The Impact of Disappearing Tropical Andean Glaciers on Pastoral Agriculture: A Few Surprises

Current progress: July 2011 – March 2013

Dan Slayback, SSAI / NASA Goddard, Biospheric Sciences

LCLUC 2013 Science Team Meeting – 03 April 2013, Rockville MD

Project Team & Collaborators

NASA Goddard Space Flight Center

Dan Slayback (SSAI/Biospheric Sciences)
Karina Yager (SSAI/Biospheric Sciences)
Matt Smith (SSAI/Biospheric Sciences)
Karen Mohr (Mesoscale Atmospheric Processes)
Stephen Nicholls (NASA Postdoctoral Program, Mesoscale Atmospheric Processes)
Compton Tucker (Earth Sciences)

Ohio State University
Geography Dept & Byrd Polar Research Center

Bryan Mark
Oliver Wigmore
Colin Sinclair

ETS (Montreal)

Michel Baraer

Colorado State University
Department of Forest & Rangeland Stewardship

David Cooper
Jeremy Sueltenfuss
Evan Wolf (UC Davis)

Michigan Tech
Wetland Ecology

Rod Chimner
John Hribljan

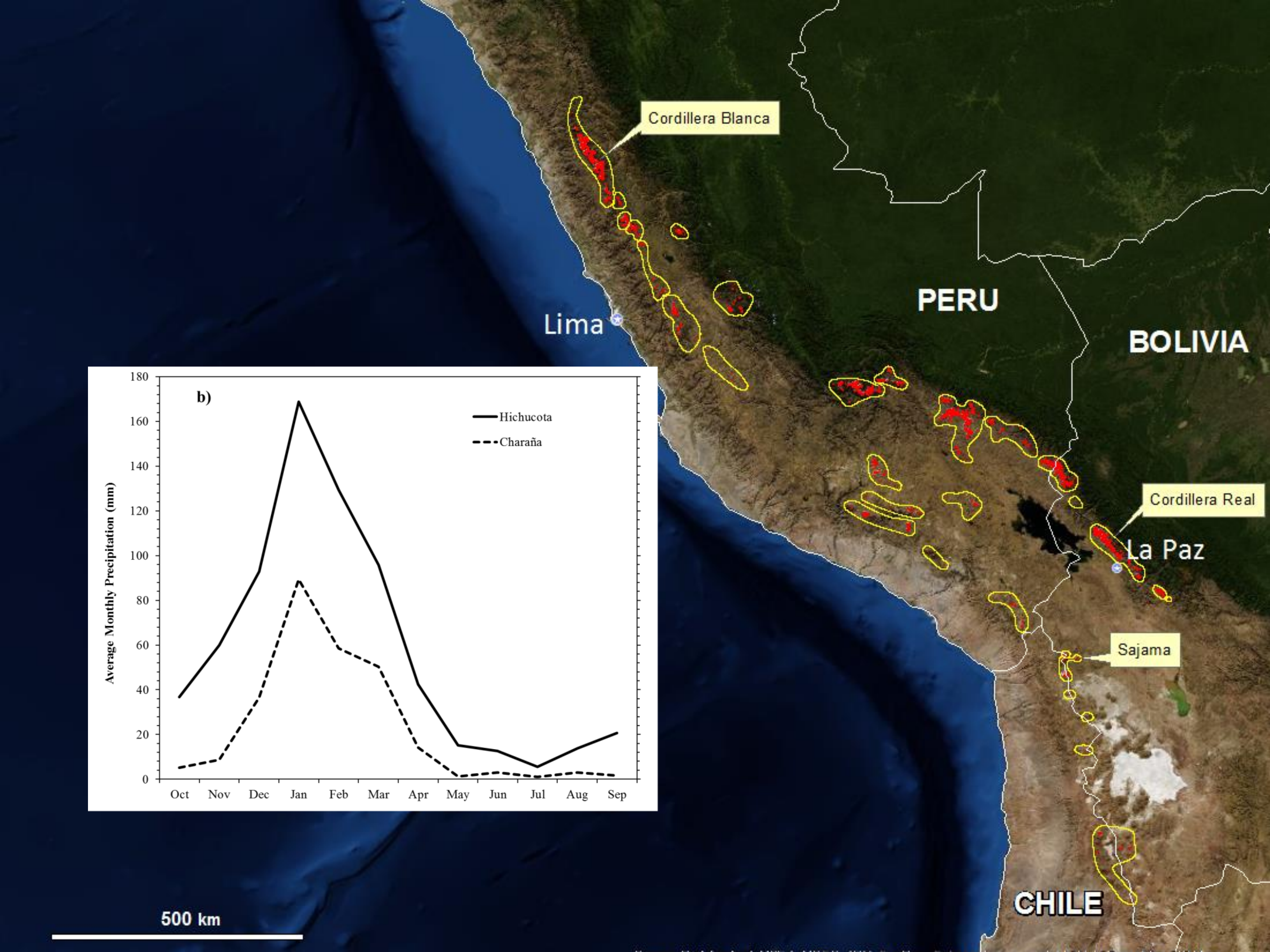
IRD (La Paz office)

Olivier Dangles
Gabriel Castellon

UMSA (Universidad Mayor de San Andres, La Paz)

Rosa Isela Meneses (Director, National Herbarium)
Jaime Argollo (Geology Dept)
Marcelo Cabero (Geology Dept)


PERU
BOLIVIA
Lima
La Paz
CHILE
500 km

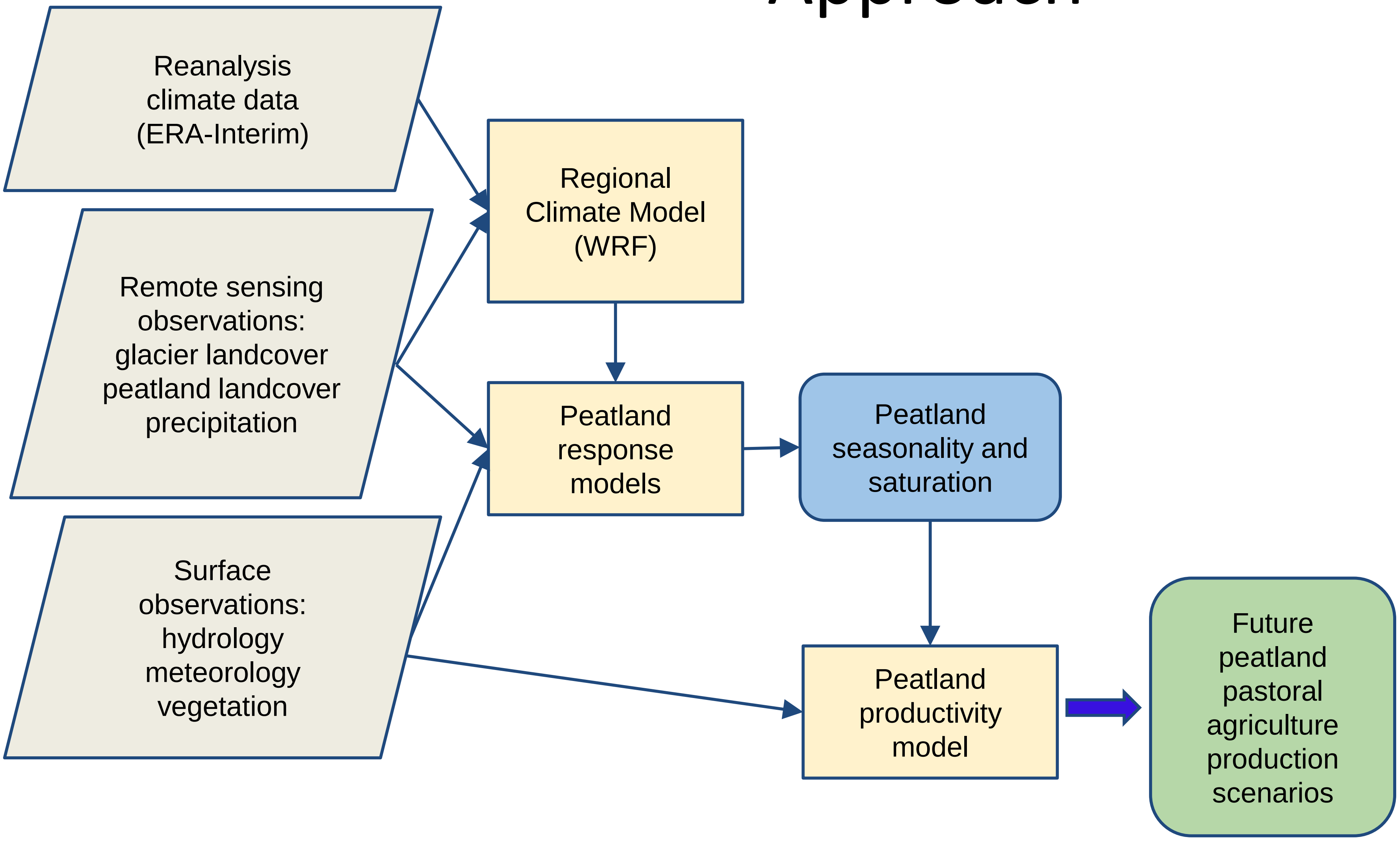

Cordillera Blanca
Lima
PERU
BOLIVIA
Cordillera Real
La Paz
Sajama
CHILE
500 km
b)
Hichucota
Charaña
Average Monthly Precipitation (mm)
180
160
140
120
100
80
60
40
20
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep

Research Questions

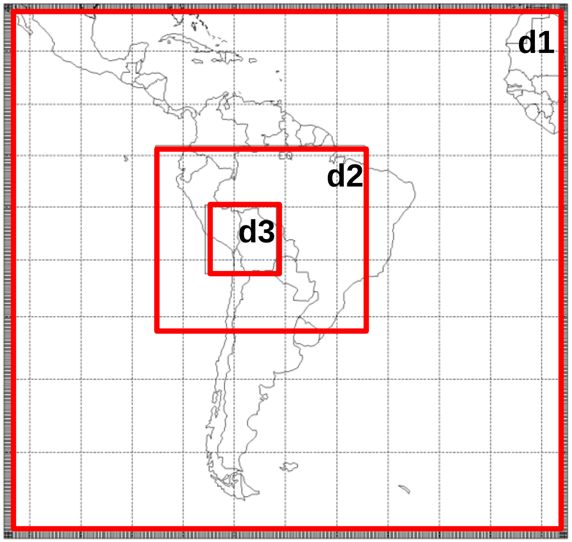
1. History: what is the recent landcover history of the region?
   - Glaciers are already declining: is the rate constant or accelerating?
   - Where are the bofedales, and are they already responding?

2. Future: What may happen in coming decades, given likely climate change scenarios?
   - What is current bofedale forage production?
   - How will climate change affect future production?
   - How sensitive is the hydrologic support to different future climate scenarios?

Approach



Reanalysis climate data (ERA-Interim)
Remote sensing observations: glacier landcover peatland landcover precipitation
Surface observations: hydrology meteorology vegetation
Regional Climate Model (WRF)
Peatland response models
Peatland seasonality and saturation
Peatland productivity model
Future peatland pastoral agriculture production scenarios



Regional Climate Model

Modeling Grid

Spatial resolutions: 27, 9, 3 km

Vertical resolution: 61 layers

Temporal resolution:

With 2 outer nests running:

Δt = 36 and 12 seconds

With 3 nests running:

Δt = 3.6, 1.2, 0.4 seconds

Model

1. NASA Unified WRF model – test runs successful
2. Test COAWST version, with interactive ocean model (Woods Hole)
3. Test climate-WRF (CWRF, UMD-College Park).

Select model with best simulations of mountain precip

Modeling tasks

1. Simulate present climate, 2003-2004 ENSO neutral wet season (DJF) to validate model set up and test glacier albedo feedbacks.
2. Simulate 33%, 66%, and 100% of the CO_2 value at 2033 of the IPCC AR5 Representative Concentration Pathways (RCP) 8.5 scenario of Meinhausen et al. (2011).

Inputs

ERA-Interim global reanalysis:

1. Radiation
2. Humidity
3. Temperature (air and soil)
4. Soil moisture
5. Winds
6. SST

Remote sensing estimates:

7. Glacier extent (current)
8. Glacier recession rate (projected based on observed historical trends)

Outputs

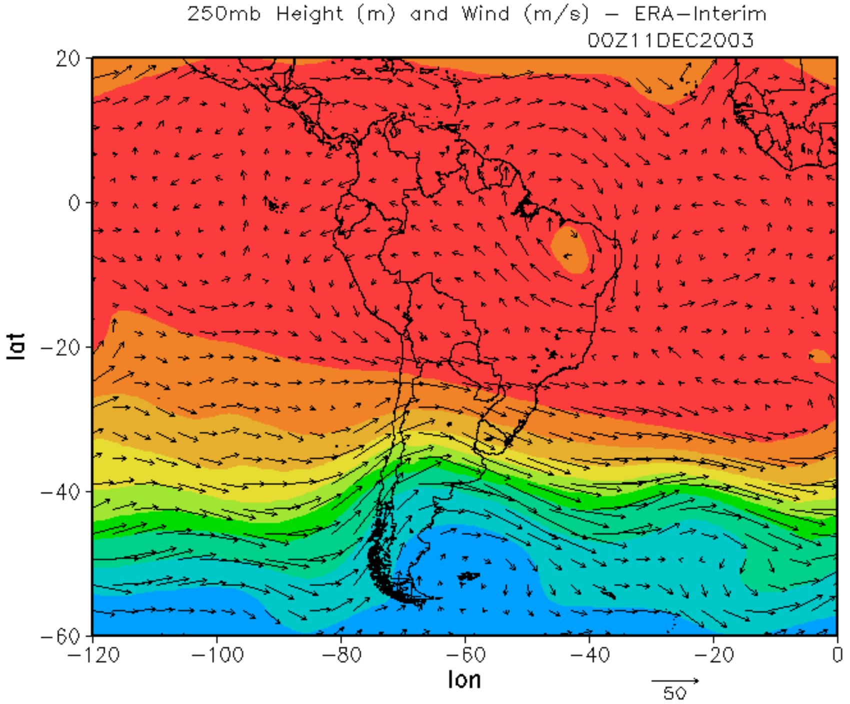
1-5 at the nested grid locations

6. Precipitation amount and type
7. Snow cover
8. Cloud cover
9. Surface runoff
10. Evapotranspiration
11. Surface latent and sensible heat fluxes
12. Atmospheric latent heating
13. Surface albedo

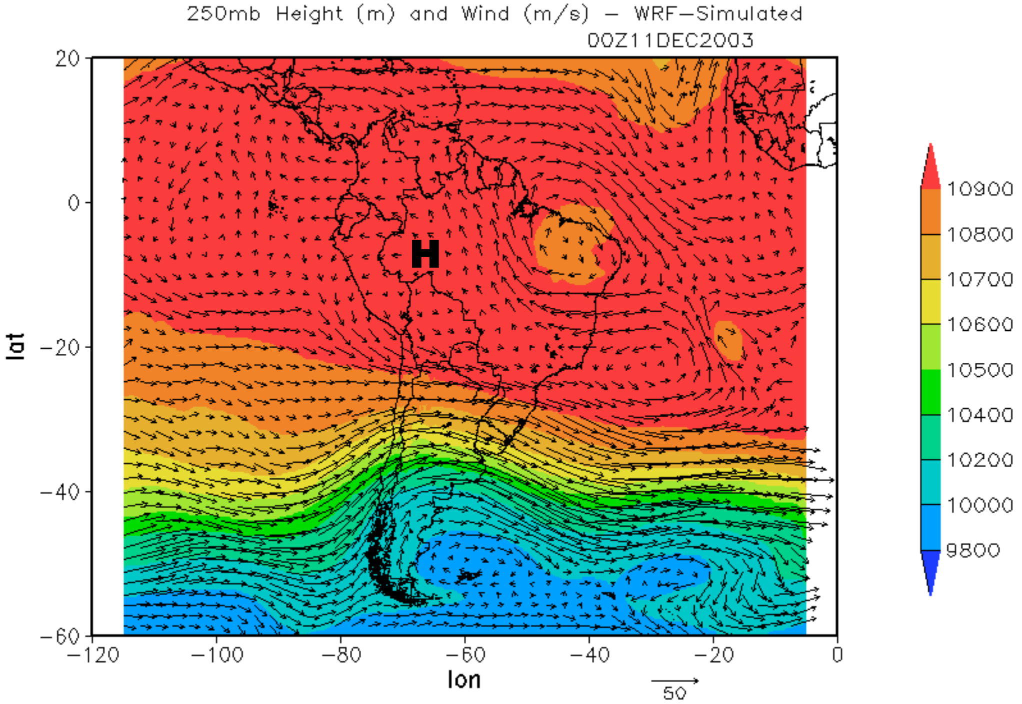
NASA WRF – Validation Exercises

250 mb winds

ERA-Interim

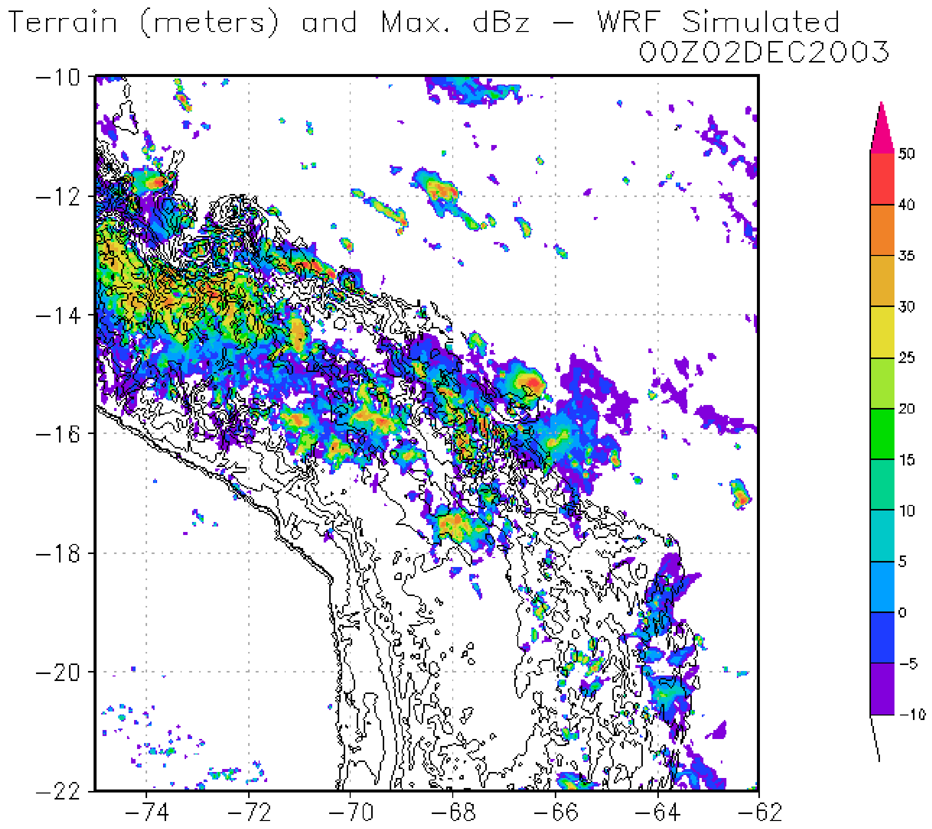


WRF Simulated



NASA WRF – Validation Exercises

Simulated 3 km convection / precipitation

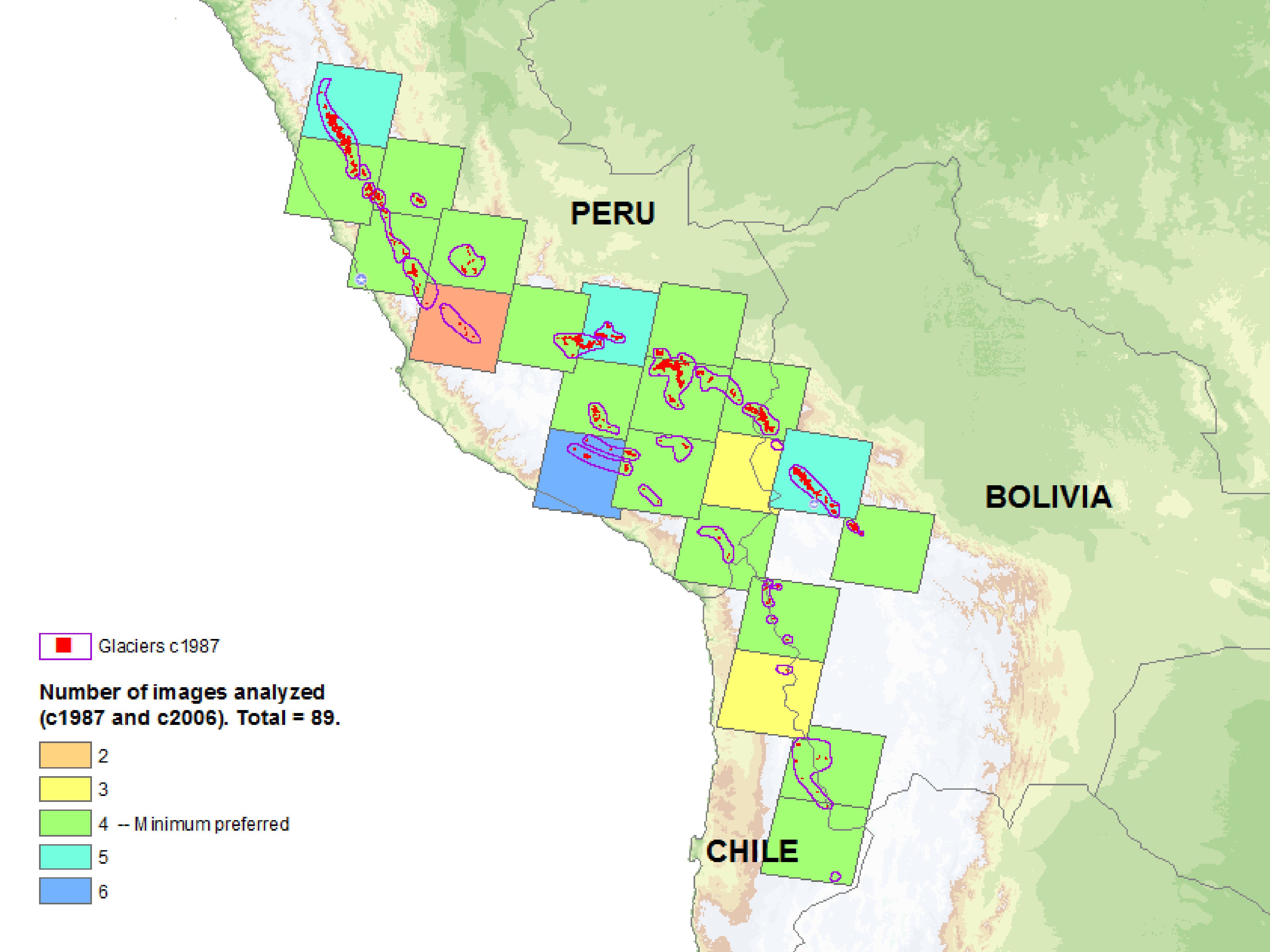


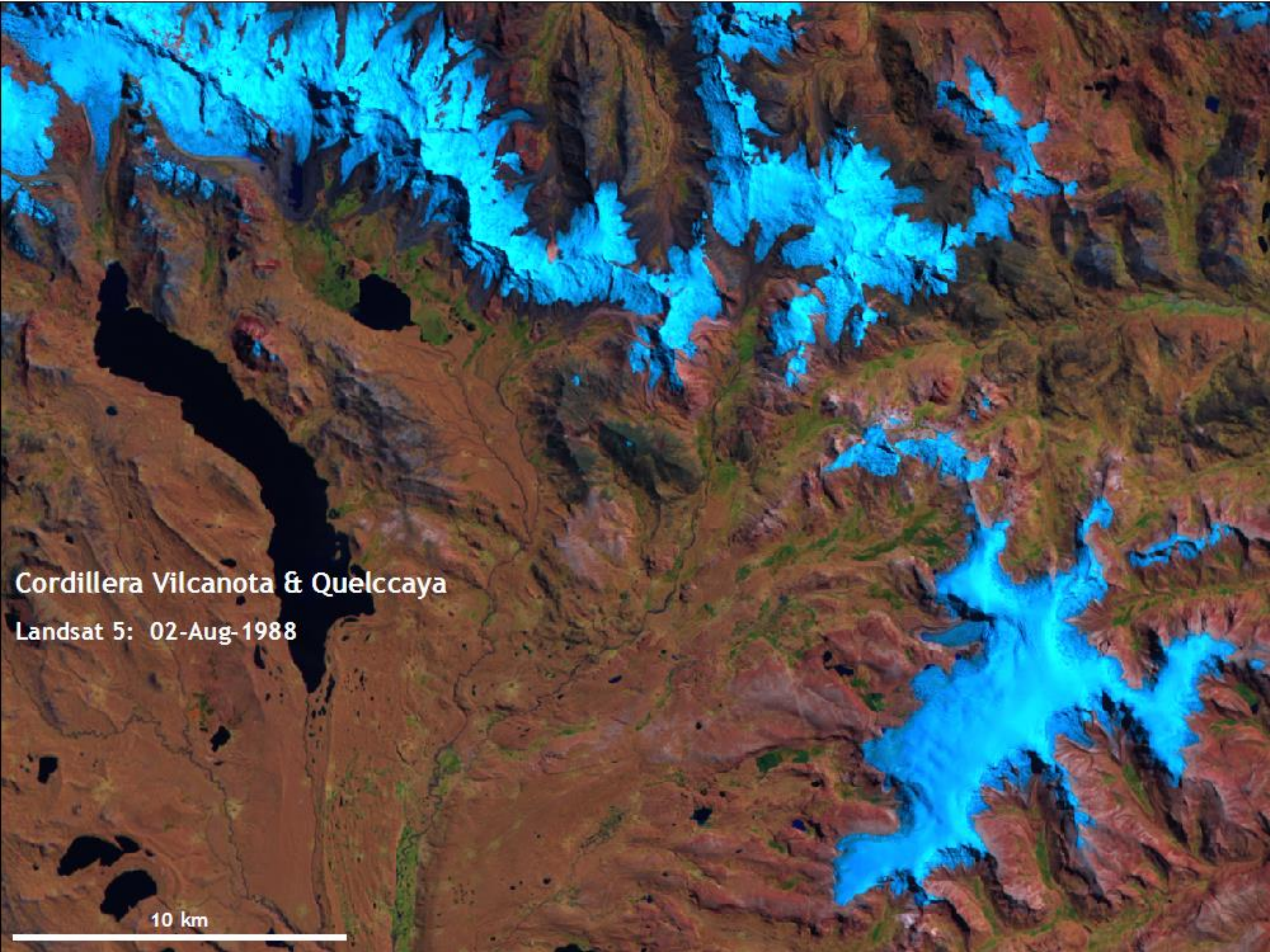
Glacier Extent & Recession

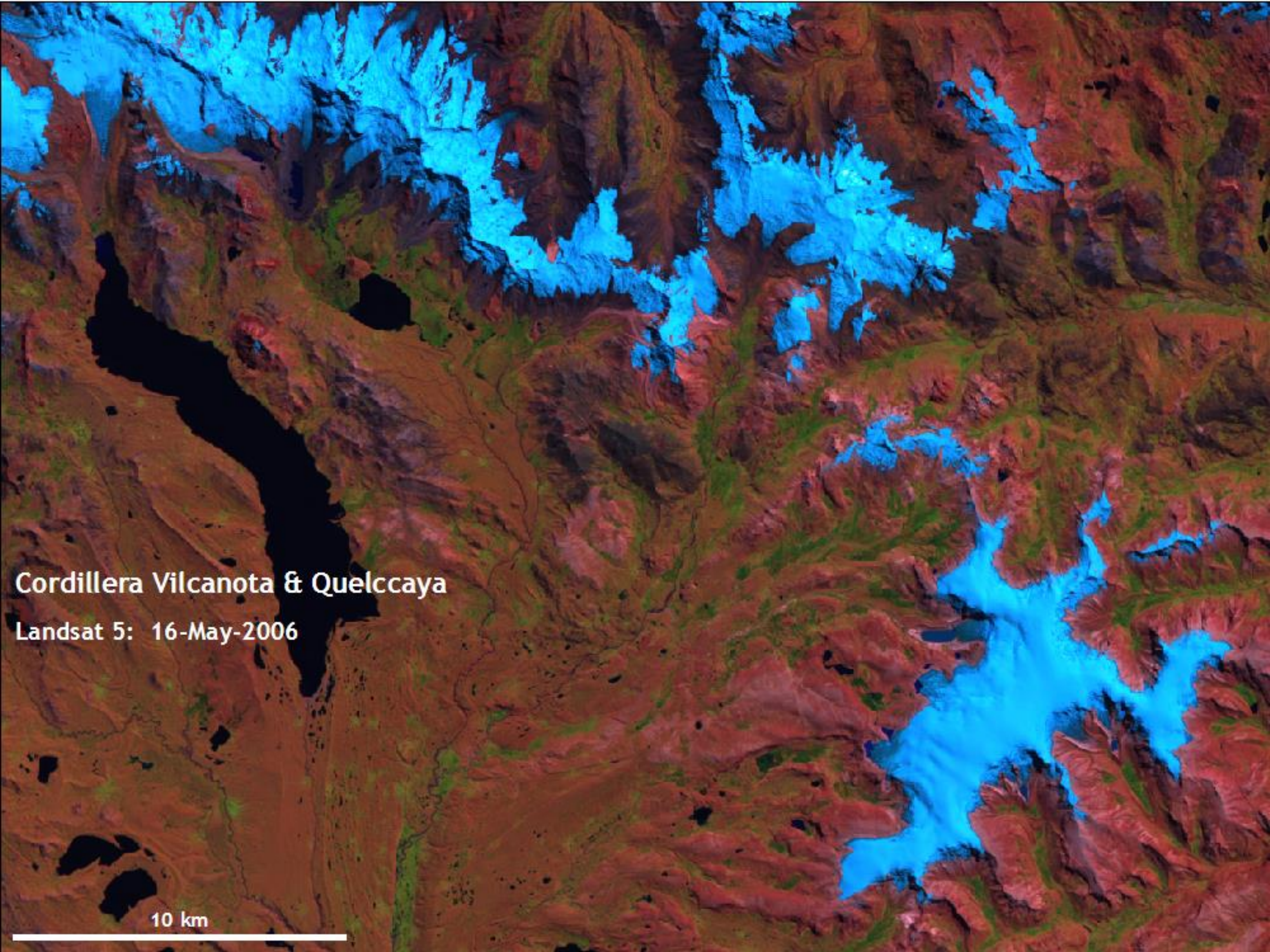
- Detailed studies of a handful of individual glaciers by glaciologists (mass balance, etc)
- No consistent region-wide study of extent or change
- Obstacles
  - Need dense data archive
  - Orthorectification required for change detection
  - Glaciers small in size, but spread out over large area (1500 km north-south)
  - Confusion between snow and glacier and cloud
  - Confusion in topographic shadows
  - Complications of varying solar illumination

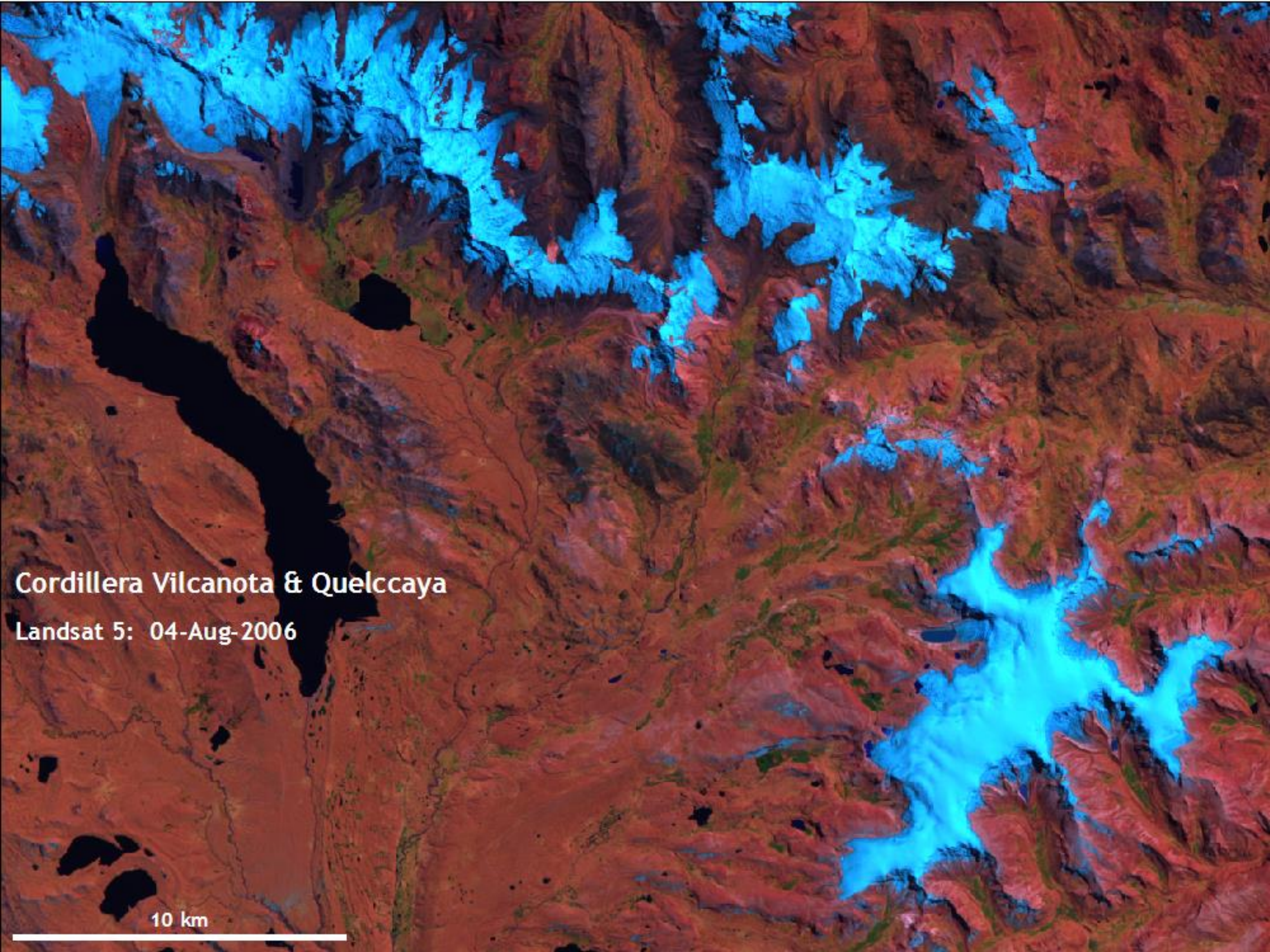
Glacier analysis approach

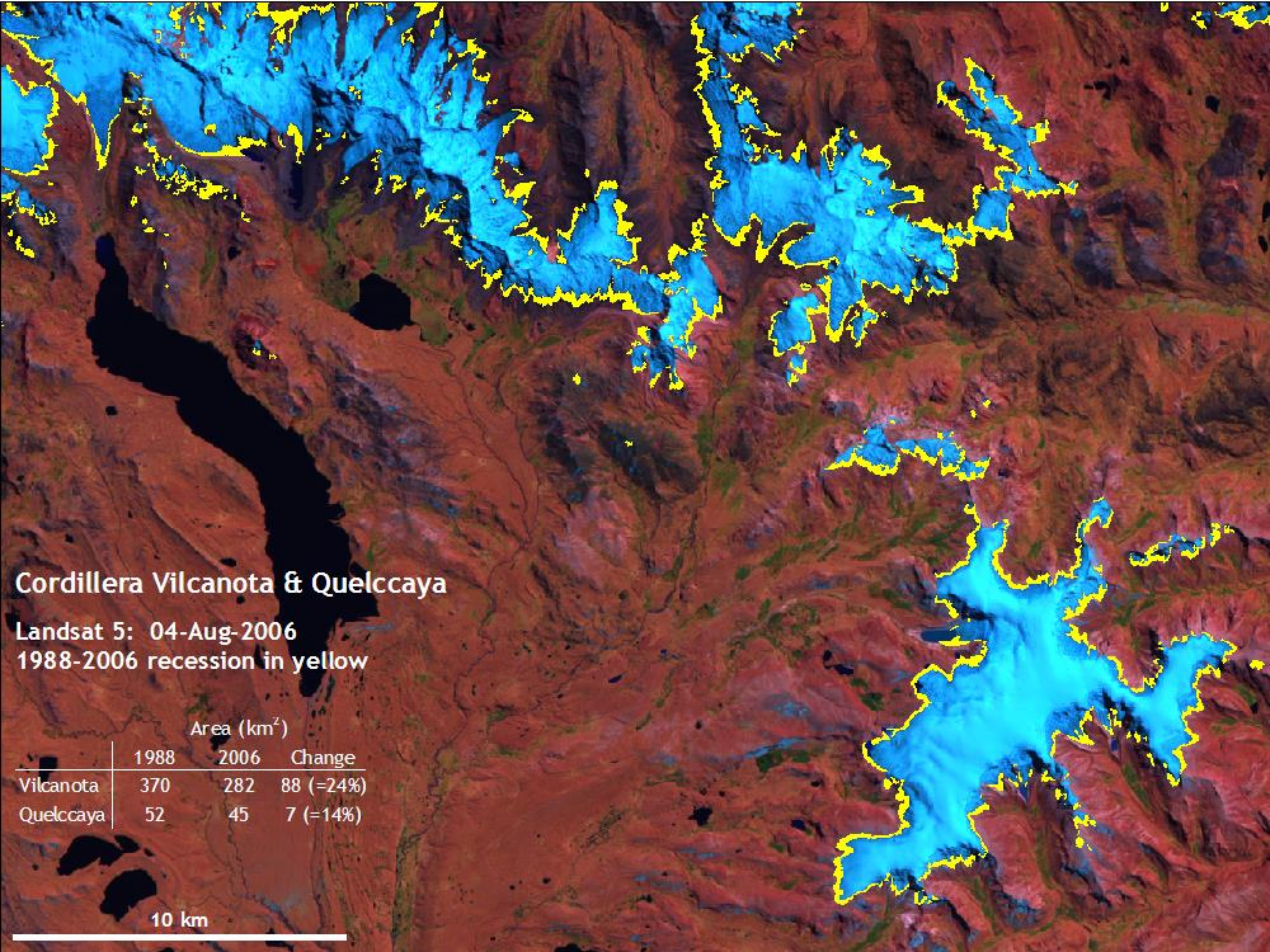
- Analyze glacier extent at ~10-year epochs:
  - mid 1970s – Landsat 1/2/3 MSS
  - mid 1980s, mid 1990s, mid 2000s – Landsat 4/5/7 TM
  - 2013 – Landsat 8 OLI ?
- 2+ dates per epoch, manually selected for:
  - Minimum snow/apparent glaciers/cloud
  - Different years: glacier = minimum common extent within epoch
- Unsupervised classification: 1980s, mid-2000s.
- SVM with unsupervised results as training
  - More easily use additional dates
  - Reclassify 1980s, 2000s
  - Add 1990s, 2013, 1970s (?)
- Conservative aggregation and change rules
- Validate with high resolution imagery

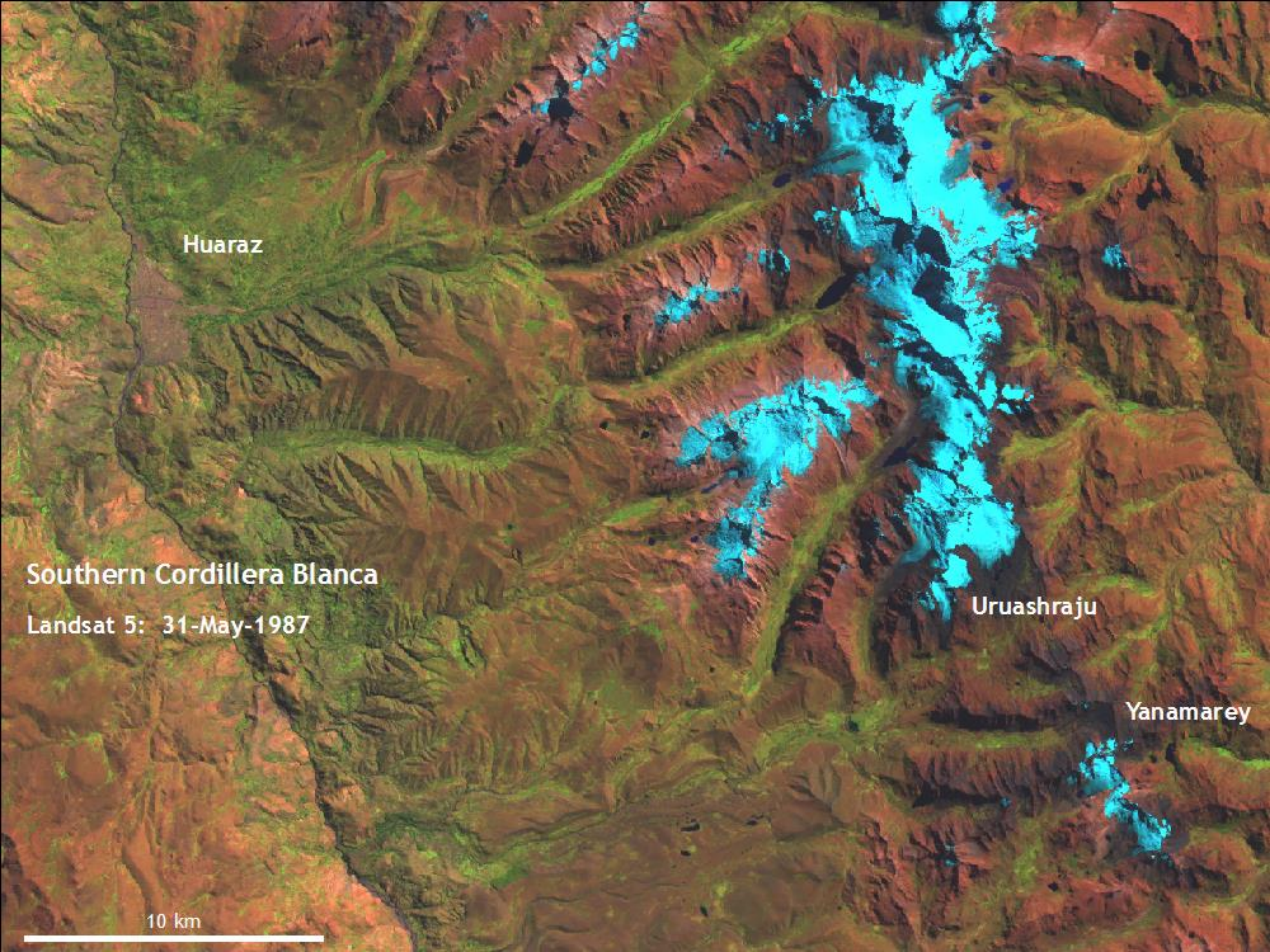

PERU
BOLIVIA
CHILE
Glaciers c1987
Number of images analyzed
(c1987 and c2006). Total = 89.
2
3
4 -- Minimum preferred
5
6

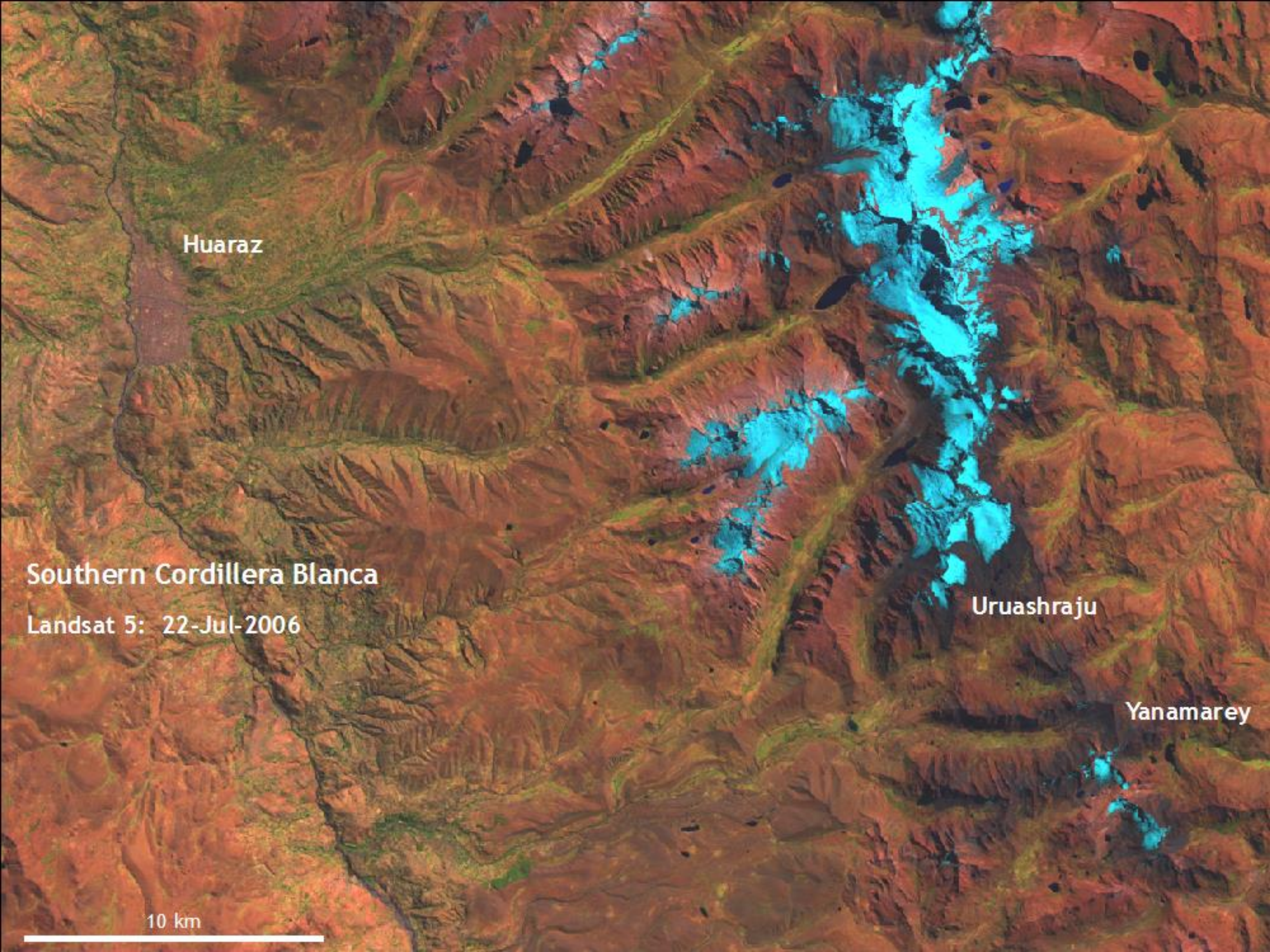

Cordillera Vilcanota & Quelccaya
Landsat 5: 02-Aug-1988
10 km

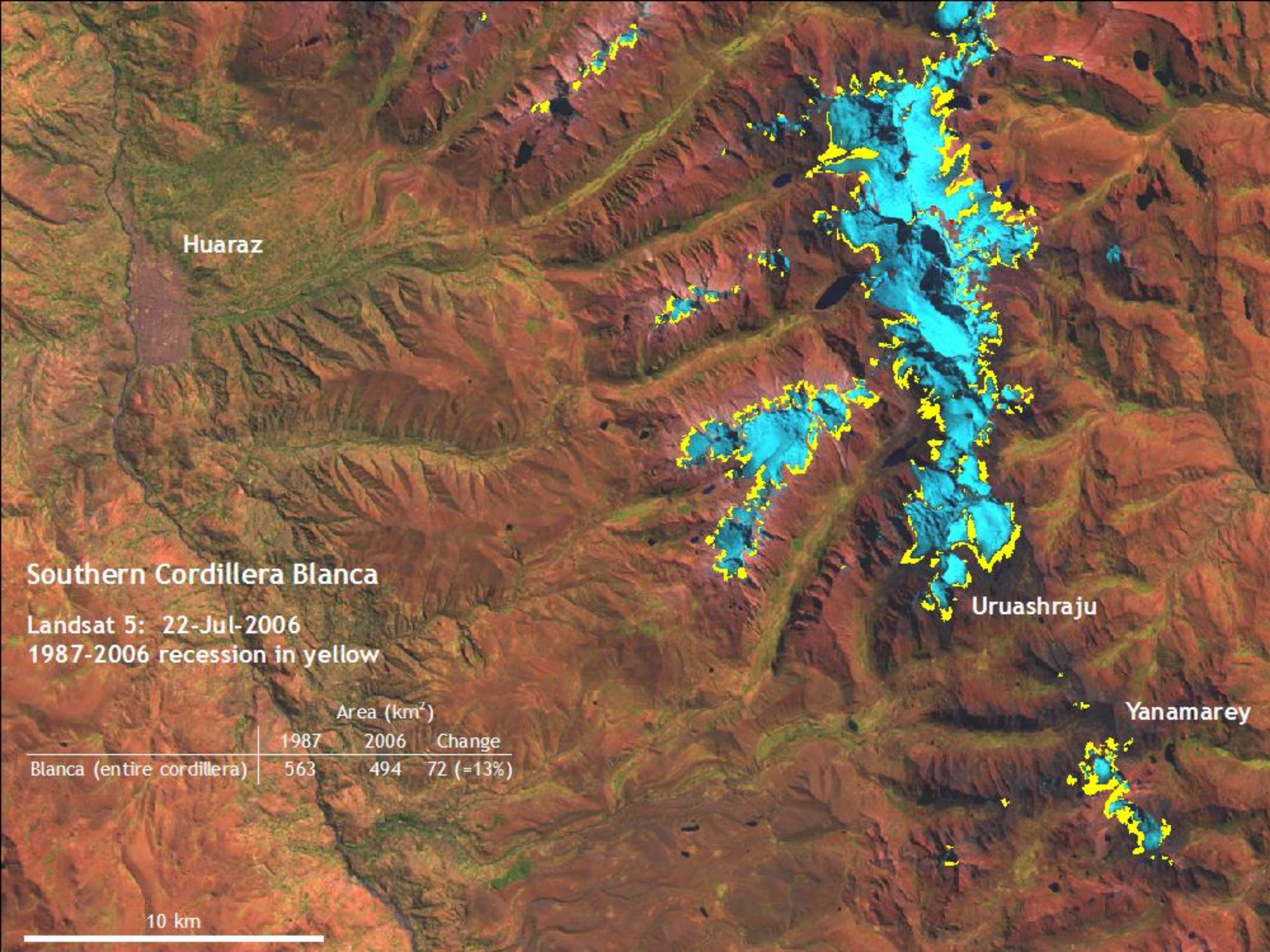

Cordillera Vilcanota & Quelccaya
Landsat 5: 16-May-2006
10 km


Cordillera Vilcanota & Quelccaya
Landsat 5: 04-Aug-2006
10 km


Cordillera Vilcanota & Quelccaya
Landsat 5: 04-Aug-2006
1988-2006 recession in yellow
Area (km2)
	1988	2006	Change
Vilcanota	370	282	88 (=24%)
Quelccaya	52	45	7 (=14%)
10 km

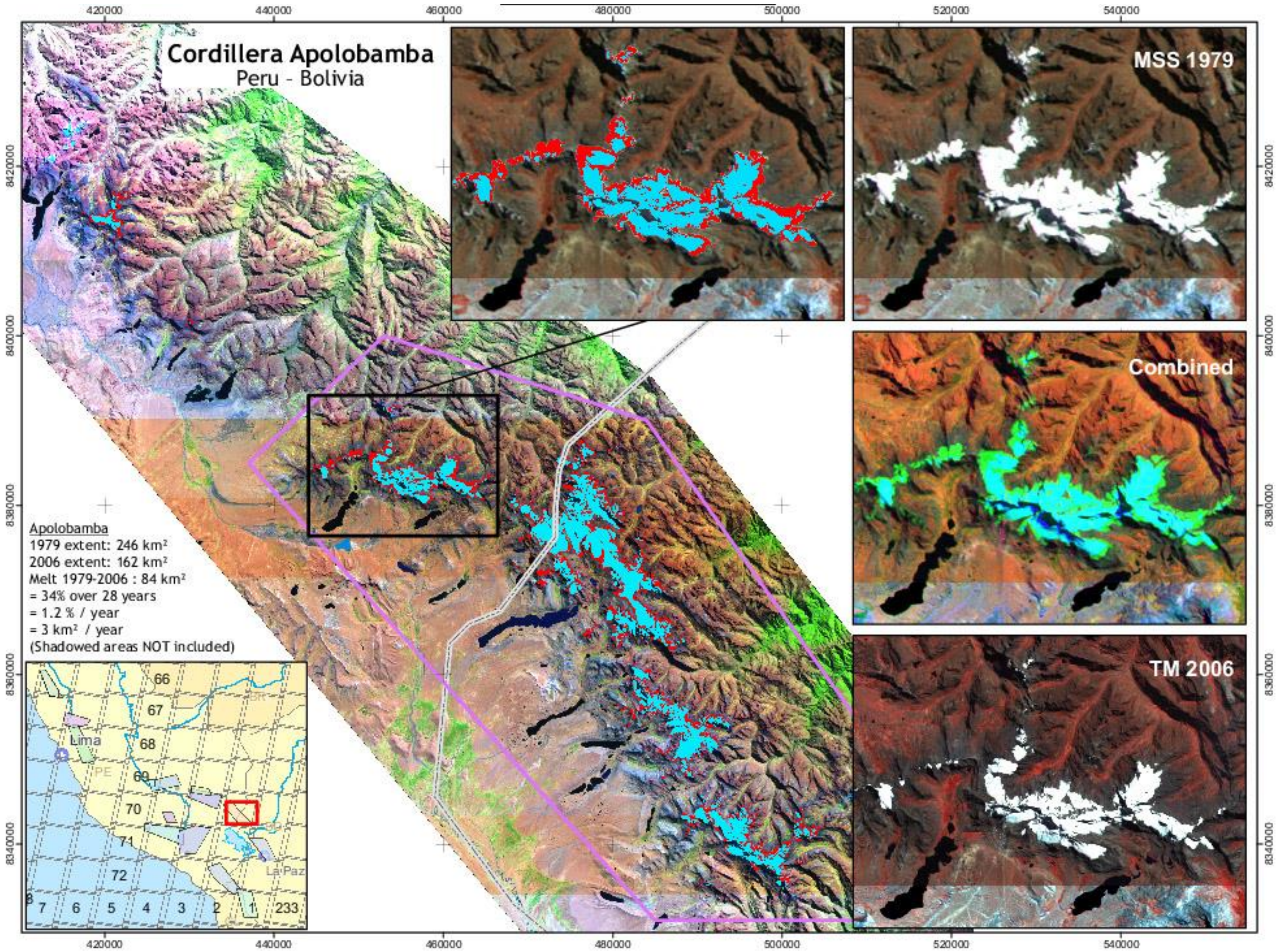

Huaraz
Southern Cordillera Blanca
Landsat 5: 31-May-1987
Uruashraju
Yanamarey
10 km


Huaraz
Southern Cordillera Blanca
Landsat 5: 22-Jul-2006
Uruashraju
Yanamarey
10 km


Huaraz
Uruashraju
Yanamarey
Southern Cordillera Blanca
Landsat 5: 22-Jul-2006
1987-2006 recession in yellow
Area (km²)
1987 2006 Change
Blanca (entire cordillera) 563 494 72 (=13%)
10 km

Landsat MSS: extend to 1970s

- Limitations
  - More difficult to manually assess snow vs glacier cover at 80 m resolution
  - Less dense image archive
- Preliminary study comparing coincident TM vs MSS classification results for early 1980s showed comparable results
- Useful estimate where sufficient data available

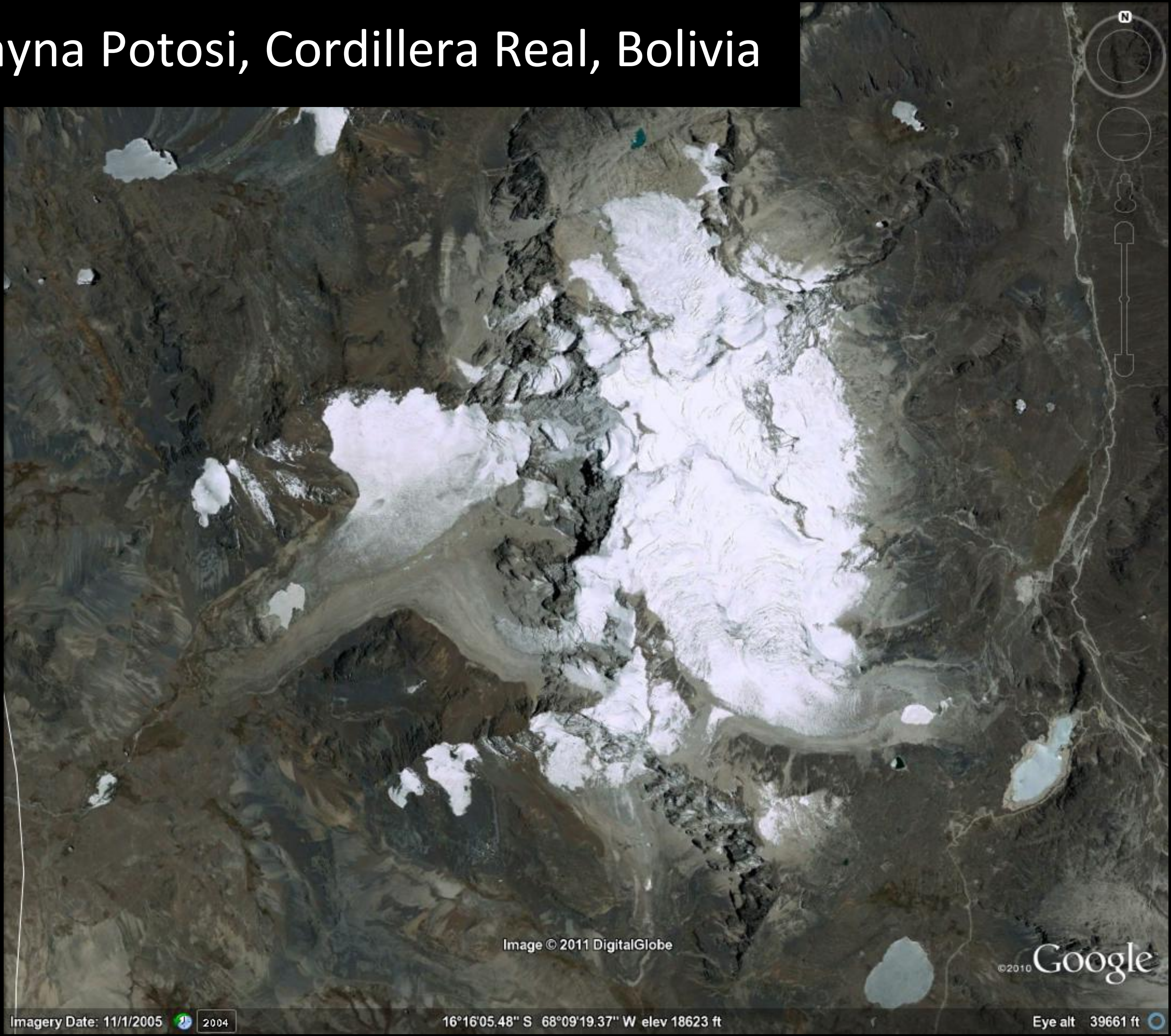


Cordillera Apolobamba
Peru - Bolivia
MSS 1979
Combined
TM 2006
Apolobamba
1979 extent: 246 km²
2006 extent: 162 km²
Melt 1979-2006 : 84 km²
= 34% over 28 years
= 1.2 % / year
= 3 km² / year
(Shadowed areas NOT included)
Lima
PE
La Paz
420000
440000
460000
480000
500000
520000
540000
8420000
8400000
8380000
8360000
8340000

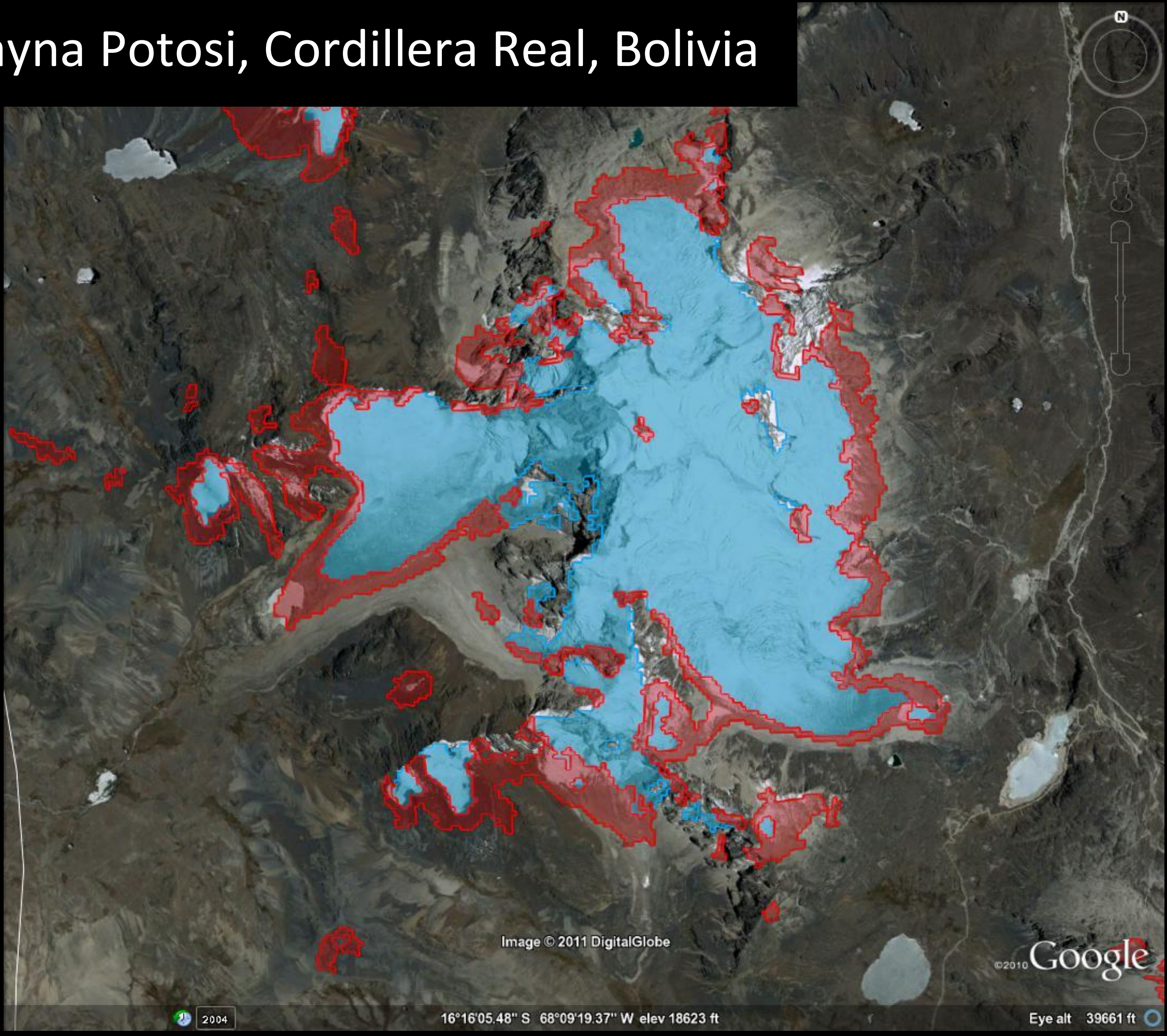
Validation

- Field visits
  - Difficult, expensive, and limited ability to assess outside point locations
- High resolution commercial imagery
  - Allows quick manual assessment of accuracy
  - Quantitative assessment requires good orthorectification
  - Expensive….except:
    - Google Earth
    - CRSSP (Commercial Remote Sensing Space Policy) acquired imagery from USGS or NGA

Huayna Potosi, Cordillera Real, Bolivia



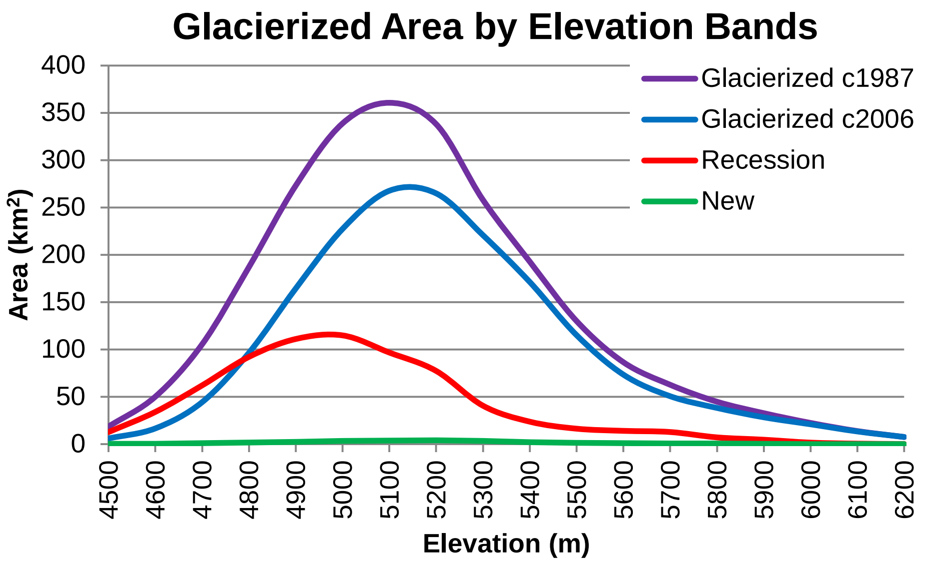
Huayna Potosi, Cordillera Real, Bolivia

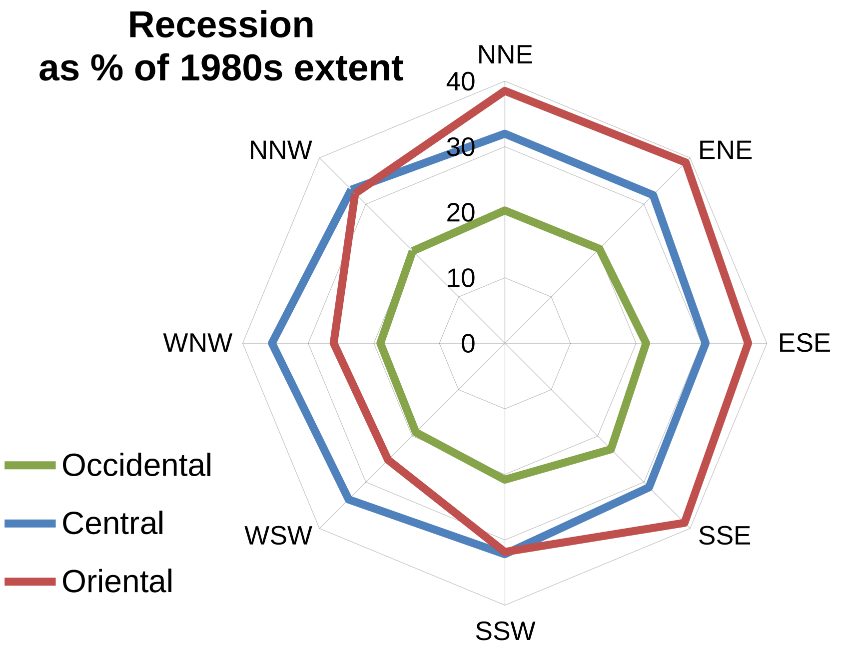


Huascaran, Cordillera Blanca, Peru

Results: c1987 – c2006

Country	Cordillera	Group	Area c1987	Area c2006	Recession km²	Recession %c87	Advance km²	Advance %c87
Bolivia	Occidental	Occidental	47.8	27.0	21.5	45.0	0.6	1.4
		Occidental +	23.8	4.7	19.9	83.7	0.8	3.3
		Total	71.6	31.6	41.4	57.9	1.4	2.0
	Oriental	Apolobamba	214.2	131.2	92.8	43.3	9.8	4.6
		C. Real North	264.9	179.2	85.9	32.4	0.2	0.1
		C. Real South	52.6	28.9	23.9	45.4	0.2	0.4
		Munecas	0.7	0.0	0.7	100.0	0.0	0.0
		N Sta Vera Cruz	1.1	0.7	0.4	37.6	0.0	0.0
		Tres Cruces	39.3	29.8	9.5	24.1	0.0	0.0
		Total	572.8	369.9	213.1	37.2	10.3	1.8
	Total		644.4	401.5	254.5	39.5	11.7	1.8
Peru	Central	Huaytapallana	40.1	24.5	16.0	39.9	0.4	1.0
		La Raya	7.3	0.7	6.6	90.7	0.0	0.0
		Vilcabamba	193.6	137.9	56.0	28.9	0.3	0.1
		Total	241.0	163.1	78.6	32.6	0.7	0.3
	Occidental	Ampato	76.0	59.5	17.3	22.7	0.8	1.1
		Barroso	1.6	0.0	1.6	100.0	0.0	0.0
		Blanca	562.6	494.3	72.2	12.8	3.8	0.7
		Central	64.3	45.6	19.1	29.6	0.4	0.6
		Chila	3.2	1.4	2.1	64.2	0.2	7.2
		Chonta	2.7	1.1	1.6	60.1	0.0	0.0
		Huallanca	12.5	7.4	5.1	41.1	0.0	0.0
		Huanzo	16.8	13.9	4.1	24.4	1.2	7.4
		Huayhuash	58.5	48.1	10.8	18.5	0.4	0.7
		Raura	49.3	33.1	16.2	32.9	0.0	0.0
		Volcanica	1.7	1.9	0.5	28.1	0.7	40.3
		Total	849.0	706.2	150.4	17.7	7.6	0.9
	Oriental	Apolobamba	96.7	47.1	52.5	54.3	2.9	3.0
		Carabaya	31.2	22.8	8.5	27.3	0.1	0.3
		Huagaruncho	16.3	10.6	5.7	34.9	0.0	0.0
		Urubamba	56.1	38.4	17.8	31.7	0.1	0.2
		Vilcanota	422.3	326.8	95.8	22.7	0.3	0.1
		Total	622.6	445.7	180.3	29.0	3.4	0.5
	Total		1712.7	1315.0	409.3	23.9	11.6	0.7
Total			**2358**	**1717**	**664**	**28%**	**23**	**1%**



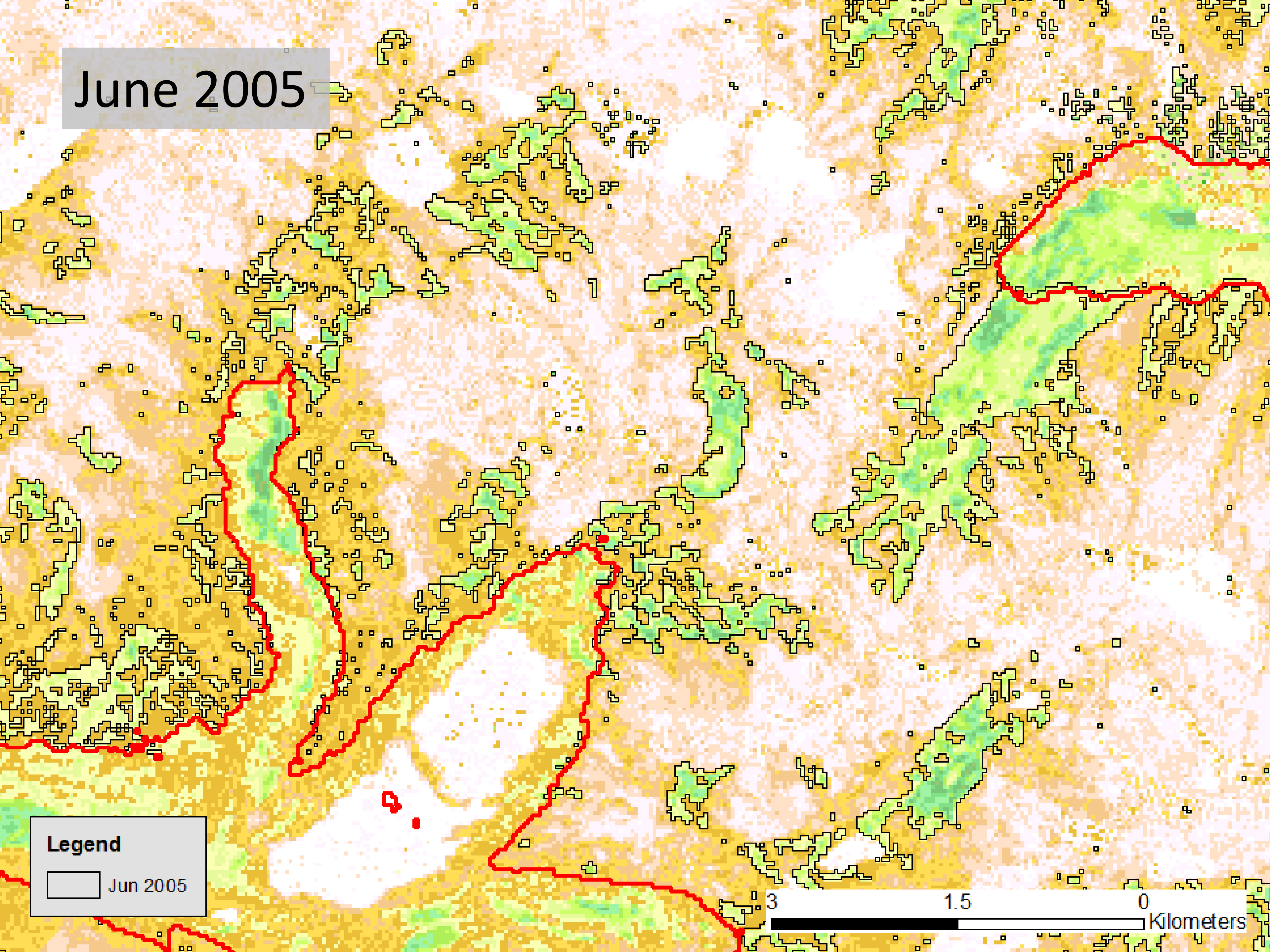


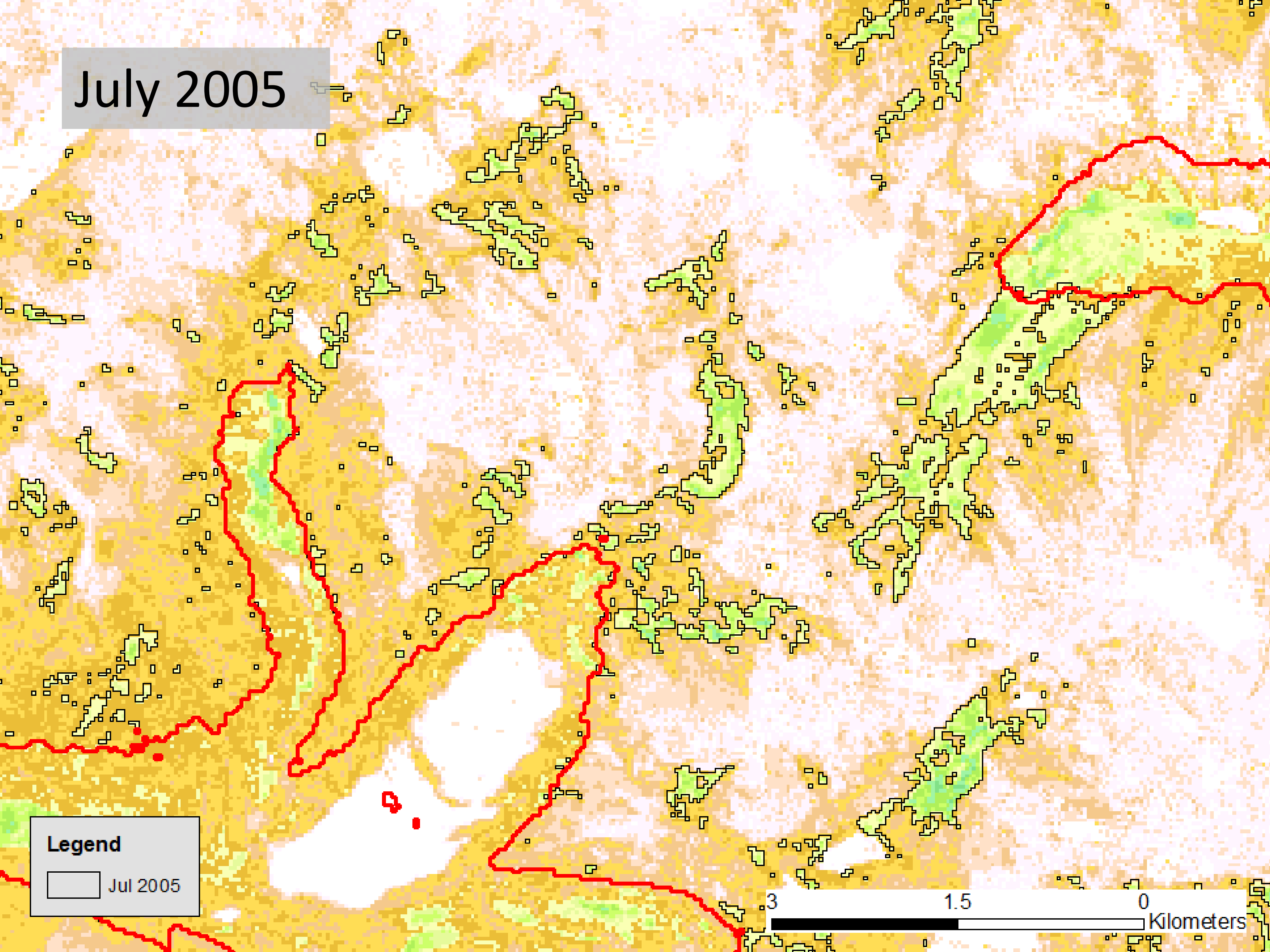
Summary

- All glaciers receded
- Total area 2,500 km^2 → 1,800 km^2
- ~28% area loss in 20 years
- Differences associated with elevation and aspect.

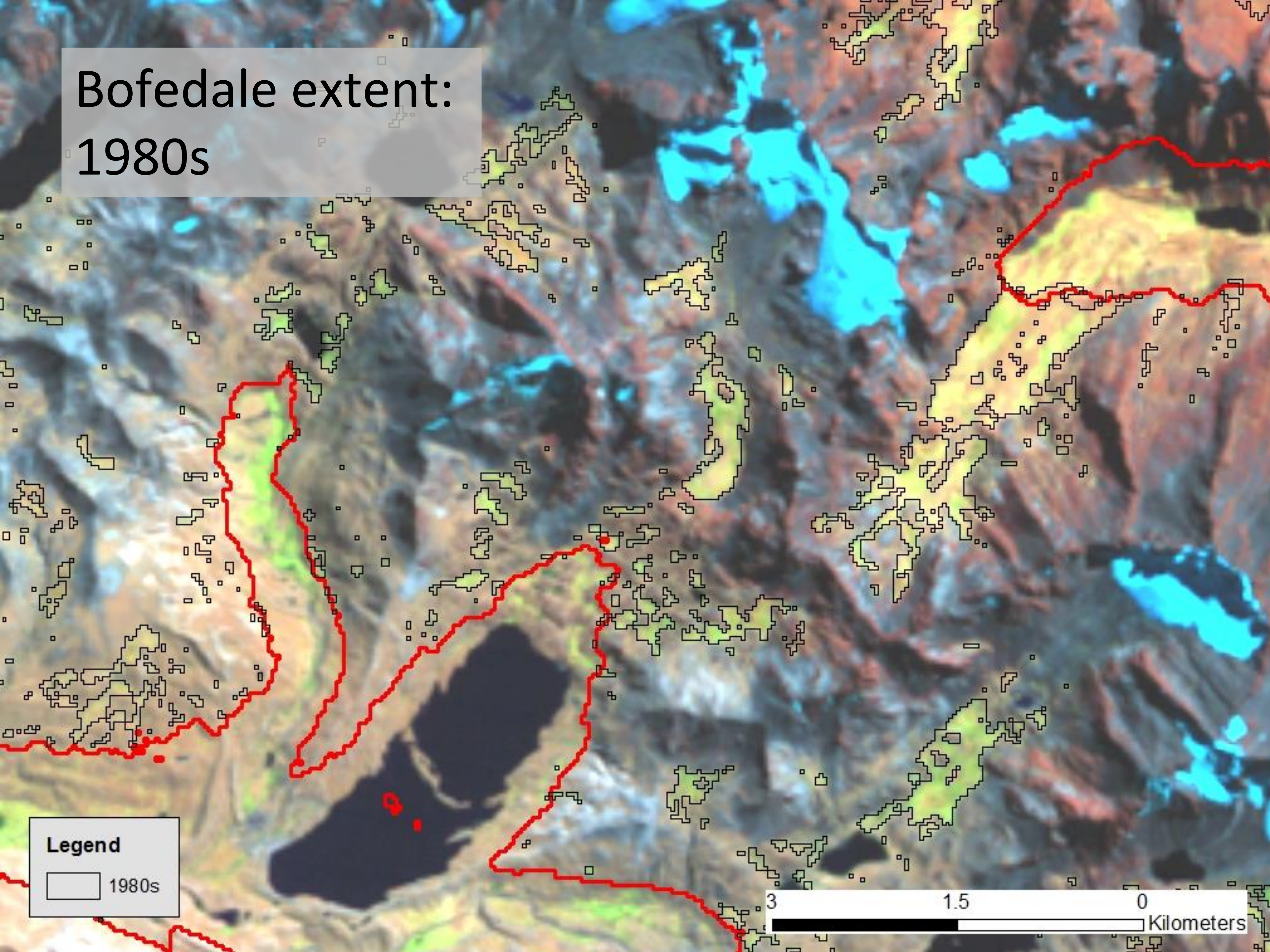
Bofedale Extent

- Where are they??
  - No existing regional maps of bofedale extent
  - Limited maps from local studies
- Approach
  - Elevation and NDVI thresholds
  - Identify areas that maintain greenness throughout dry season
    - Differentiates from dryer grasses and annual vegetation
    - Indicates suitable dry-season pasturage
  - Landsat: monthly dry-season images (May – October)
  - Currently evaluating:
    - Constant NDVI-based threshold
    - SVM approach trained with data from conservative thresholding
  - Validation: field sites, and high resolution imagery

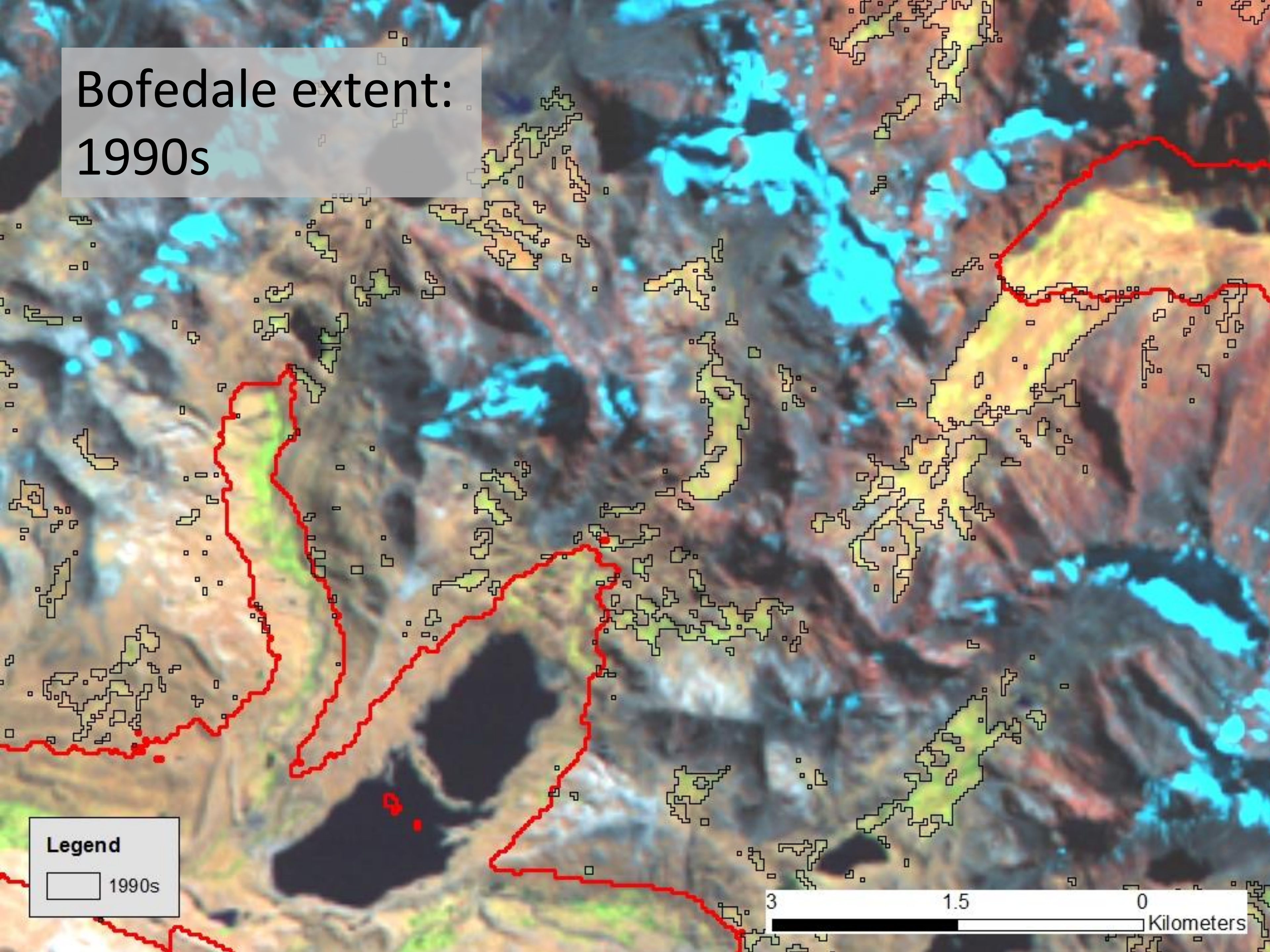

June 2005
Legend
Jun 2005
3
1.5
0
Kilometers



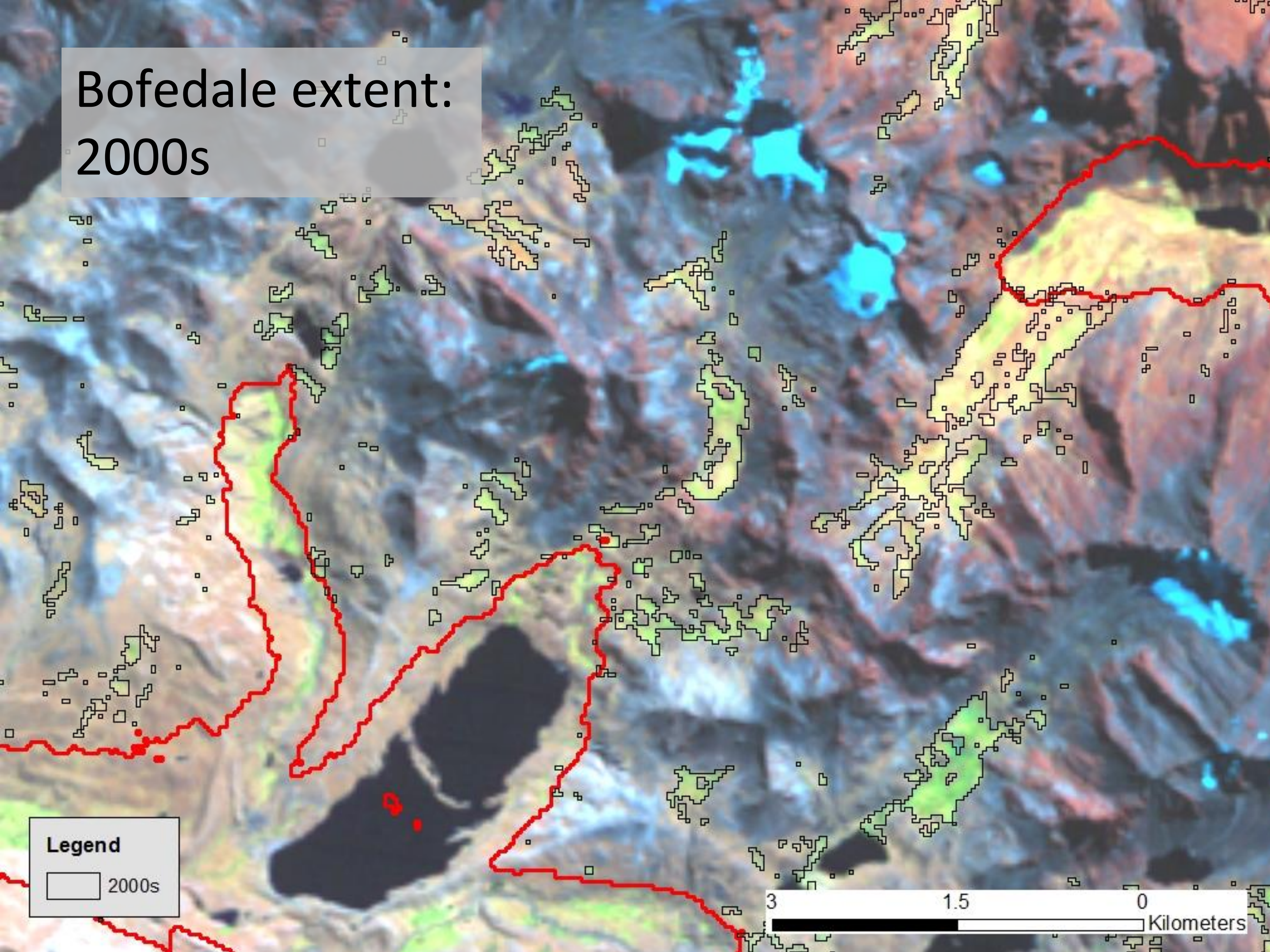
July 2005
Legend
Jul 2005
3
1.5
0
Kilometers


Bofedale extent:
1980s
Legend
1980s
3
1.5
0
Kilometers

Bofedale extent: 1990s



Bofedale extent: 2000s

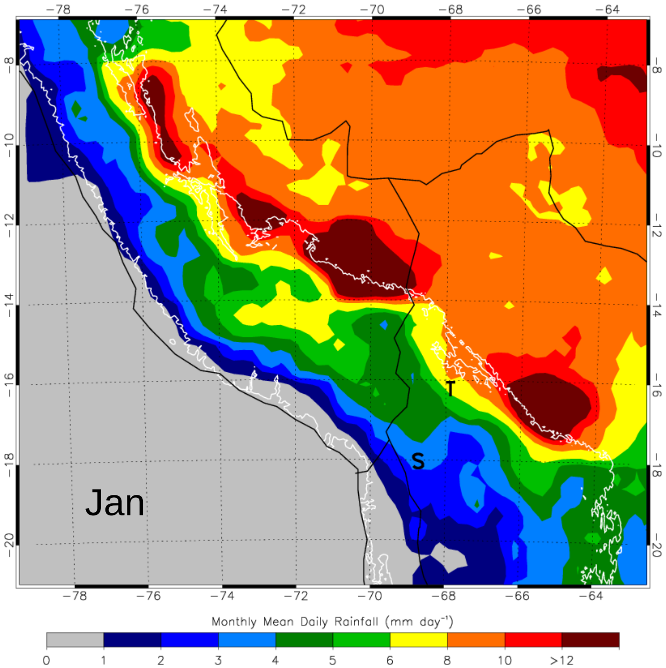


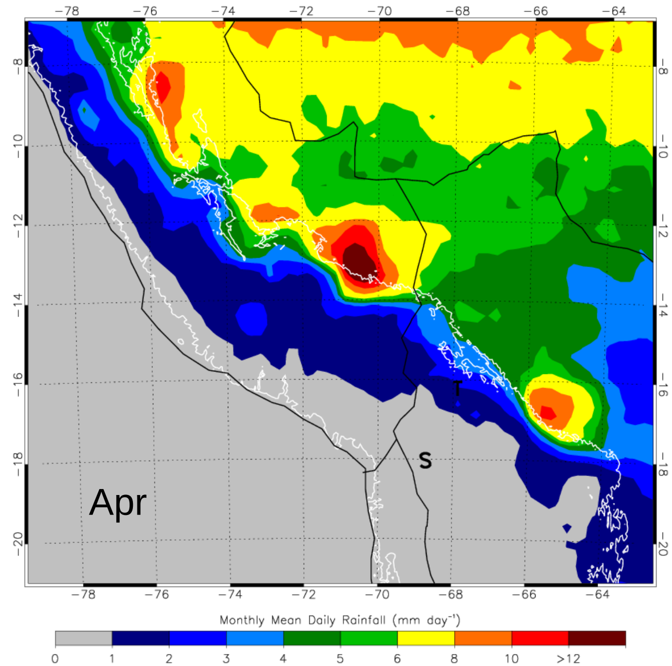
Mesoscale Meteorology

- Boring area meteorologically, dominated by small storms. Poorly studied.

- TRMM: reasonable approximation of precipitation distribution (if overpredicting raw amounts).
- Precipitation that does fall currently is ideal for maintenance of the bofedales: light and frequent.
- Change to heavy and less frequent might be disastrous for bofedales

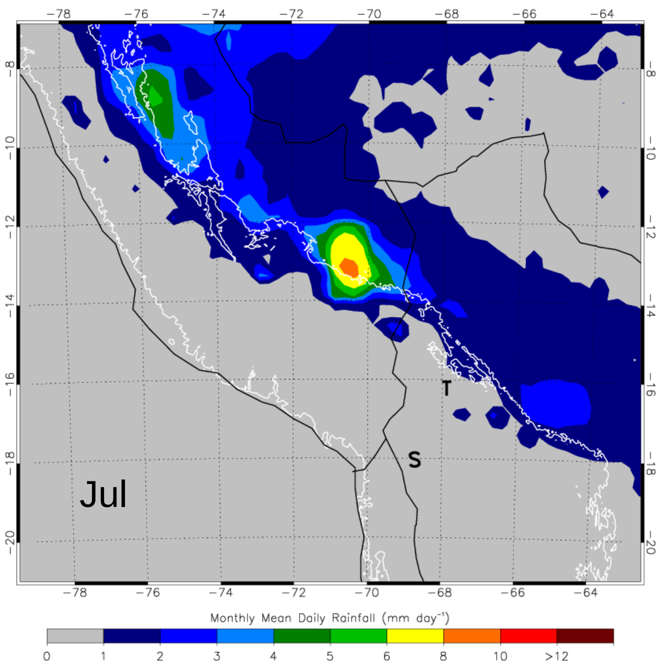
Seasonal Rainfall: TRMM 3B43

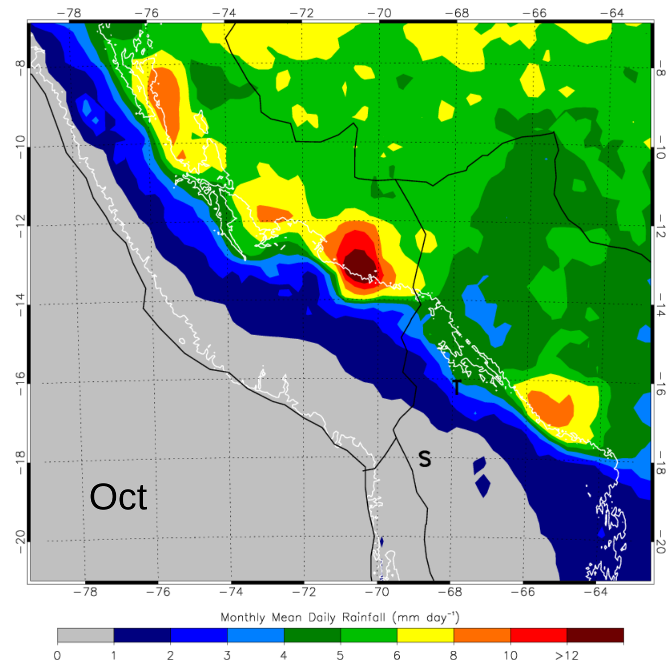




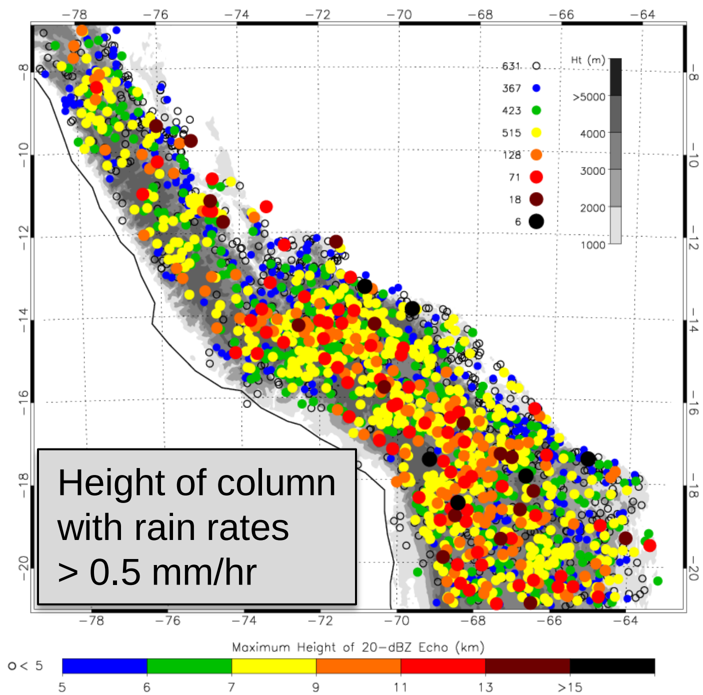
- White contour = 3000 m elevation
- Heaviest rainfall is east of 3000 m contour.
- Longer wet season in Tuni (T) than Sajama (S)

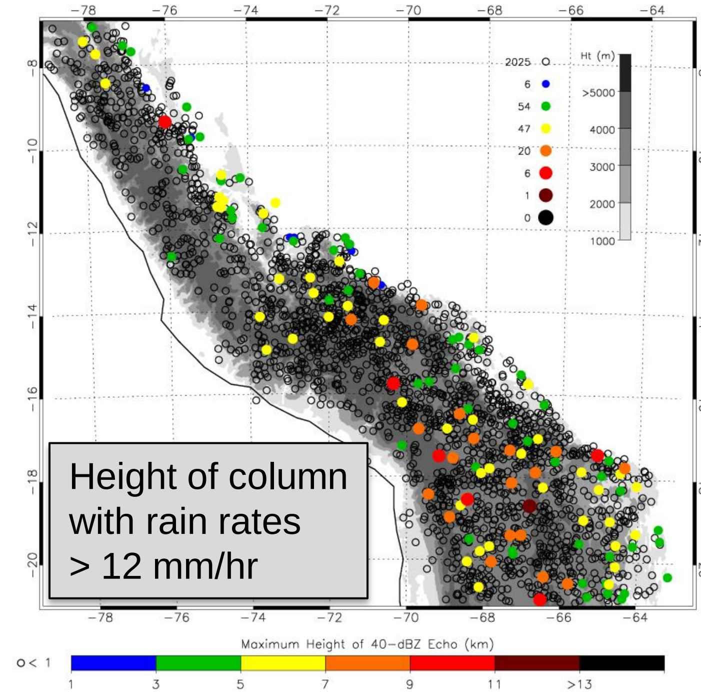
➡TRMM appears to be reasonable approximation of regional precipitation

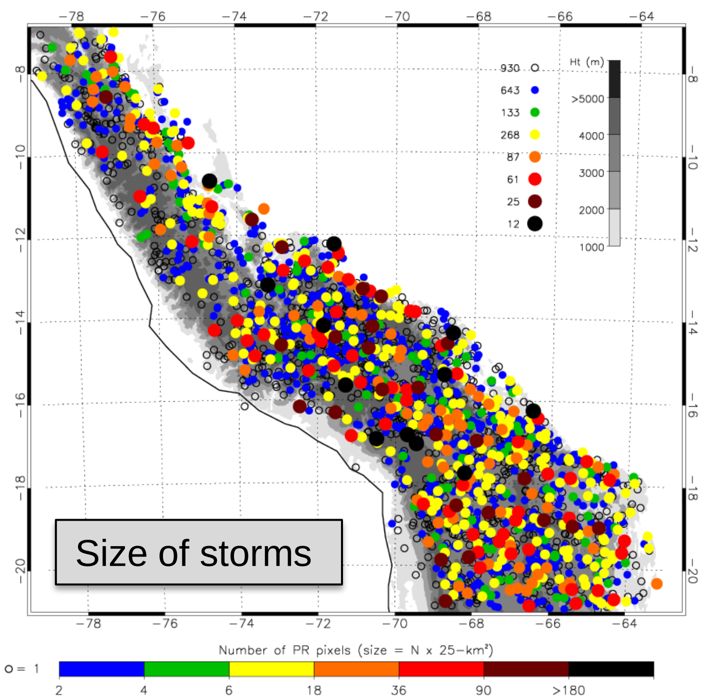




Storm Size and Intensity: TRMM PFs (precipitation features)

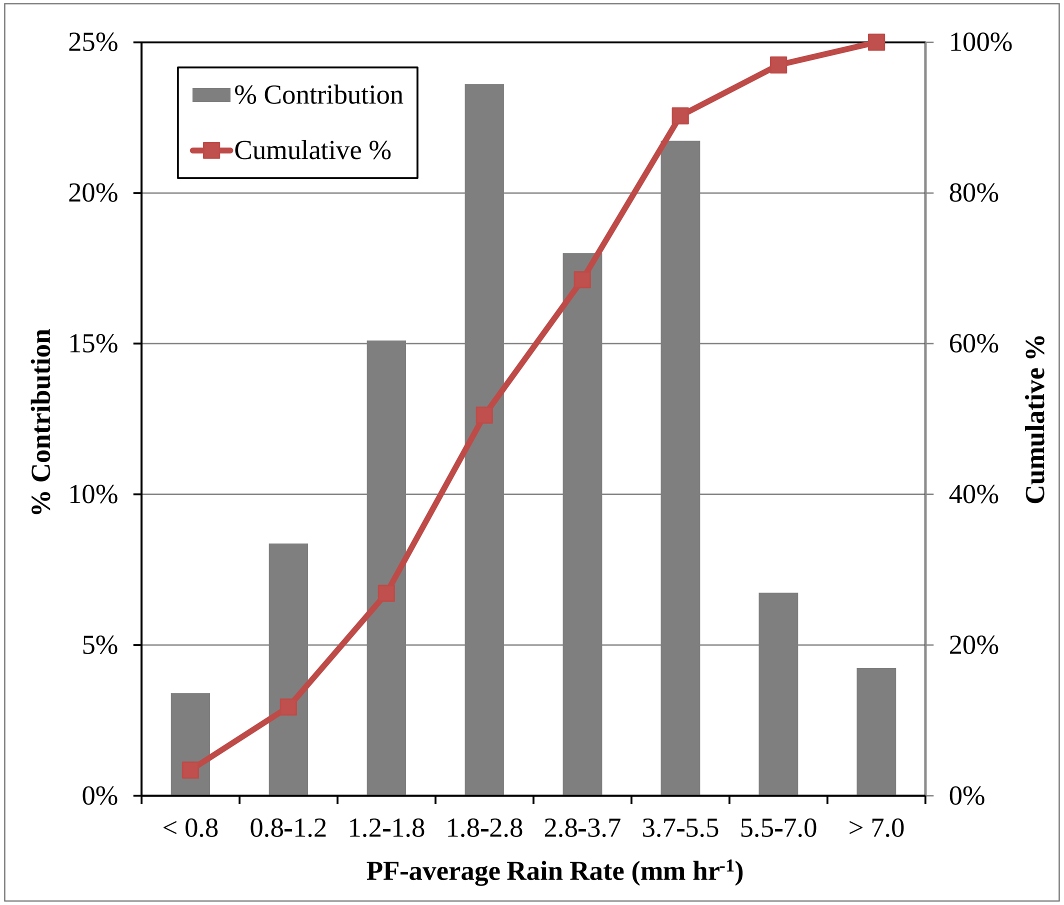






- January 2004, ENSO neutral, close to seasonal mean, an illustrative example of the distribution of precipitation features (PFs)
- The larger, stronger PFs are more likely to occur
  - On the eastern side, 3000 m >
  - Around the Altiplano
  - On the western side, > 4000 m (locally highest peaks)
- < 10% of the PFs produce moderate (12 mm/hr) or higher rain rates (all years).

Rainfall Contribution vs. Rain Rate



% Contribution = <u>(total rainfall in rain rate bin)</u>
(total rainfall in all bins)

- The majority of the annual rainfall in the Central Andes occurs at rain rates defined by the NWS as "moderate" (5.6 mm/hr) or lighter.
- The largest contribution is at light rain rates (1.8-2.8 mm/hr), about 15% of the PF population.
  - PFs with heavy (> 23.7 mm/hr) rainfall are about 0.05% of the PF population and 2% of the contribution.
- Percentile rankings

  0.8 = 25th

  1.2 = 50th

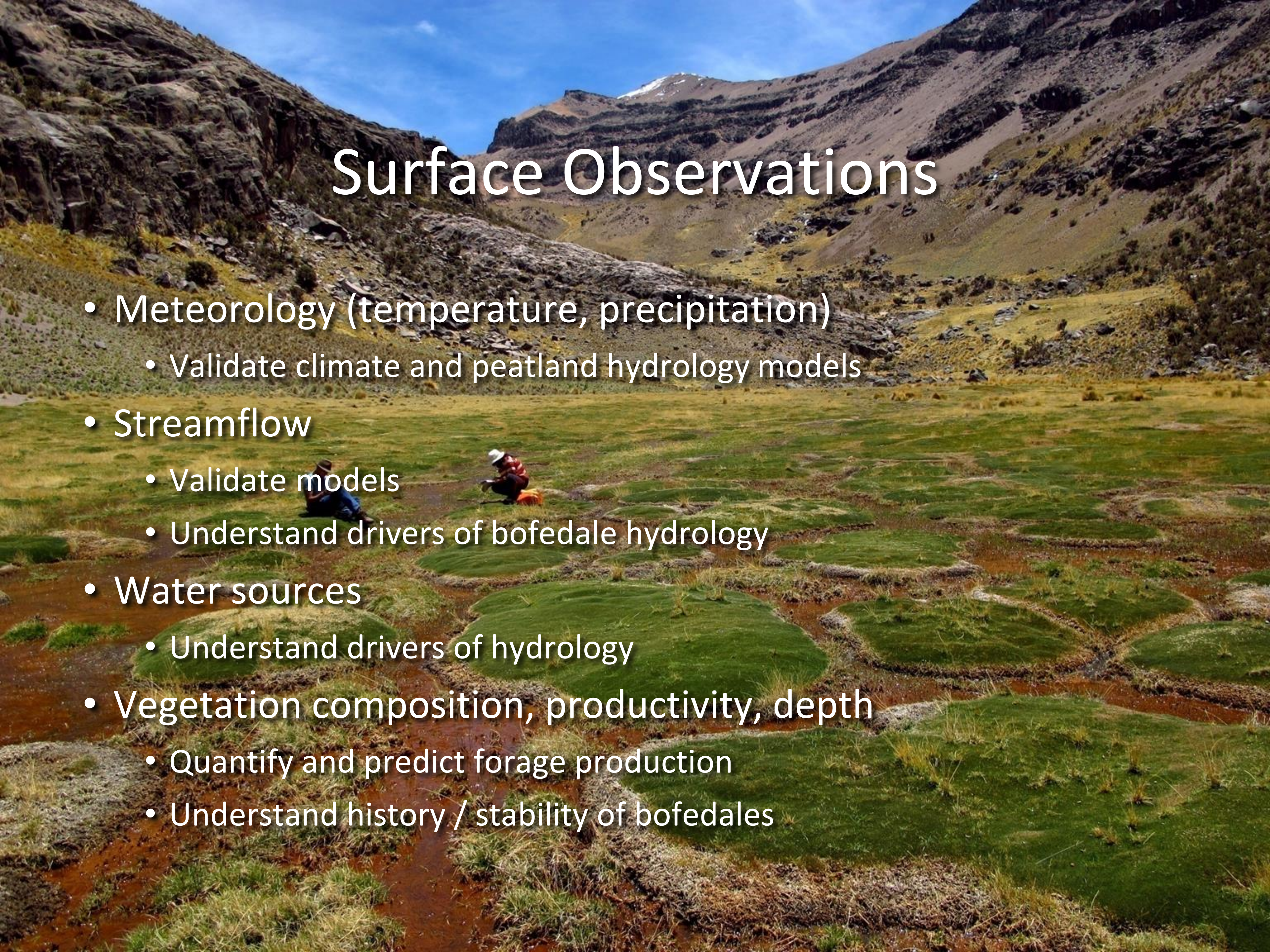
  1.8 = 75th

  2.8 = 90th

  3.7 = 95th

  5.5 = 98th

  7.0 = 99th



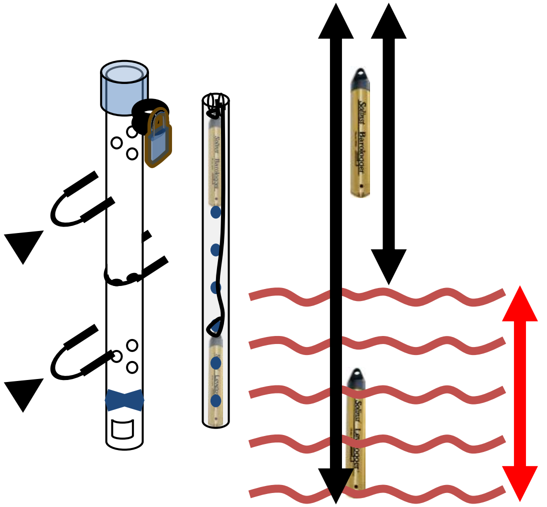
Surface Observations

- Meteorology (temperature, precipitation)
  - Validate climate and peatland hydrology models
- Streamflow
  - Validate models
  - Understand drivers of bofedale hydrology
- Water sources
  - Understand drivers of hydrology
- Vegetation composition, productivity, depth
  - Quantify and predict forage production
  - Understand history / stability of bofedales

Surface Meteorology

- Critically important to understand what's going on at bofedale and glacier elevations
- Some existing data, mostly from lower elevations (dams, power companies, govt. agencies). Intermittent, & golden age is past.
- Difficult: expensive, maintenance, protection
- Deployment:
  - Full weather stations (mostly by collaborators)
    - Tuni, Sajama, Chacaltaya, Blanca
  - Mini-stations: temp, precip, RH
    - 2 sites plus additional via collaborators
    - Security issue

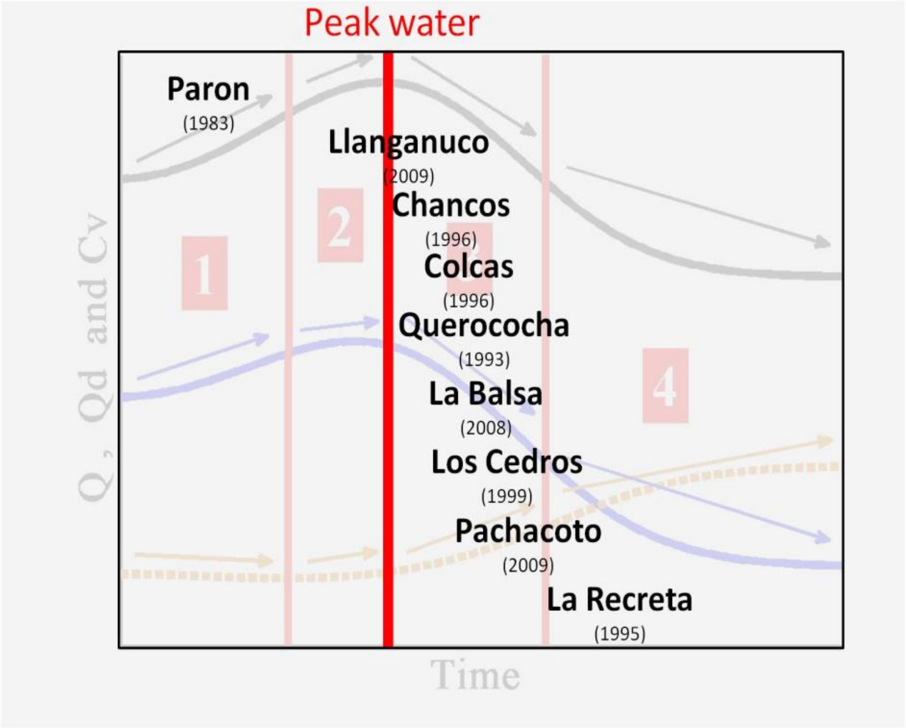
Stream gauges


M. Baraer

- Pressure loggers installed in streams to record streamflow variations
- Installed in 3 Bolivia sites
- Several more in C. Blanca maintained by Co-I Mark/OSU

Passing "peak water"

Seven of the nine study watersheds in Cordillera Blanca have crossed a critical transition, and now exhibit decreasing dry season discharge.



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Glacier recession and water resources in Peru's Cordillera Blanca

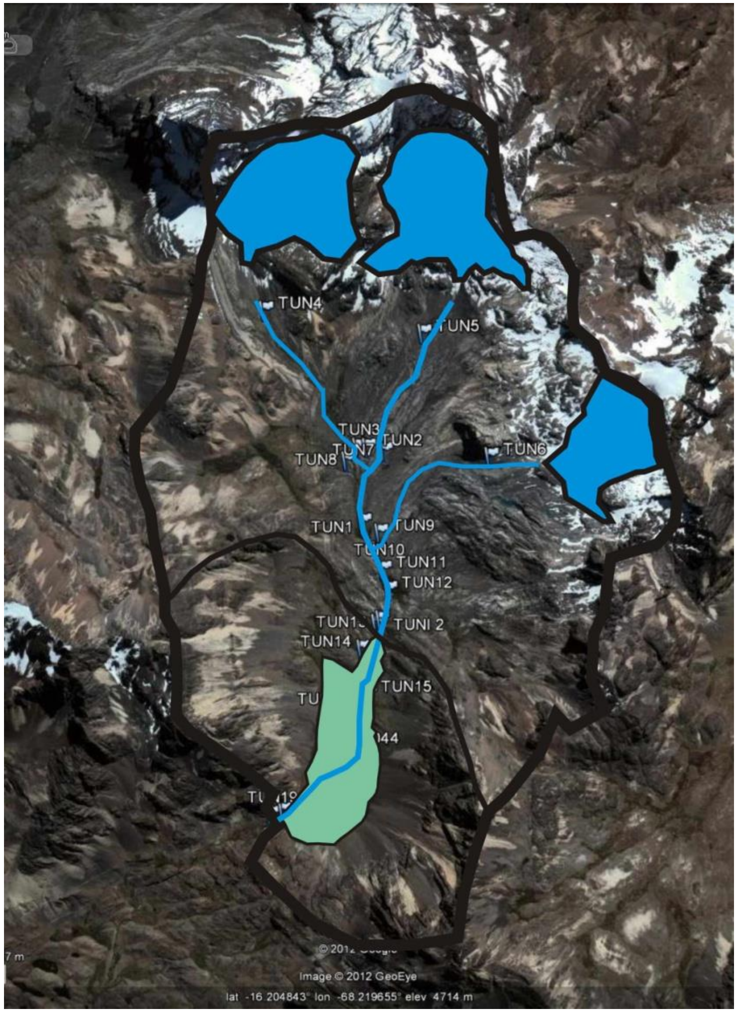
Michel BARAER,[1] Bryan G. MARK,[2] Jeffrey M. McKENZIE,[1] Thomas CONDOM,[3] Jeffrey BURY,[4] Kyung-In HUH,[2] Cesar PORTOCARRERO,[5] Jesús GÓMEZ,[5] Sarah RATHAY[1]

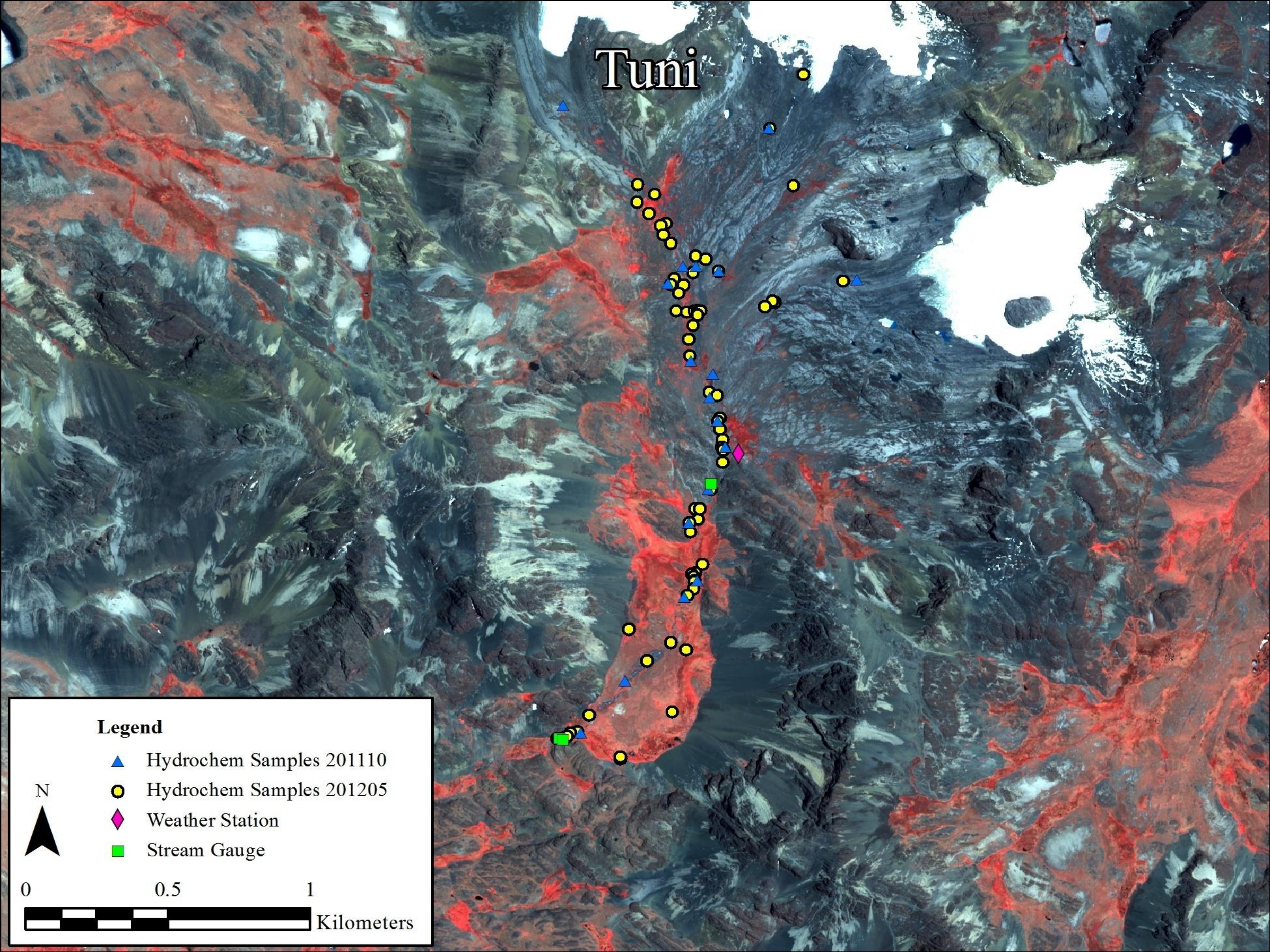
Water sources

- Key question: where does the water come from that sustains the bofedales?

  Glacier melt? Groundwater? Precipitation?
- Install network of shallow wells to monitor water levels in bofedales
- Use natural chemical and isotopic tracers with Michel Baraer's Hydrochemical Basin Characterization Method (HBCM) to identify glacier meltwater contribution

  Test water samples from many sites for isotopes (^{18}O, ^{2}H), anions, and cations.




Tuni
Legend
Hydrochem Samples 201110
Hydrochem Samples 201205
Weather Station
Stream Gauge
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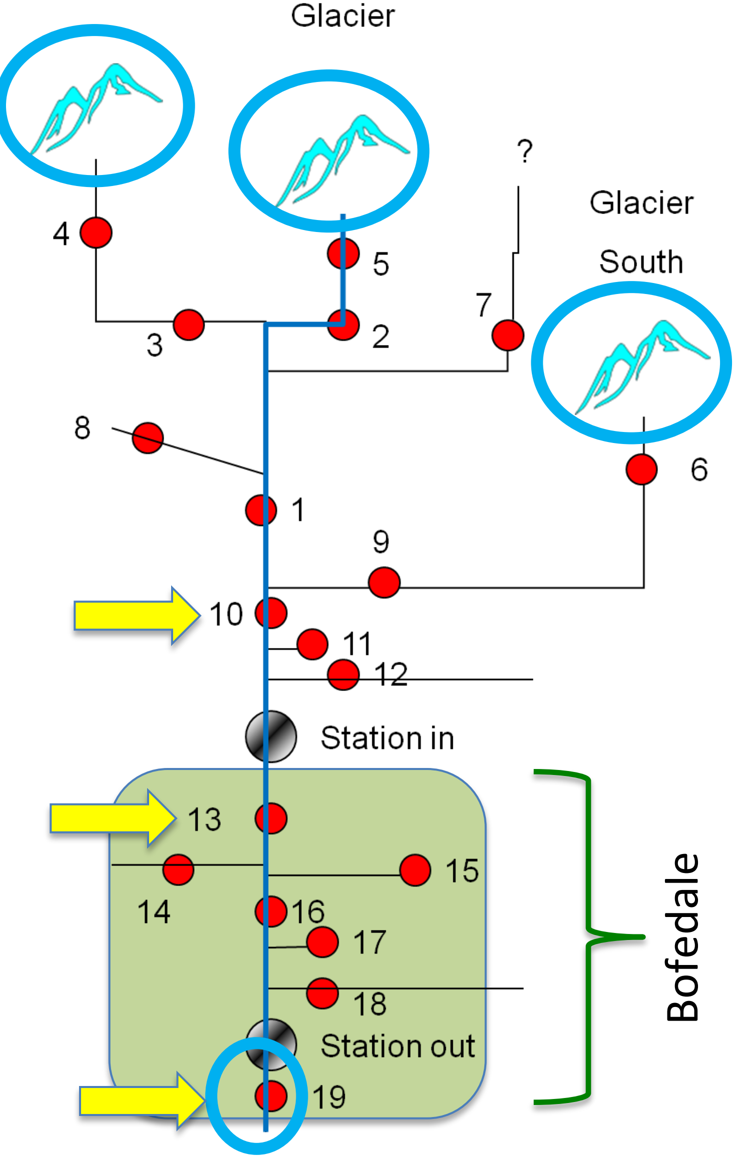
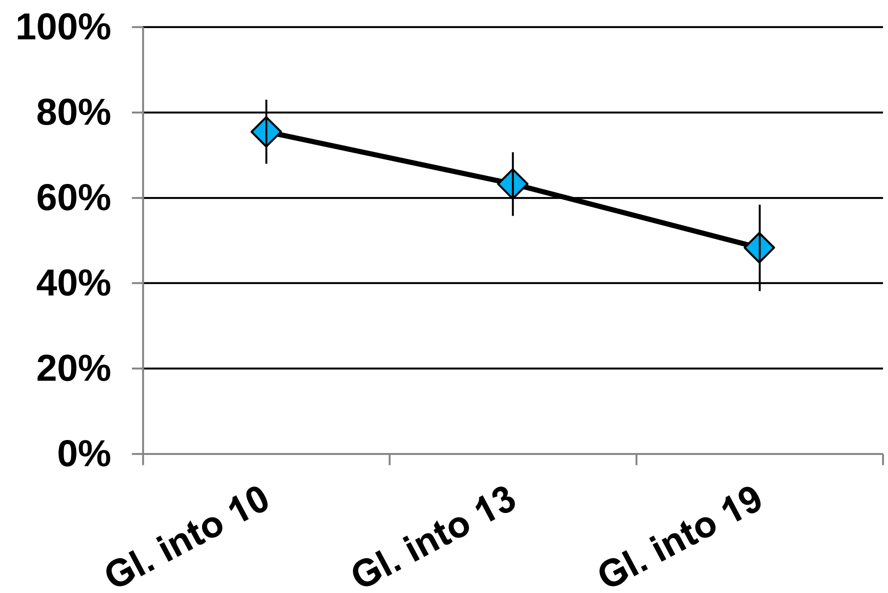
HBCM Results



1. Glacier contribution to stream



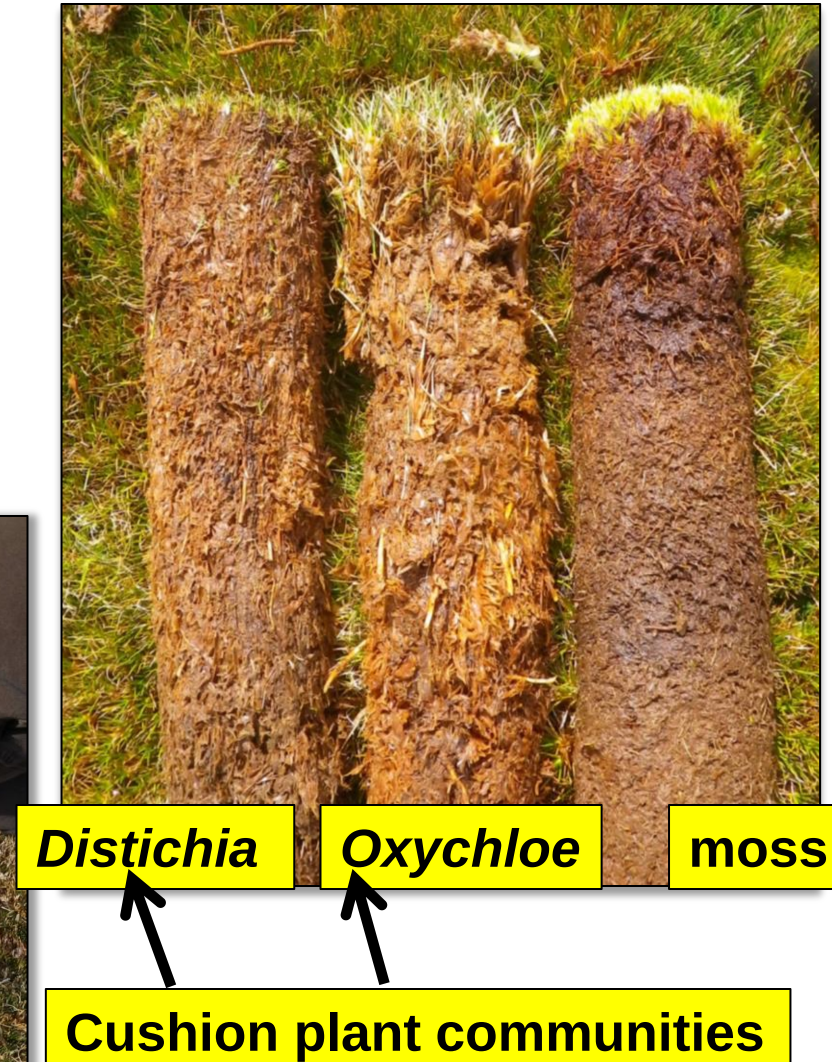
2. Bofedale contribution to stream: 50% at bofedale outlet
3. Glacier contribution to bofedale sites off main stream:
   ➔ Minimal!

Vegetation Surveys

Surveys of vegetation communities at sites with differing hydrologic support (glacier, precipitation, groundwater) to measure:

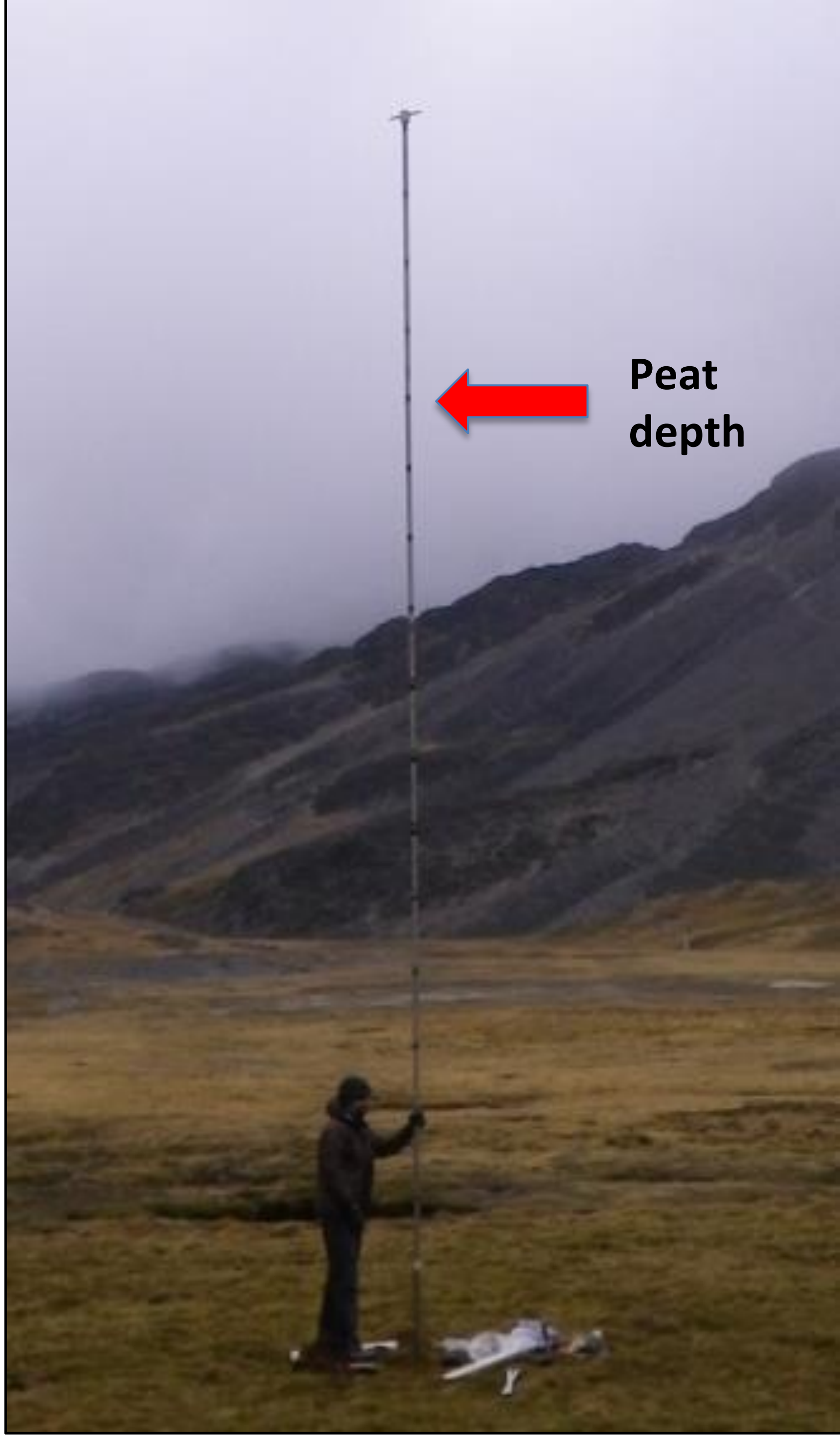
- **Species composition and diversity**
- **Net primary production**
- **Net ecosystem exchange (carbon storage)**
- **Overgrazing impacts**

Unique mountain peatland plant communities and high water table can create *extremely dense & fibric peat*



Bofedales Vertically

- Questions:
  - How deep?
  - How old?
  - Are they stable?
  - Peat/carbon storage?
  - How have they changed over time in composition?
- Depth probes: some > 10 m
- Cores for detailed analysis (John Hribljan, Michigan Tech)
  - Prelim dating: 2500 years @ 6m



Summary

- Factors affecting bofedales and thus the dependent pastoral agriculture:
  - Hydrologic support more dependent on rainfall than glacier melt
  - Increased glacier outwash directly damaging via silt deposition and erosive undercutting
  - Overgrazing
- Modeling will help predict future impacts of changing precip and glacier melt streams
- Bofedale response:
  - Data not yet in on extent
  - Vegetation characteristics and productivity in process…
  - Differential response of those associated with glaciers?


Questions?