnon, D. J., Raup, B. H., & Shroder, J. F. (2000). Remote-sensing science and technology for studying glacier processes in High Asia. Annals Glaciol., Vol. 31 (pp. 164–170).

Bishop, M. P.,Shroder, J. F., &Ward, J. L. (1995). SPOT multispectral analysis for producing supraglacial debris_load estimates for Batura Glacier, Pakistan. Geocarto International, 10, 81-90.

Bolch, T., M. Buchroithner, T. Pieczonka and A. Kunert (2008). Planimetric and volumetric glacier changes in the Khumbu Himalaya since 1962 using Corona, Landsat TM, and ASTER Data, Jour. of Glaciology, 54, 592-600.

Bolch, T., M. F. Buchroithner, J. Peters, M. Baessler, and S. Bajracharya (2008). Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery, Nat. Hazards Earth Syst. Sci., 8, 1329-1340.

Che, T., X. Li, P.K. Mool and J. Xu, 2005, Monitoring glaciers and associated glacial lakes on the east slopes of Mount Xixabangma from remote sensing images, Journal of Glaciology and Geocryology, 27(6), 801-805.

Dyurgerov, M.B., & Meier, M.F. (2005). Glaciers and the changing earth system: a 2004 snapshot. Occasional Paper #58 http:// instaar.colorado.edu/ other/download/OP58dyurgerovmeier.pdf

Gades, A., H. Conway, N. Nereson, N. Naito, and T. Kadota, 2000, Radio echo-sounding through supraglacial debris on Lirung and Khumbu Glaciers, Nepal Himalayas, in: Debris-covered Glaciers,IAHS-AISH publication, no 264, pp 13-22.

Fujita K, Nakawo M, Fujii Y, Paudyal P., 1997, Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994.Journal of Glaciology, 43(145), 583-588.

Fujita K, Takeuchi N, Seko K., 1998, Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalayas, 1994 and 1996.Bulletin of Glacier Research, 16, 75-81.

Fujita K, Kadota T, Rana B, Kayastha RB, Ageta Y., 2001, Shrinkage of Glacier AX010 in Shorong region, Nepal Himalayas in the 1990s.Bulletin of Glaciological Research, 18, 51-54.

Fujita, K., Suzuki, R., Nuimura, T., and Sakai, A.: Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya, J. Glaciol., 54(185), 220–228, 2008.

References on glacier remote sensing and field glaciology of the Himalayan zone:

Fujita K, 2008, Effect of precipitation seasonality on climatic sensitivity of glacier mass balance.Earth and Planetary Science Letters, 276(1-2), 14-19. doi:10.1016/j.epsl.2008.08.028.

Fujita K, Sakai A, Nuimura T, Yamaguchi S, Sharma RR, 2009. Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in-situ surveys and multi-temporal ASTER imagery. Environmental Research Letters, 4, 045205.

Haritashya, U., M.P. Bishop, J.F. Shroder · A.B.G. Bush, and H.N.N. Bulley, 2009, Space-based assessment of glacier fluctuations in the Wakhan Pamir, Afghanistan, Climatic Change (2009) 94:5–18.

Hewitt K (2005) The Karakoram anomaly? Glacier Expansion and the 'Elevation Effect,' Karako-ram Himalaya. Mt Res Dev 25(4):332–340.

Immerzeel, W.W., D. Droogers, S.M. de Jong and M.F.P. Blerkens, 2009, Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing, Rem Sens Env 113, 1, 40-49.

Kääb, A. (2005). Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya. Remote Sensing of Environment, 94(4), 463-474.

Kääb, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., et al. (2005). Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview. Natural Hazards and Earth System Science, 5, 527-554.

Kargel, J., Abrams, M., Bishop, M., Bush, A., Hamilton, G., Jiskoot, H., et al. (2005). Multispectral imaging contributions to global land ice measurements from space. Rem Sens Environ, 99(1–2), 187 219.

Kaser, G., Cogley, J. G., Dyurgerov, M. B., Meier, M. F., & Ohmura, A. (2006). Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004. Geophysical Research Letters, 33, L19501Khromova TE, Osipova GB, Tsvetkov DG, Dyurgerov MB, Barry RG (2006) Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery. Rem Sens Environ 102:24–32.

Kaser, G., M. Großhauser, and B. Marzeion, 2009, The contribution potential of glaciers to river runoff in different climate regimes, Poster #GC51A-0706, Fall Amer. Geophys. Union, San Francisco.

Kulkarni, A. V. (1992). Mass balance of Himalayan glaciers using AAR and ELA methods. Journal of Glaciology, 38(128), 101-104.

Kulkarni, A.V., and 6 others, 2007, Glacial retreat in Himalaya using Indian Remote Sensing satellite, Current Science, 92(1), 69-74.

Kulkarni, A.V., B.P. Rathore, S. Mahajan and P. Mathur, 2005, Alarming retreat of Parbati glacier, Beas basin, Himachal Pradesh, Current Science, 88(11), 1844-1850.

Li, X., L. Wu, R. Jin, T. Che, P. Mool and S. Bajracharya, 2007, Glacier change in the Himalayas: an overview, Annals of Glaciology, 46, submitted??

Liu, S., and 7 others, 2006a, Glacier retreat as a result of climate warming and increased precipitation in the Tarim river basin, northwest China, Annals of Glaciology, 43, 91-96.

Naito, N., Nakawo, M., Kadota, T., & Raymond, C. F. (2000). Numerical simulation of recent shrinkage of Khumbu Glacier, Nepal Himalayas. In M. Nakawo, C. F. Raymond, & A. Fountain (Eds.), Debris-covered glaciers, IAHS Publ., vol. 264 (pp. 245–254).

Quincey, D. J., Richardson, S. D., Luckman, A., Lucas, R. M., Reynolds, J. M., Hambrey, M. J., and Glasser, N. J. (2007). Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets, Global Planet. Change, 56(1–2), 137–152.

Raina, V.K., *Himalayan Glaciers*. Discussion Paper, Ministry of Environment and Forests, Government of India, New Delhi (2009).

References on glacier remote sensing and field glaciology of the Himalayan zone:

Raup, B. R., Racoviteanu, A., Khalsa, S. J. S., Helm, C., Armstrong, R., & Arnaud, Y. (in press). The GLIMS geospatial glacier database: A new tool for studying glacier change. Global and Planetary Change.

Rupper, S., G. Roe and A. Gillespie, 2009, Spatial patterns of glacial advance and retreat in Central Asia, Quat. Res. 72, 337-346.

Sakai A, Nishimura K, Kadota T, Takeuchi N/, 2009, Onset of calving at supraglacial lakes on debris covered glaciers of the Nepal Himalayas.Journal of Glaciology, 55(193), 909-917.

Salerno, F., E. Buraschi, G. Bruccoleri, G. Tartari and C. Smiraglia, 2008, Glacier surface-area changes in Sagarmatha national park, Nepal, in the second half of the 20th century, by comparison of historical maps, Journal of Glaciology, 54(187), 738-752.

Shangguan, D., Sh. Liu and Y. Ding, 2007, Glacier changes in the West Kunlun Shan from 1970 to 2001 derived from Landsat TM/ETM+ and Chinese Glacier Inventory data, Annals of Glaciology, 46, 204-208.

Shangguan, D., and 9 others, 2006, Monitoring the glacier changes in the Muztag Ata and Konggur mountains, east Pamir, based on Chinese Glacier Inventory and recent satellite imagery, Annals of Glaciology, 43, 79-85.

Sharma, K.P., C.J. Vorosmarty, B. Moore III, 2000, Sensitivity of the Himalayan hydrology to land-use and climatic changes, Climatic Change 47, no. 1-2, 117-139.

Shiyin, L., Wenxin, S., Yongping, S., & Gang, L. (2003). Glacier changes since the Little Ice Age maximum in the western Qilian Shan, northwest China, and consequences of glacier runoff for water supply. Journal of Glaciology, 49, 117–124.

Su, Zh., and Y. Shi, 2002, Response of monsoonal temperate glaciers to global warming since the Little Ice Age, Quaternary International, 97/98, 123-131.

Su, Zh., and Y. Shi, 2000, Response of monsoonal temperate glaciers in China to global warming since the Little Ice Age, Journal of Glaciology and Geocryology, 22(3), 223-229.

Tangborn, W., & Rana, B. (2000). Mass balance and runoff of the partially debris-covered Langtang glacier, Nepal. In M. Nakawo, C. F. Raymond, & A. Fountain (Eds.), Debris-covered glaciers, Vol. 264 IAHS Publications.

Tartari, G., F. Salerno, E. Buraschi, G. Bruccoleri, and C. Smiraglia, 2008, Lake surface area variations in the North-Eastern sector of Sagarmatha National Park (Nepal) at the end of the 20th Century by comparison of historical maps, J. Limnol. 67, 139-154.

Wessels, R., Kargel, J. S., & Kieffer, H. H. (2002). ASTER measurements of supraglacial lakes in the Mount Everest region of the Himalaya. Annals Glaciol., Vol. 34 (pp. 399-408).

Yadav, R. R., Park, W. K., Singh, J., & Dubey, B. (2004). Do the western Himalayas defy global warming? Geophysical Research Letters, 31(17).

Yamada, T., & Motoyama, H. (1988). Contribution of glacier meltwater to runoff in glacierized watersheds in the Langtang Valley, Nepal Himalayas. Bulletin of Glacier Research, 6, 65–74.

Ye, Q., T. Yao and R. Naruse, 2008, Glacier and lake variations in the Mapam Yumco basin, western Himalaya of the Tibetan Plateau, from 1974-2003 using remote-sensing and GIS technologies, Journal of Glaciology, 54 (188), 933-935.

Ye, Q., L. Zhu, H. Zheng, R. Naruse, X. Zhang, and Sh. Kang, 2007, Glacier and lake variations in the Yamzhog Yumco basin, southern Tibetan Plateau, from 1980 to 2000 using remote-sensing and GIS technologies, Journal of Glaciology, 53(183), 673-676.

Ye, Q., T. Yao, Sh. Kang, F. Chen and J. Wang, 2006a, Glacier variations in the Naimona'nyi region, western Himalaya, in the last three decades, Annals of Glaciology, 43, 385-389.