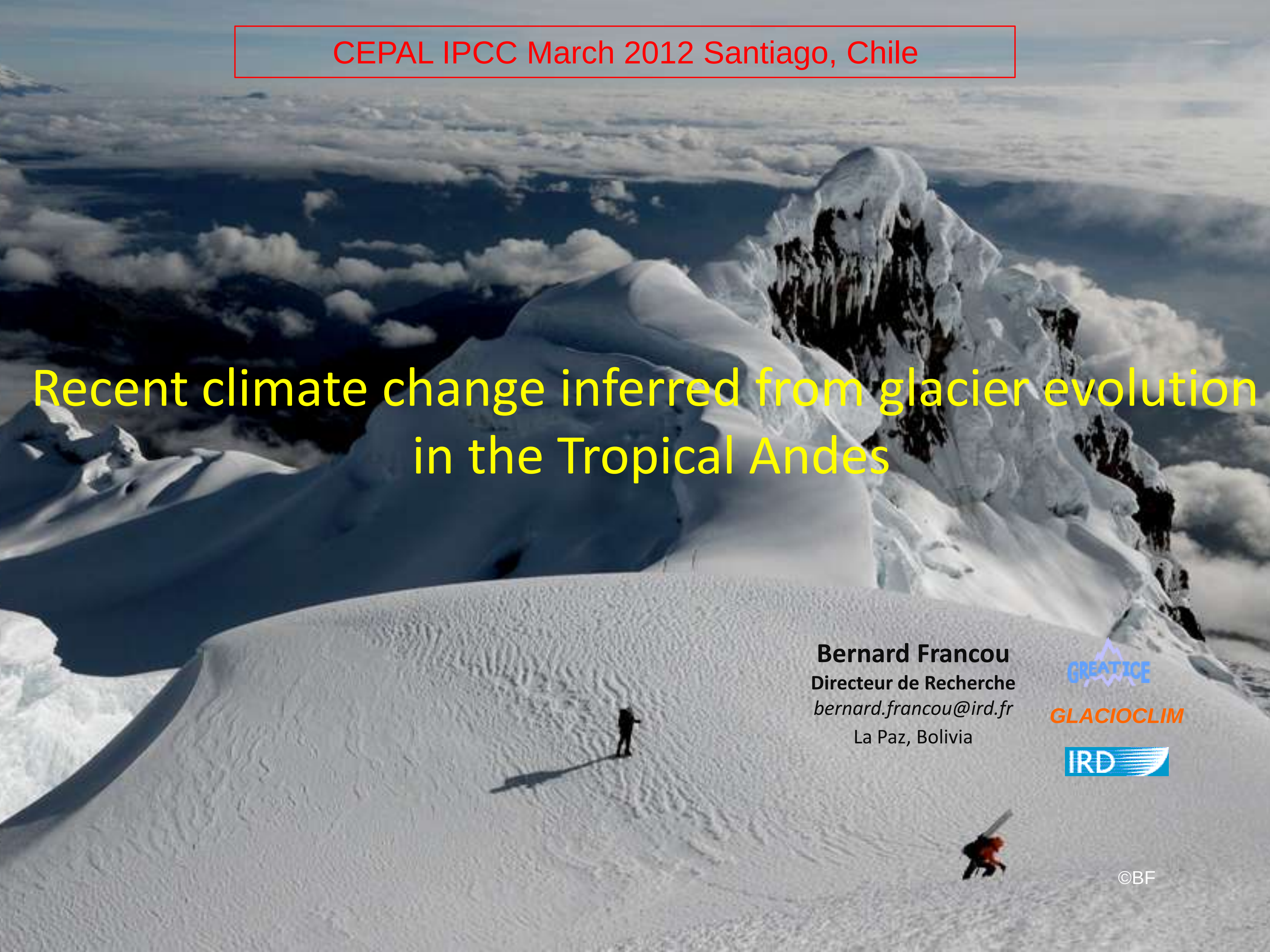
CEPAL IPCC March 2012 Santiago, Chile



Recent climate change inferred from glacier evolution in the Tropical Andes

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La Paz, Bolivia

GREAT ICE

GLACIOCLIM

IRD

©BF

GLACIOCLIM, a global network

French Alps (LGGE)

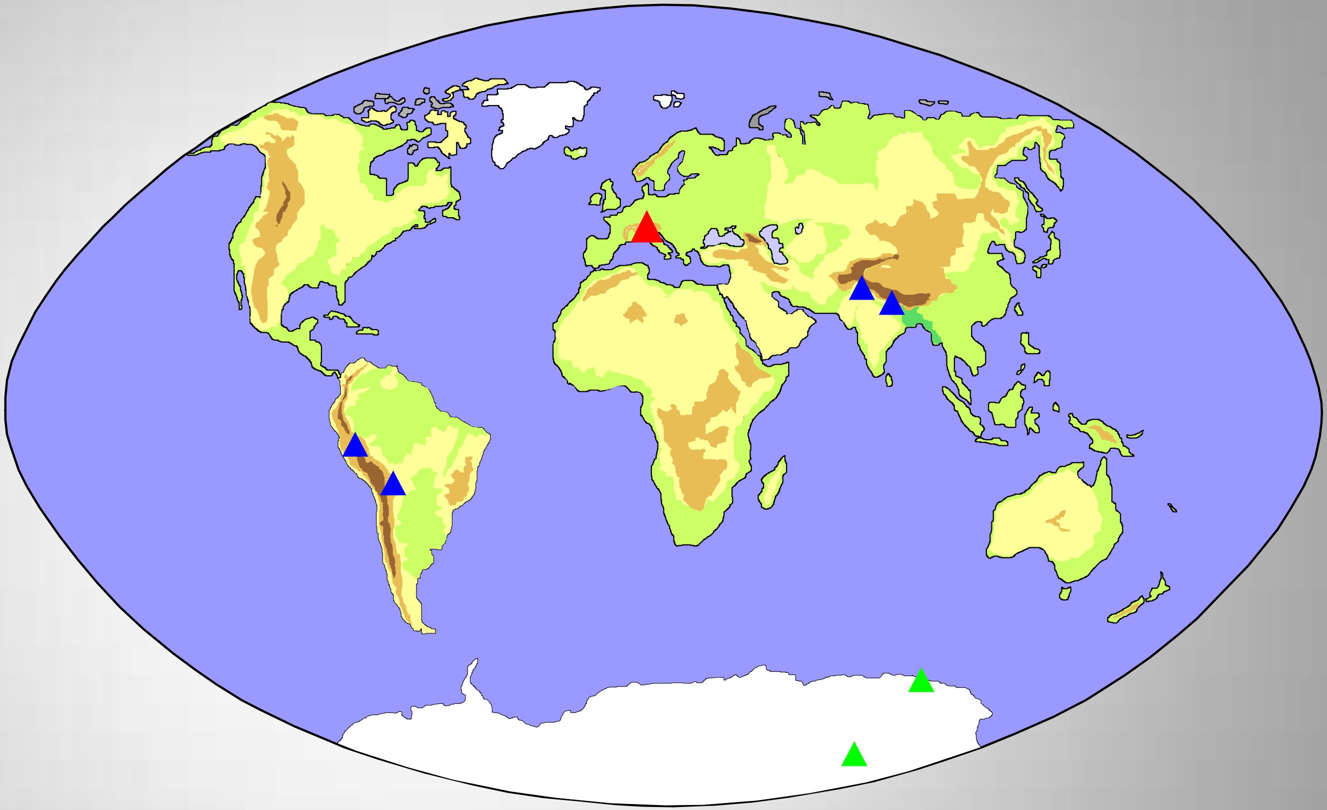
Saint Sorlin, Argentière (45°N)
Gébroulaz, Mer de Glace,
Sarennes

Andes / Himalaya (IRD et local partners)

Antizana (Ecuador, 0°)
Zongo (Bolivia, 16°S)
Chhota Shigri (India, 32°N)
Mera (Nepal, 27°N)

Antarctica (LGGE-IPEV)

Cap Prud'Homme (67°S)
Dôme C (75°S)

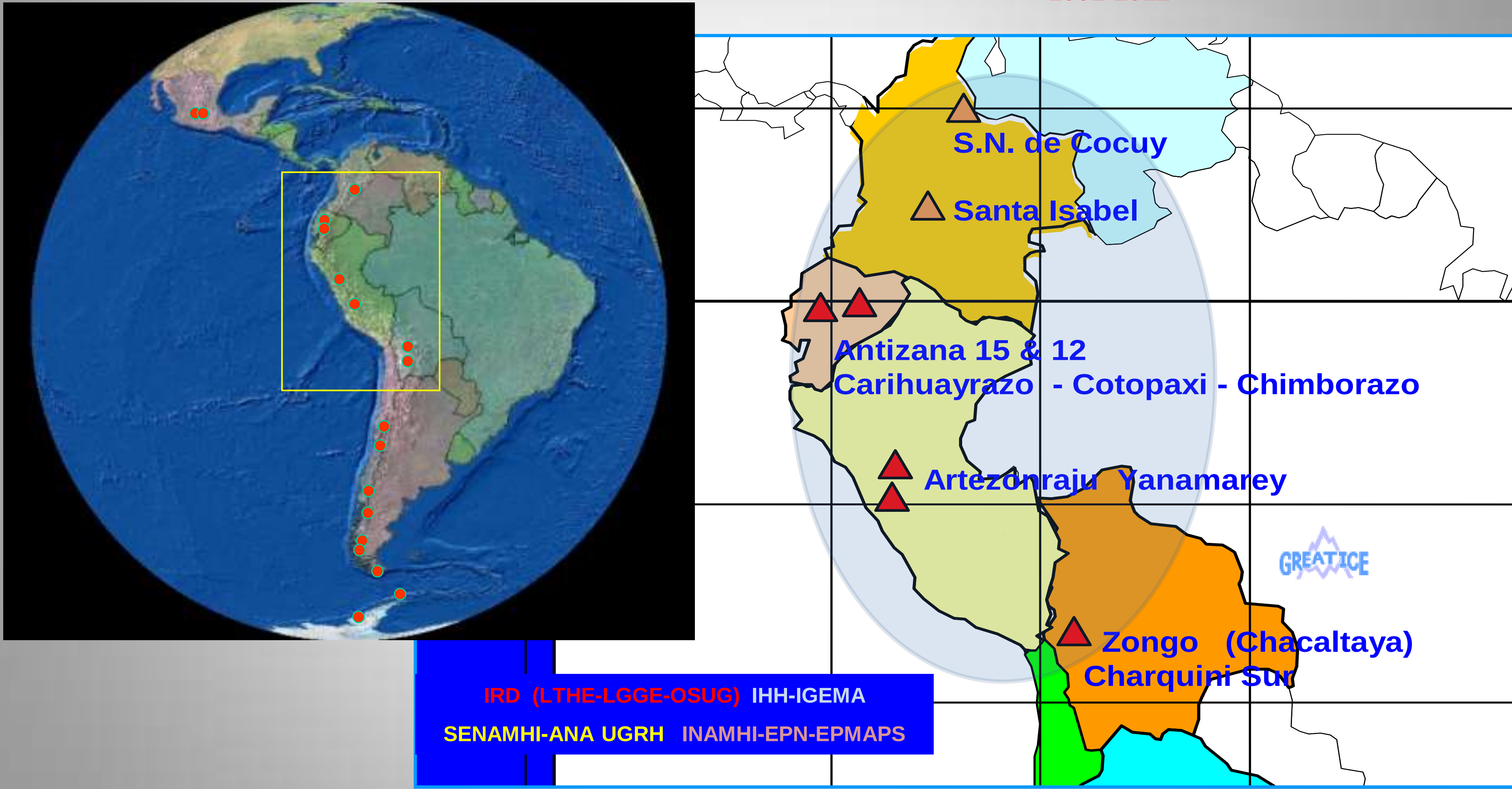


A (French) Global network including glacio-meteo-hydrological observations :
>50 yrs (Alps), >20 yrs (Andes), 8 yrs (Himalaya) et 7 yrs (Antarctica)

http://www-lgge.ujf-grenoble.fr/ServiceObs/index.htm

Data generation

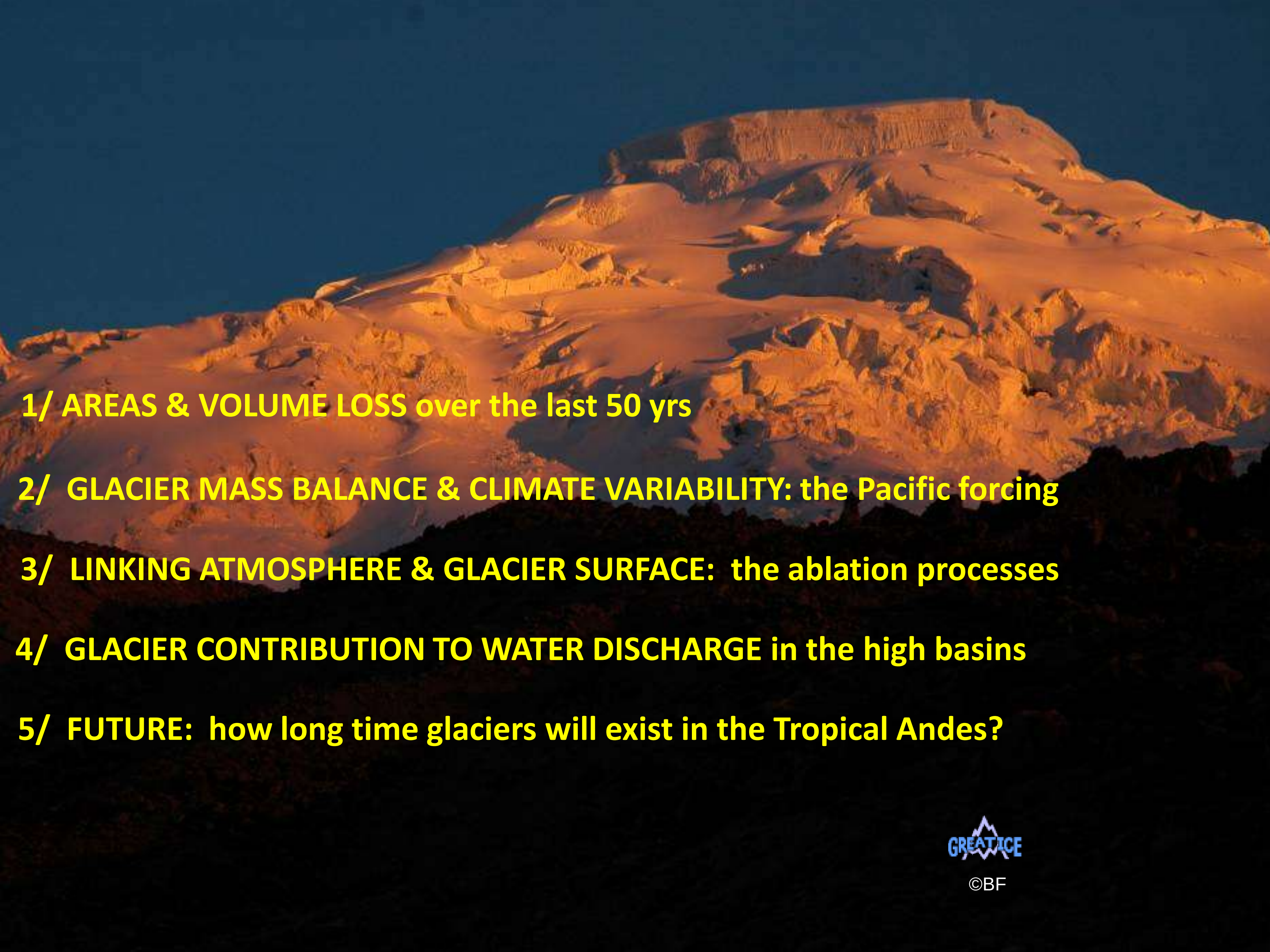
GLACIER MONITORING NETWORK
1991-2012



IRD (LTHE-LGGE-OSUG) IHH-IGEMA

SENAMHI-ANA UGRH INAMHI-EPN-EPMAPS

GLACIOCLIM



1/ AREAS & VOLUME LOSS over the last 50 yrs

2/ GLACIER MASS BALANCE & CLIMATE VARIABILITY: the Pacific forcing

3/ LINKING ATMOSPHERE & GLACIER SURFACE: the ablation processes

4/ GLACIER CONTRIBUTION TO WATER DISCHARGE in the high basins

5/ FUTURE: how long time glaciers will exist in the Tropical Andes?

GREATICE

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1/ AREAS & VOLUME LOSS OVER THE LAST 50 YR

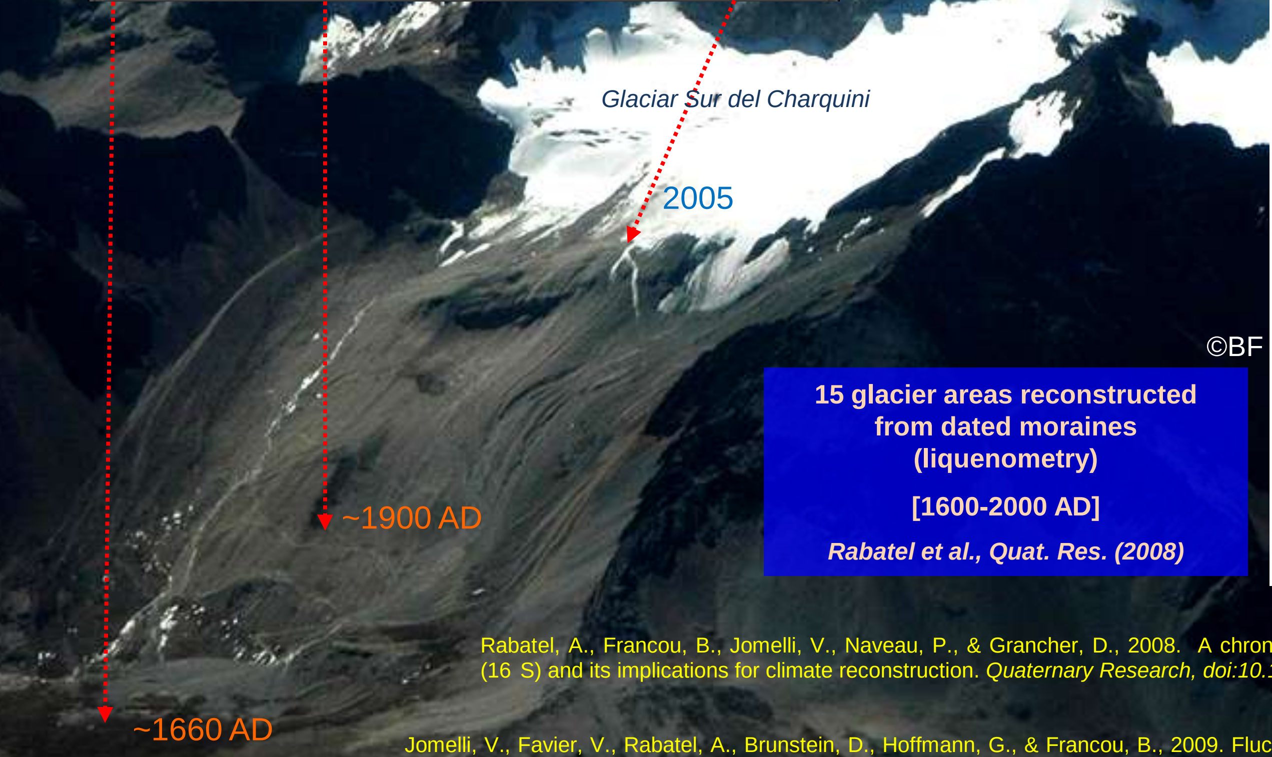
©BF

Ritacuba Blanca SN Cocuy/Colombia

1/ Area & Volume loss over the last 50 yr

In the Central Andes, glacier depletion is a century-scale phenomena But its intensity increased since 30-50 years (Jomelli, 2005; Rabatel, 2005)

~10 morrenas datadas en Bolivia

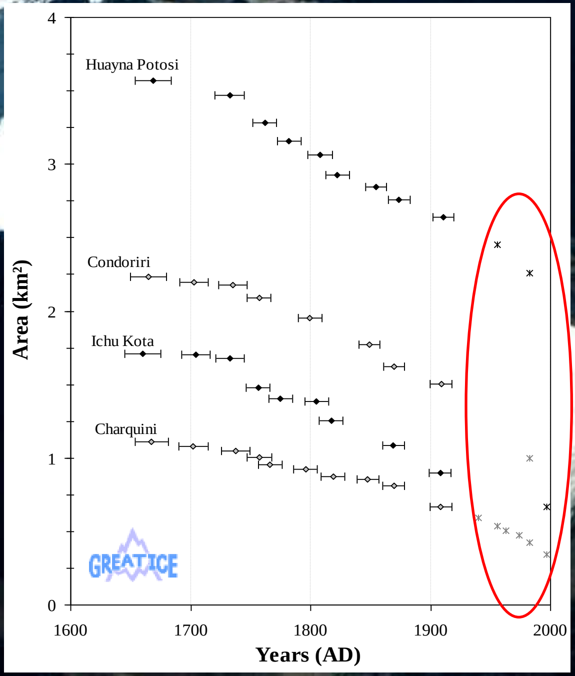


15 glacier areas reconstructed from dated moraines (liquenometry)

[1600-2000 AD]

Rabatel et al., Quat. Res. (2008)

Cordillera Real - Bolivia

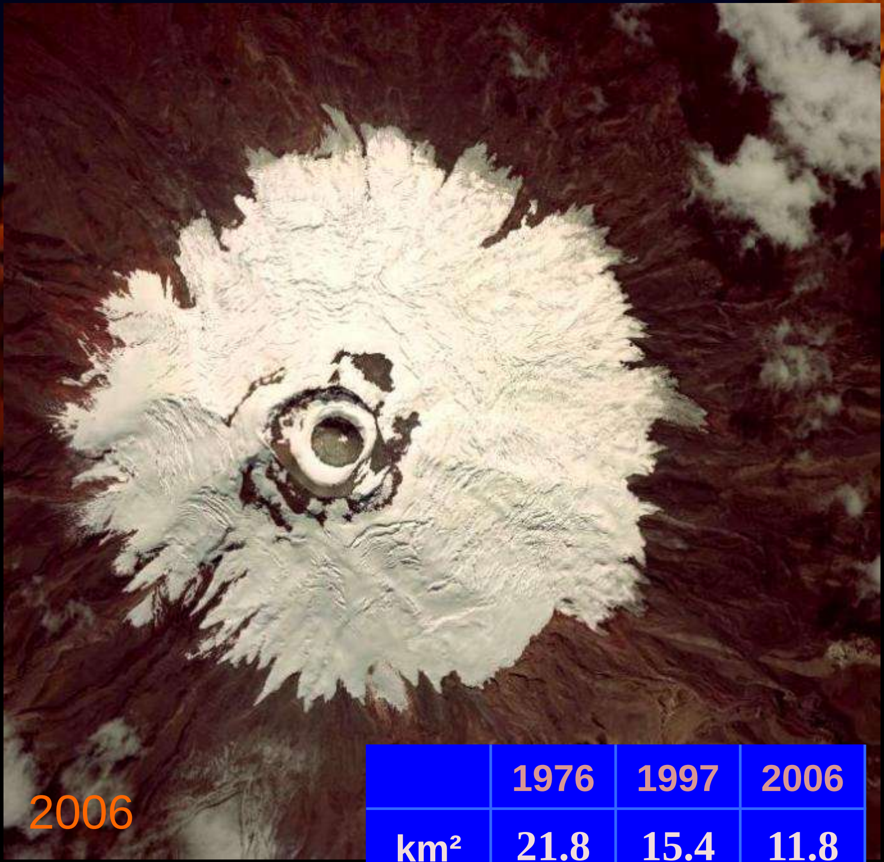


Rabatel, A., Francou, B., Jomelli, V., Naveau, P., & Grancher, D., 2008. A chronology of the Little Ice Age in the tropical Andes of Bolivia (16 S) and its implications for climate reconstruction. *Quaternary Research, doi:10.1016/j.yqres.2008.02.012.*

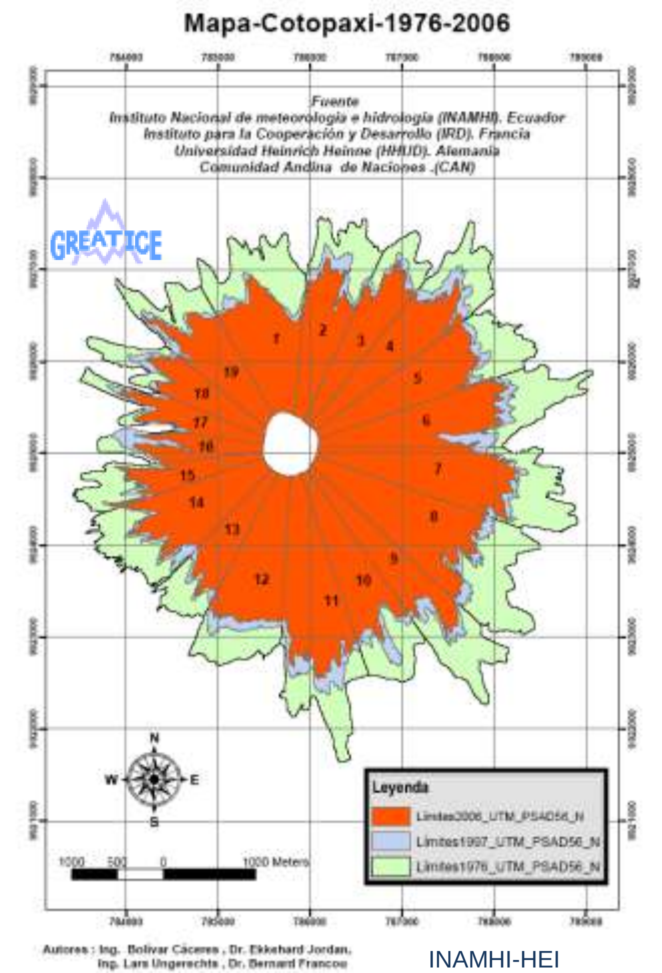
Jomelli, V., Favier, V., Rabatel, A., Brunstein, D., Hoffmann, G., & Francou, B., 2009. Fluctuations of glaciers in the tropical Andes over the last millennium and palaeoclimatic implications: A review. In: *Palaeogeography, Palaeoclimatology, Palaeoecology, Vol. 281, Issues 3-4, Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives: 269-282.*

Ecuador: depletion of ice-capped volcanos *(Caceres, 2005, 2010)*

Aerophogrammetry on the (active) Volcán Cotopaxi, Ecuador (~12km² en 2006)



	1976	1997	2006
km²	21.8	15.4	11.8
%		-30	-45

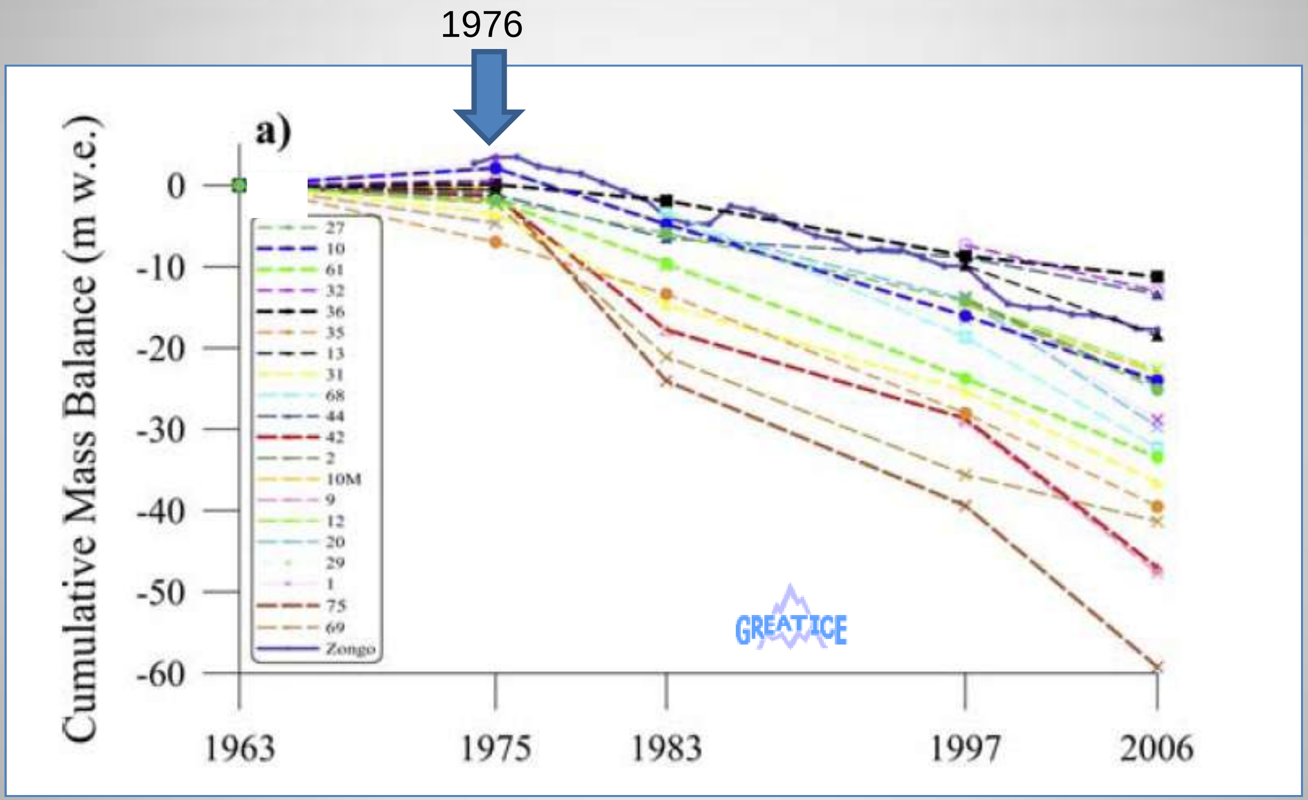


Jordan, E., Ungerechts, L., Cáceres, B., Peñafiel, A. **& Francou, B.,** 2005. Estimation by photogrammetry of the glacier recession on the Cotopaxi Volcano (Ecuador) between 1956 and 1997. *Hydrological Sciences/Journal des Sciences Hydrologiques, IAHS, 50, n 6: 949-961. UPDATED*

Bolivia 16°S: glacier recession in the Cordillera Real

Aerophogrammetric analysis of 20 glaciers: loss of 40-50% (in area & volume)

(Soruco, 2008)



Cumulative mass balance of 20 glaciers in the Cordillera Real

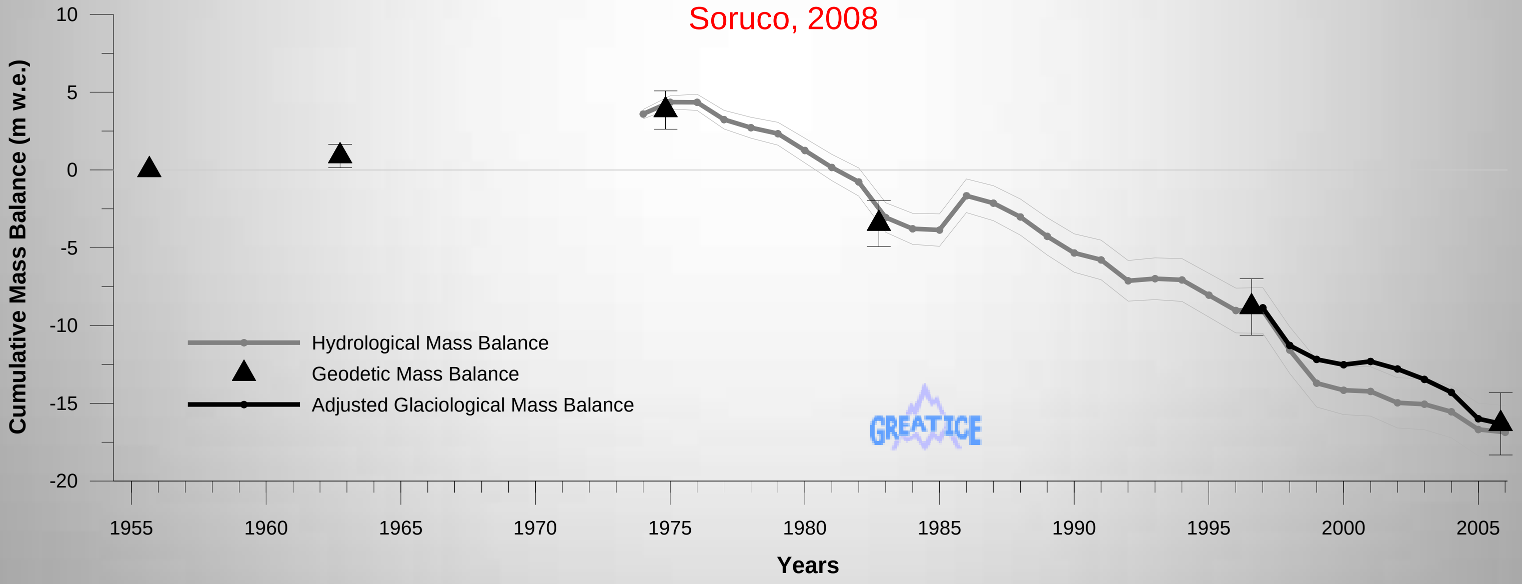
Soruco, A., Vincent, C., & Francou, B., 2009. Glacier decline between 1963 and 2006 in the Cordillera Real, Bolivia. *Geophysical Research Letters, vol. 36, L03502, doi:10.1029/2008GL036238*

1/ Areas & Volume loss over the last 50 yr

©AS

The Glaciar de Zongo, Cordillera Real, Bolivia, the best monitored in the Tropics (> 30yr long series)

Reconstruction of 50-yr mass balance from crossed methods: glacio/hydro/aephotogrammetry

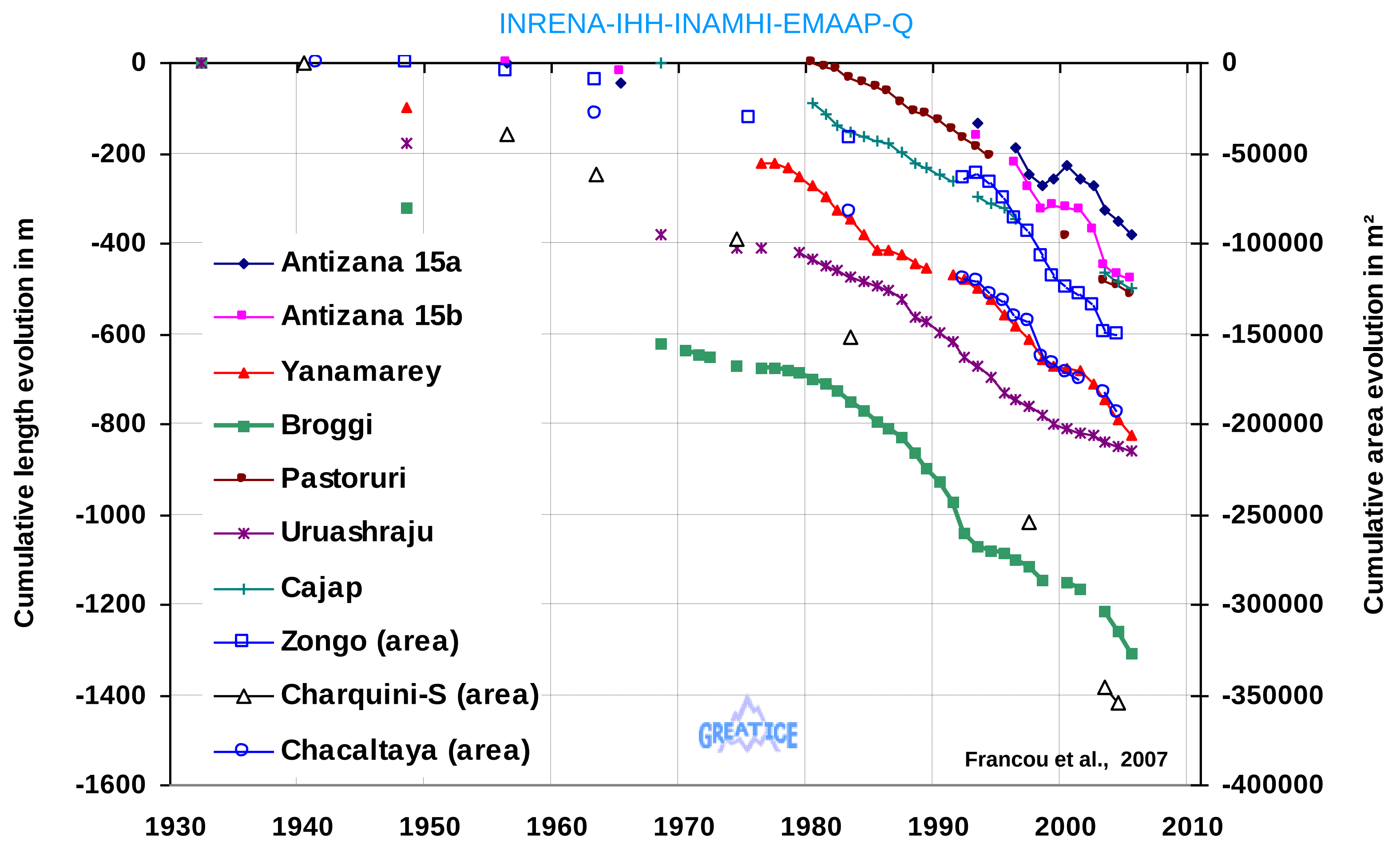


Soruco, 2008

Cumulative mass balance (mm w.e.) processed by 1) "geodetic method" (triangles), 2) by hydrological method (grey line) and 3) by glaciological method (black line). Hydrological data were available continuously since 1974. Glaciological mass balances, obtained by field measurements, were adjusted on data issued from aerophogrammetry (Soruco et al, 2008).

Soruco, A., Vincent, C., Francou, B., Ribstein, P., Berger, T., Sicart, J.E., Wagnon, P. & Arnaud, Y., 2009. Mass balance of Glaciar Zongo, Bolivia, between 1956 and 2006, using glaciological, hydrological and geodetic methods. *Annals of Glaciology, vol.50, Number 50: 1-8*

Cordillera Blanca (Peru) : the same trend since the 1980s



Areas and length of 10 glaciers monitored in the Central Andes since 50 yr and more

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G. & Bradley, R.S., 2008. Climate change and tropical Andean glaciers – Past, present, future. *Earth Science Reviews, 89 (2008): 79-96.*

1/ Areas & Volume loss over the last 50 yr

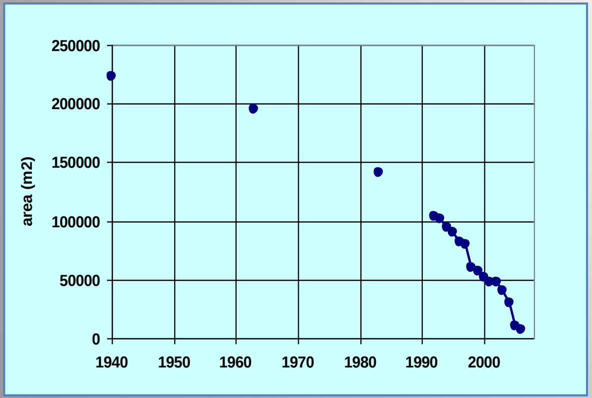
Many small-sized glaciers below 5200-5400m are desappearing

Recent history of the Chacaltaya glacier, Bolivia (0.1 km² in 1990)

1994 ©BF

2000 ©BF

2003 ©BF



Chacaltaya's area evolution 1940-2005

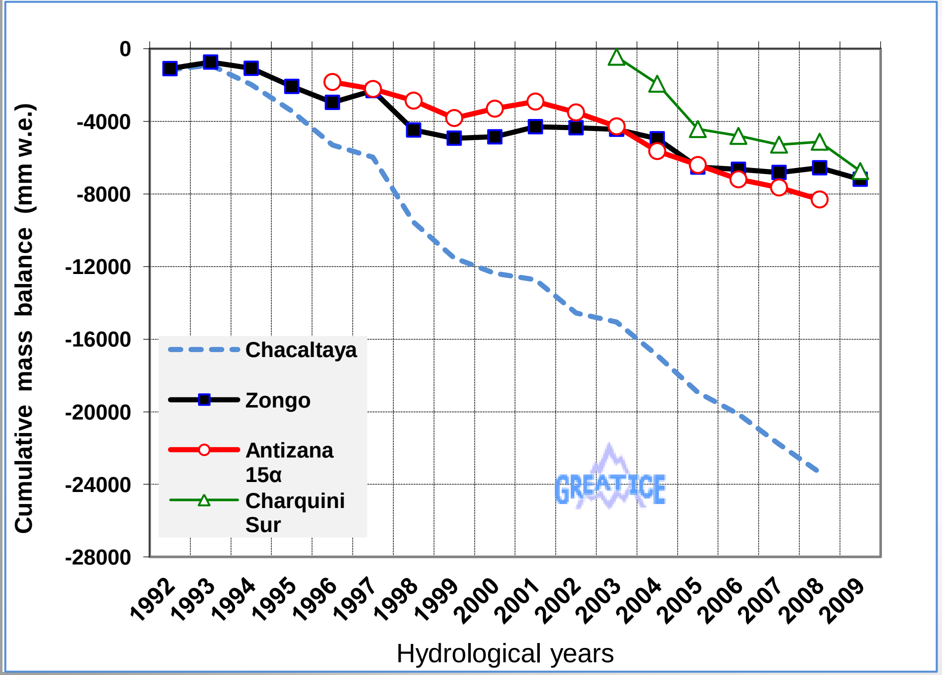
2005 ©BF

2009 ©PG

Mass balances of glaciers at regional scale show the same negative trend and respond to the same annual variability

Zongo, Chacaltaya, Charquini, Antizana 15

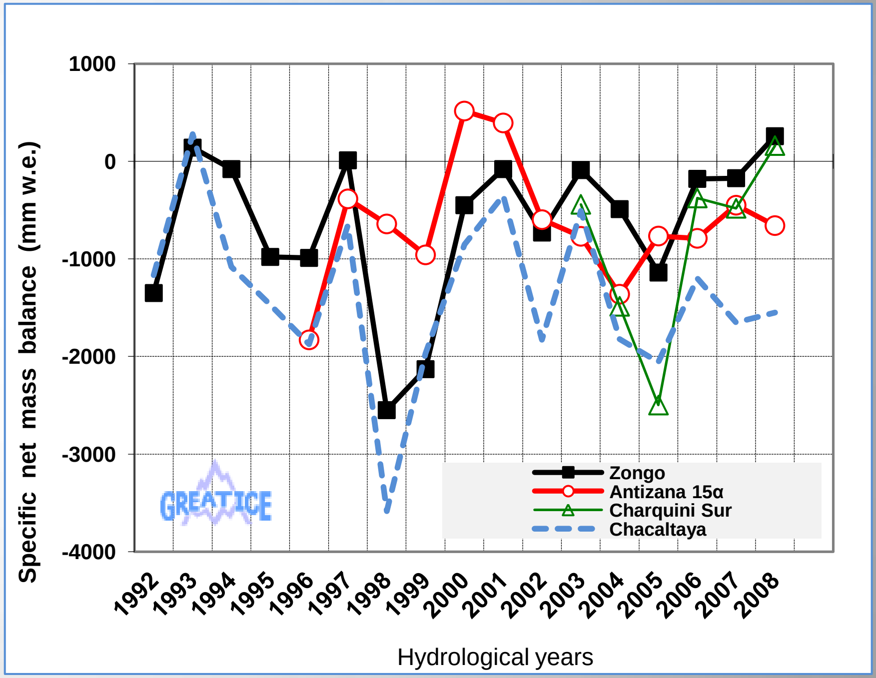
Cumulative



Cumulative mass balance of 3 glaciers of Bolivia (28°S) and 1 glacier of Ecuador (0°28S)

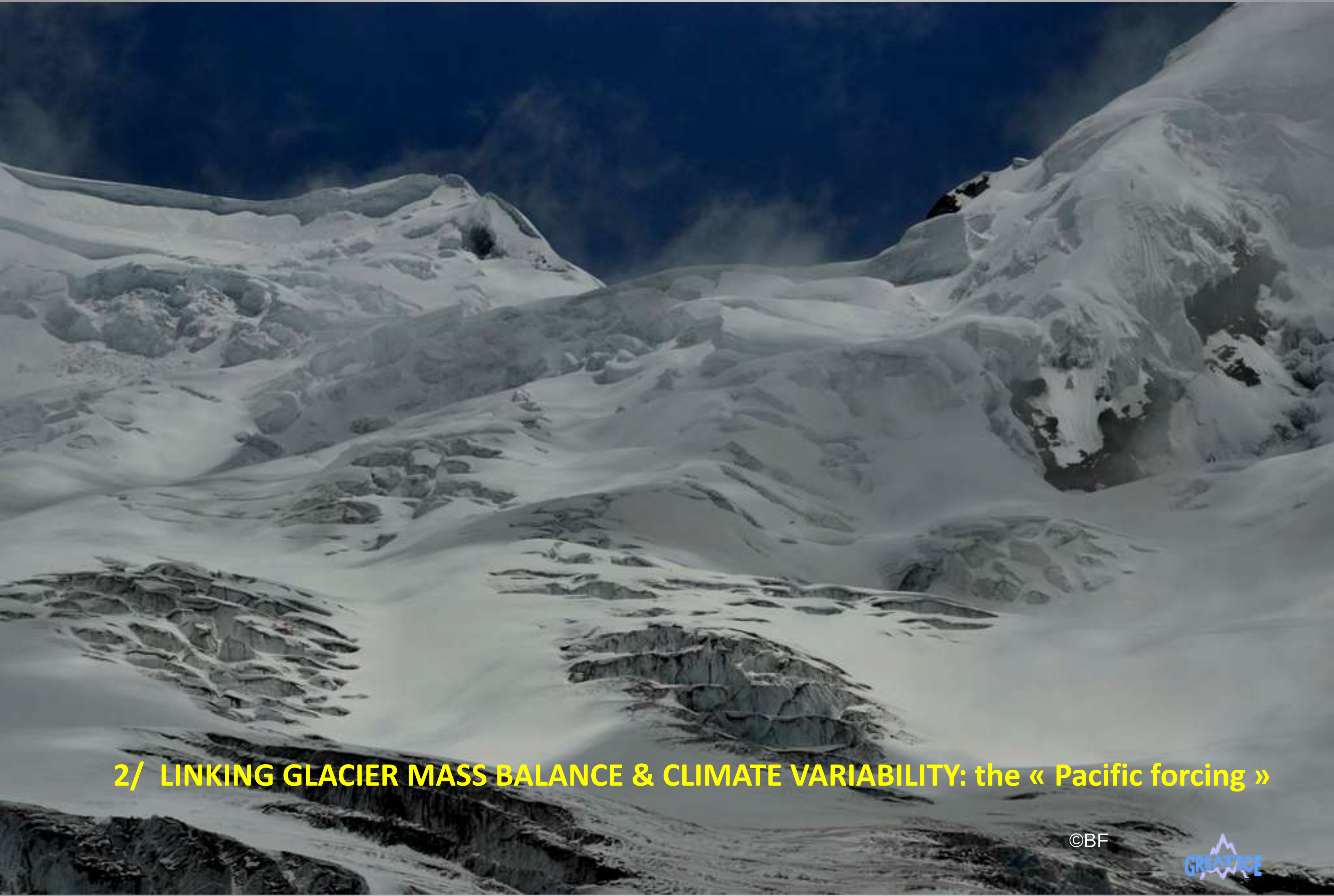
Zongo, Chacaltaya, Charquini, Antizana 15

Per years



Year per year mass balance of 3 glaciers of Bolivia (28°S) and 1 glacier of Ecuador (0°28S) over the 1991-2009 period

Francou, B., Cáceres, B., Gomez, J. & Soruco, A., 2007. Coherence of the glacier signal throughout the tropical Andes over the last decades. *Proceedings of the First International Conference on the Impact of Climate Change on High-Mountain System, IDEAM, Bogota, Novembre 2005, 87-97.* UPDATED



2/ LINKING GLACIER MASS BALANCE & CLIMATE VARIABILITY: the « Pacific forcing »

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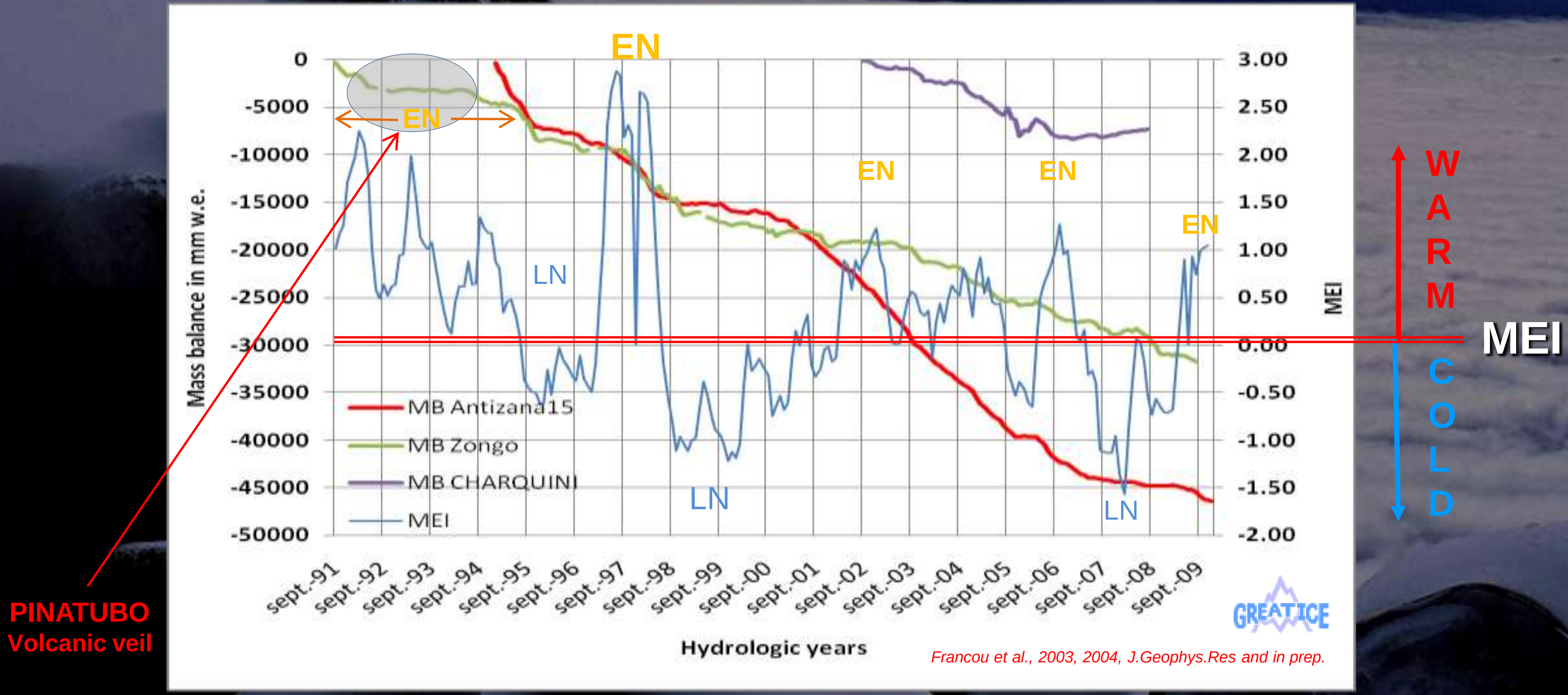
Ablation intensity increases during the warm phases of ENSO (EN), and dicreases during the cold phases (LN)



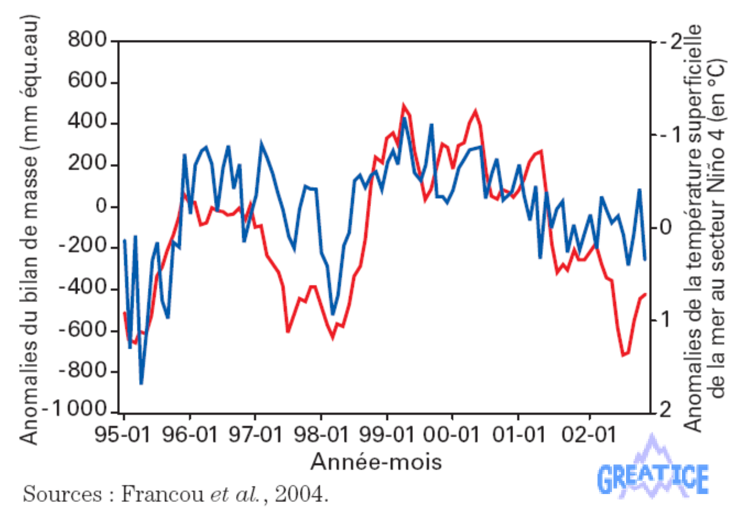
PINATUBO
Volcanic veil

Francou et al., 2003, 2004, J.Geophys.Res and in prep.

- Cumulative mass balance in ablation zones (Zongo, Charquini, Antisana 15)
- Multivariate ENSO Index (MEI): Central Pacific Niño 3-4 sectors

Complexity of thre ENSO/glacier teleconnection: Zonation of SST anomalies induces disctinct glacier response

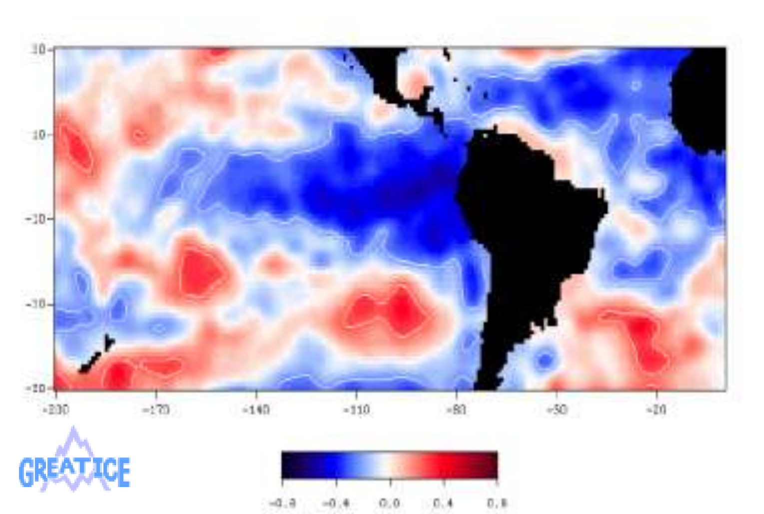
Antisana 15α /Niño4 sector 1995-2003



Sources : Francou *et al.*, 2004.

Correlation at month scale between glacier mass balance (blue) and SSTa (red) [best glacier response with a 3-months lag]

Chacaltaya/Niño1-2 sector 1991-2002



Correlation at month scale between glacier mass balance in Bolivia and the SSTa of the Pacific [best glacier response with a 2-months lag]

Blue = Cold SST anomaly and positive mass balance anomaly (La Niña)

Francou, B., Vuille, M., Wagnon, P., Mendoza, J. & Sicart, J.E., 2003. Tropical climate change recorded by a glacier of the central Andes during the last decades of the 20th *century : Chacaltaya, Bolivia, 16 S. Journal of Geophysical Research, 108, D5, 4154, doi: 10.1029/2002JD002959 UPDATED* **Francou, B.**, Vuille, M., Favier, V. & Cáceres, B., 2004. New evidences of ENSO impacts on glaciers at low latitude : Antizana 15, Andes of Ecuador, 0°28'. *Journal of Geophysical Research, 109, doi: 10.1029/2003JD004484. UPDATED*

Francou, B., Vuille, M., Favier, V. & Cáceres, B., 2004. New evidences of ENSO impacts on glaciers at low latitude : Antizana 15, Andes of Ecuador, 0°28'. *Journal of Geophysical Research, 109, doi: 10.1029/2003JD004484 UPDATED*

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3/ ENERGY BALANCE AND ABLATION PROCESSES: how climate affects the glacier mass balance?

Energy balance

Equation of energy conservation

$$R + H + LE + G + P = \Delta Q_M$$

Key-variables of the energy balance :

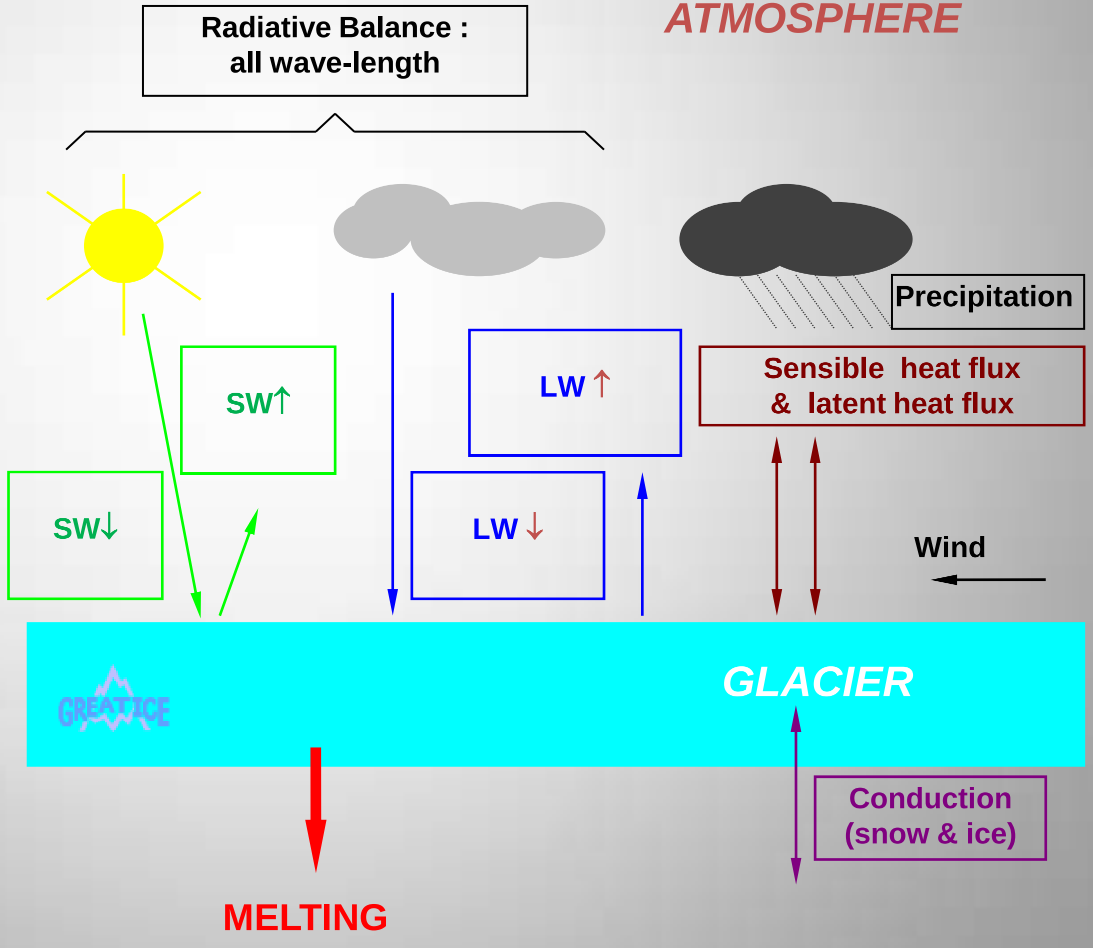
- *SW↓↑ radiative balance (albedo)*
- Long-wave radiation *LW↓↑*
- Turbulent fluxes *H, LE*
- G and P are not important

Key-variables of atmosphere :

- Precipitation (solid/líquid): *Mass alimentation, albedo*
- Cloudiness y Relative Humidity:

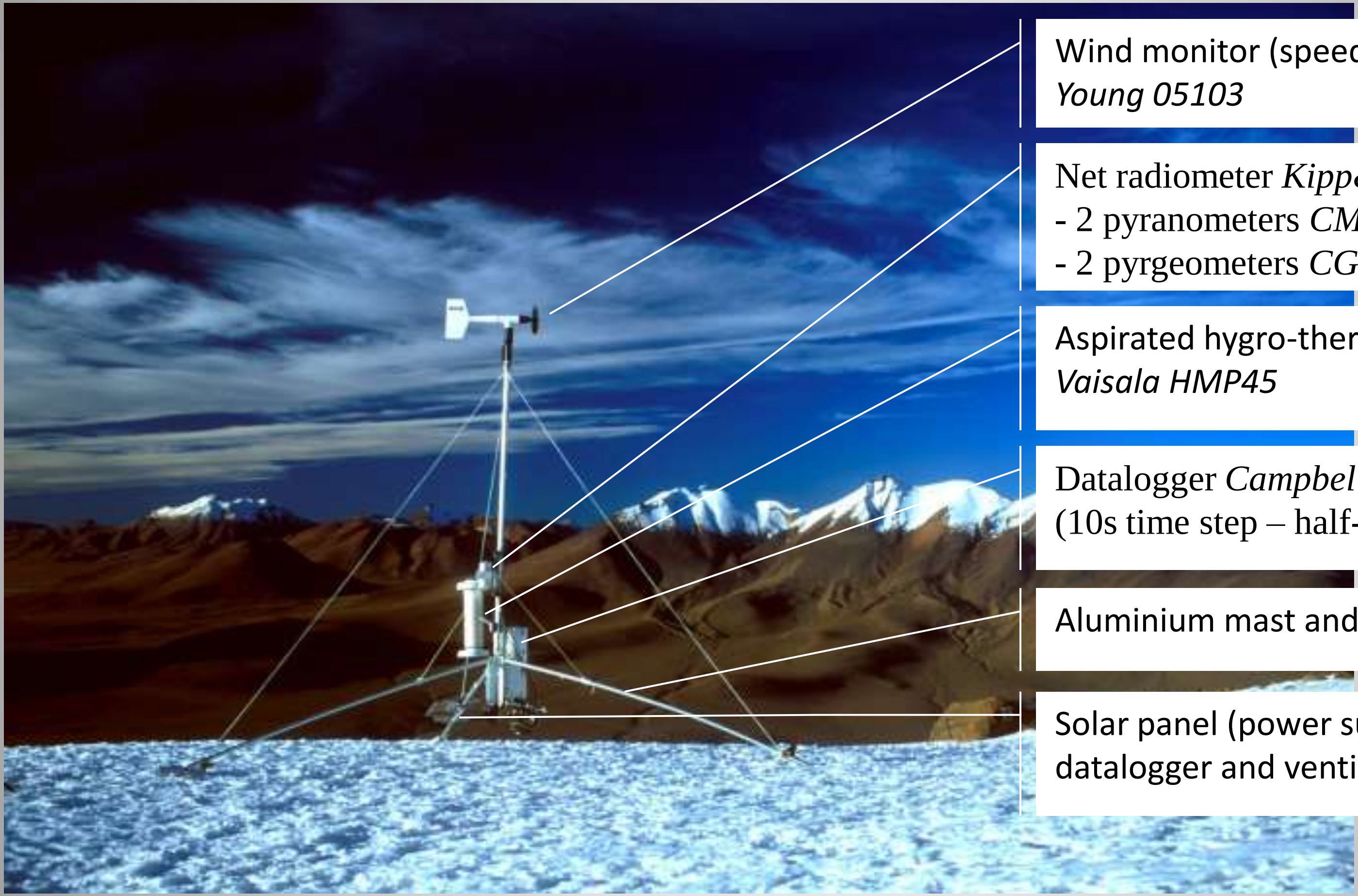
SW, LW, LE/H

- Wind velocity : *LE*
- Air temperature (sensible heat flux): *H*



Sources : P.Wagnon, J.E.Sicart, V.Favier, L.Maisincho, M. Litt

Parameters measured in the field



Wind monitor (speed and direction)
Young 05103

Net radiometer *Kipp&Zonen CNR1*
- 2 pyranometers *CM3* (S↓ and S↑)
- 2 pyrgeometers *CG3* (L↓ and L↑)

Aspirated hygro-thermometer (T and RH)
Vaisala HMP45

Datalogger *Campbell CR10X*
(10s time step – half-hourly means)

Aluminium mast and tripod

Solar panel (power supply for datalogger and ventilation)

AWS on Caquella snow field, Bolivia, 21 S, 5400 m asl ©PW GREATICE

Turbulent fluxes

Mean vertical profiles (6m) of T and U

Sonic anemometers CSAT Campbell
infrared gas analyzers Licor LI-7500

Ph.D M. Litt (2011-2013)
Tropical glaciers / Alpine snow cover

Anual fluxes measured at the glacier surface
Antizana (Ecuador, 0°28S) and Zongo (Bolivia, 16°S)

Inner Tropics: weak seasonality

$R + H + LE = \Delta Q_M$

RADIATIVE

- ***Net short radiation S***
- ***Net long radiation L***

TURBULENT

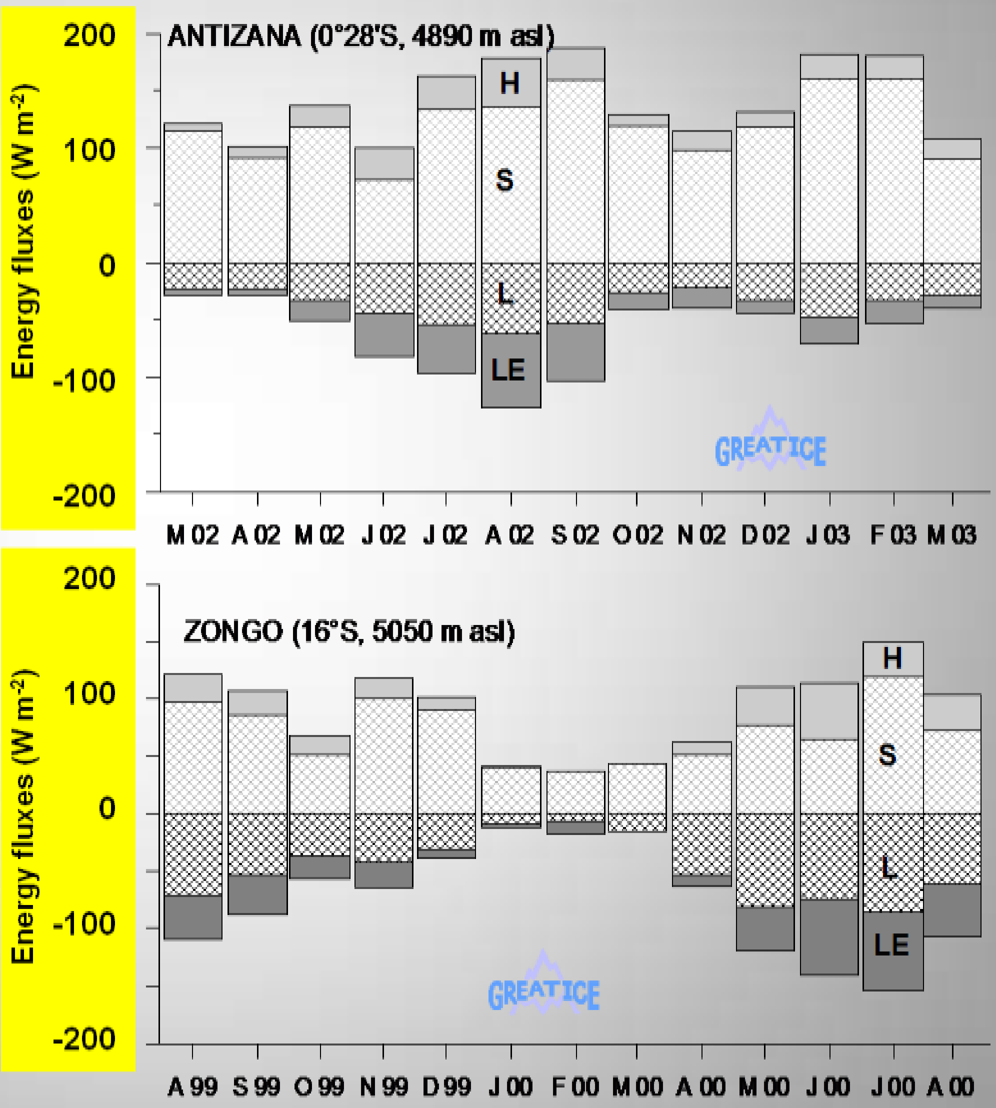
- ***Sensible Heat Flux H***
- ***Latent Heat Flux LE***

Outer Tropics: strong seasonality

Wagnon et al., 1999 *J.Geophys.Res*

Favier et al., 2004 *J.Geophys.Res*

Sicart et al., 2005 *J.Geophys.Res.*



Crucial factors for melting glaciers in the Andean tropics

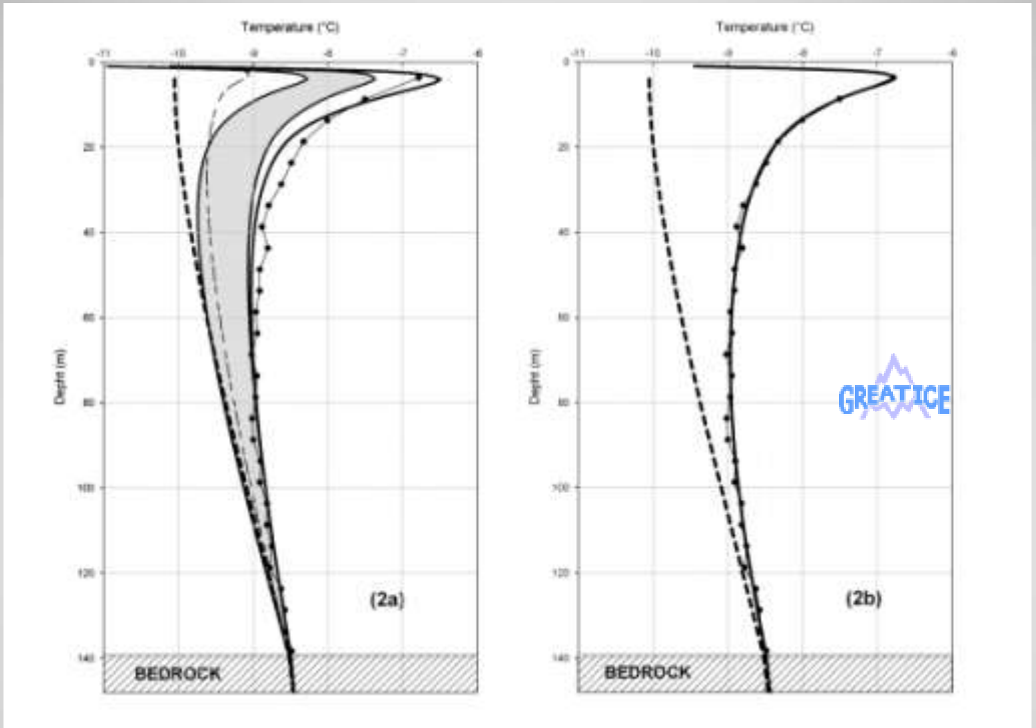
- Short-wave radiation [SW↓]: the biggest source of energy, which is strong all year round
- Long-wave radiation [LW ↓] : important incoming flux in the wet season (frequent convective clouds and high moisture content in the atmosphere). [LW ↓↑] can be positive and aliment a constant melting
- Sensible heat flux [S] : low, generally compensated by the latent heat flux [LE]. This is due to the low elevation freezing point (generally situted below the glacier terminus) and the poor density of atmosphere
- Latent heat flux [LE] is high (sublimation) in the dry season. With the [LW ↓↑] negative, the [LE] represent a strong loss of energy (low temperature at the glacier surface)
- Consequently, melting the mainly controlled by short wave [SW ↓↑] balance, which depends on **albedo**
- Albedo is controlled by the snow cover frequency on glacier surface, which depends on frequency of snowfalls and phase of precipitation (snow/rain limit)
- The snow/rain limit depends on temperature of atmosphere

Increasing temperature during the 20th century inferred from ice cores

Illimani’s drilling site (6340 m)

©BF

Increasing temperature during the 20th century inferred from Illimani’s cold ice

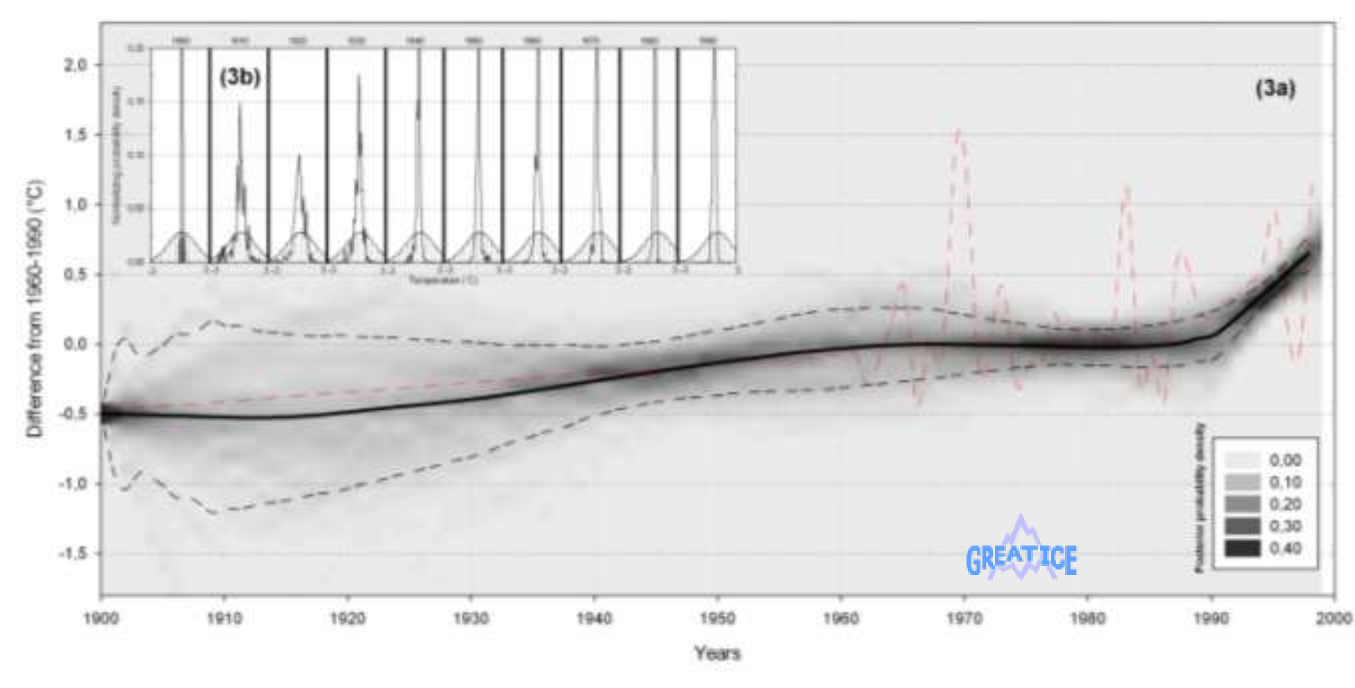


Vertical englacial temperature profile measured at Illimani (6340 m a.s.l.) in Jun-1999 (thin line with black dots). Modeled profile assuming a steady state climate with a constant secular temperature of 263.1 K (dashed line) and a constant geothermal flux of 22 10^{-3} W m^{-2}. (2a) Modeled temperature profiles assuming a steady-state before 1967 and using La Paz air temperature data after, without taking into account the latent heat resulting from surface melt water refreezing (thin dashed line) and taking into account the latent heat resulting from refreezing (melting factor *a* = 1.1 W m^{-2} K^{-1}) for a geothermal flux varying from 18 to 26 10^{-3} W m^{-2} (gray zone). Modeled temperature profile with a forced melting factor *a* = 1.7 W m^{-2} K^{-1} (thick line). (2b) Modeled temperature profile assuming a steady state before 1900, a 0.4 K warming between 1900 and 1962, and using La Paz air temperature after, with a constant geothermal flux of 22 10^{-3} W m^{-2} and a melting factor of 1.1 W m^{-2} K^{-1} (thick line)

Gilbert, A., Wagnon,P., Ginot,P., Funk, M., 2010. 20th century temperature reconstitution in a high altitude tropical site from Illimani (6340 m), Bolivia, 16°39S) englacial temperature. J.Geophys.Res., 115.

Increasing temperature during the 20th century infered from Illimani's cold ice

Temperature from Illimani's borehole vs temperature La Paz city



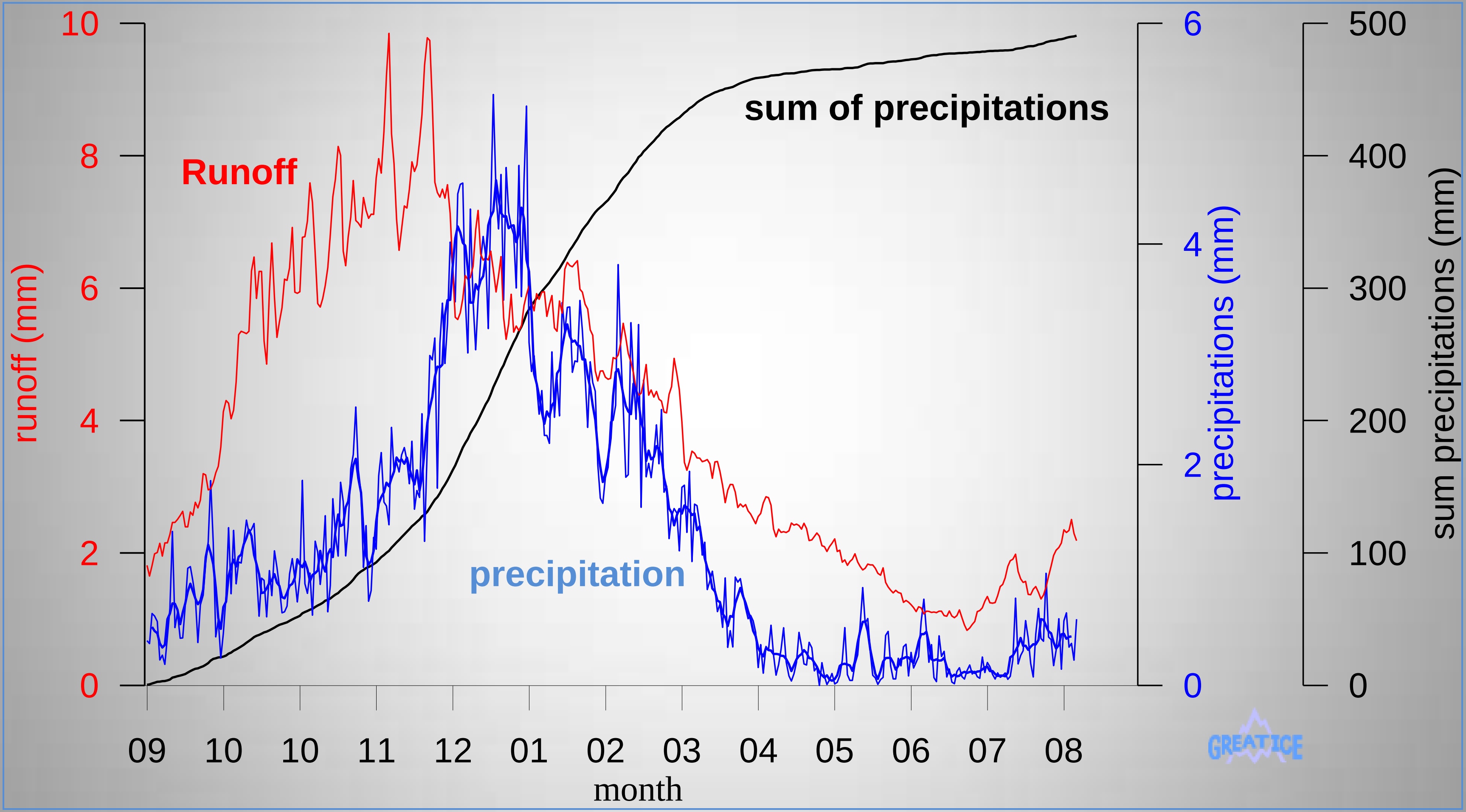
Reconstructed air temperature at Illimani (6340 m a.s.l.) over the 20th century using borehole temperature profile inversion (thick line) compared with La Paz air temperature (red dashed line after 1962). The two black dashed lines form an envelope corresponding to model uncertainties according to posterior probability density standard deviation. The grey scale represent the past surface temperature probability distribution (3b) Posterior (thin line) and prior (dotted surface) probability density functions of surface temperature each ten years (see section 5 for more details).

Gilbert, A., Wagnon,P., Ginot,P., Funk, M., 2010. 20th century temperature reconstitution in a high altitude tropical site from Illimani (6340 m), Bolivia, 16°39S) englacial temperature. J.Geophys.Res., 115.

4/ Glacier contribution to water discharge

Glaciers regulate runoff in the high mountain basins, particularly when precipitation periods are short and irregular

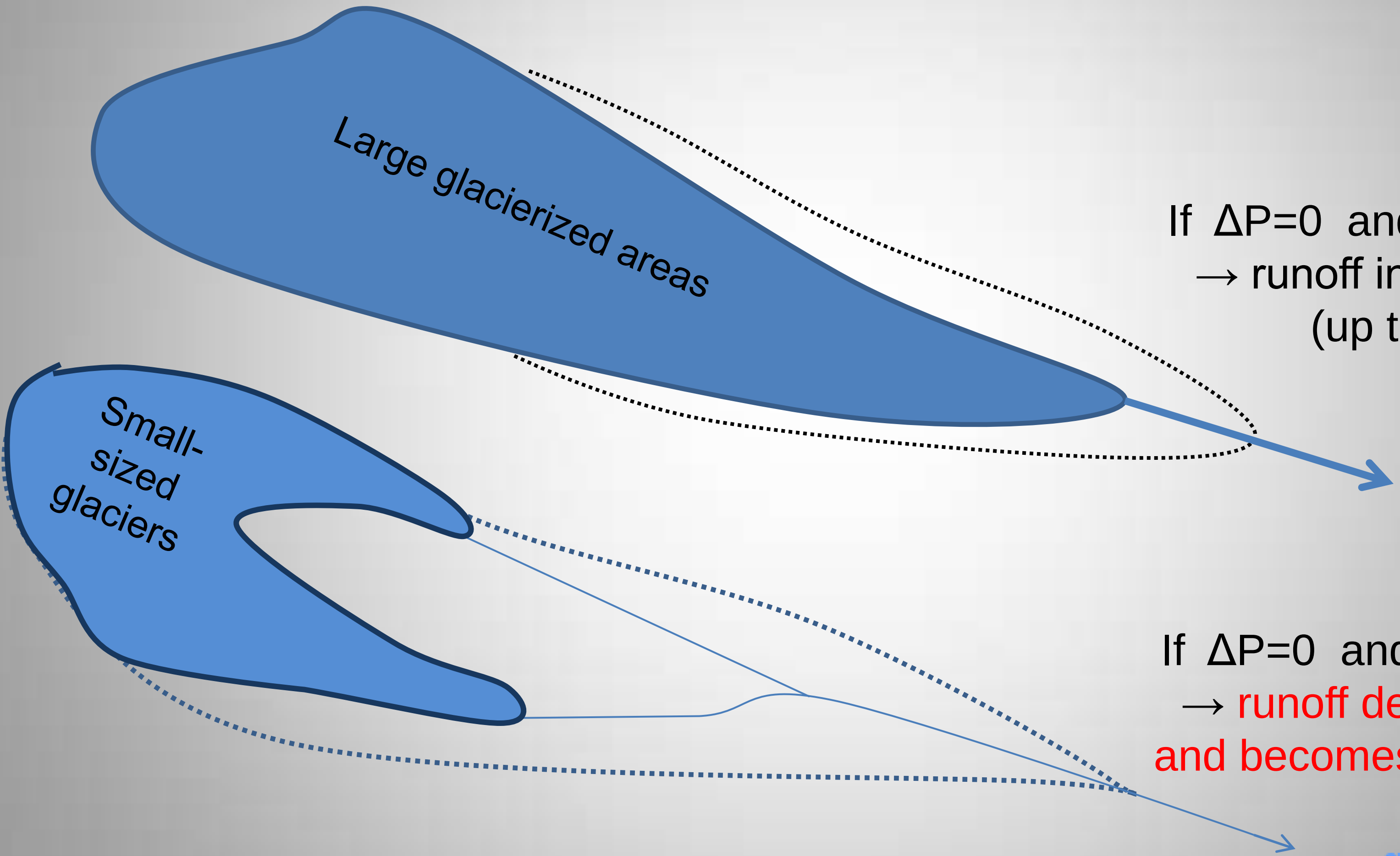
5 stations on the Altiplano, daily averages over 1991-2008



Discharge in the Zongo runoff station and wet season timing in balance / melt discharge: wet season timing and duration / precipitation intensity, frequency [PhD. C. Ramallo, 2010-2012]

Consequence of glacier shrinkage on discharge in the high elevation basins

Discharge increases in very glacierized basins (dominant glacial regime)
and decreases when glaciers are reduced (dominant snow/rain regime)

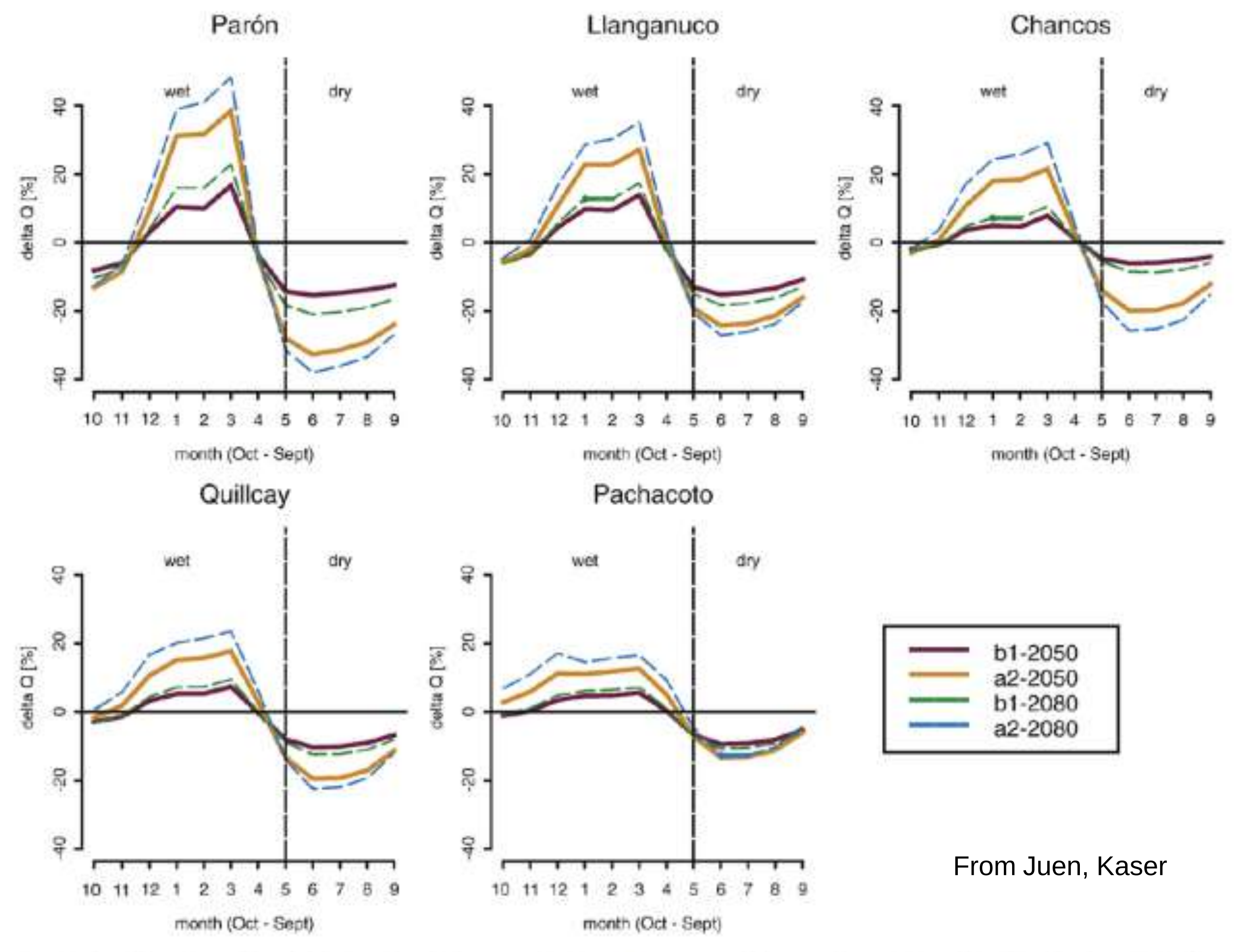


If ΔP=0 and Gmb<0
→ runoff increases
(up to a peak)

If ΔP=0 and Gmb<0
→ runoff decreases
and becomes irregular

P: precipitation
Gmb: glacier mass balance

Simulated change in runoff in Cordillera Blanca based on IPCC climate change scenarios

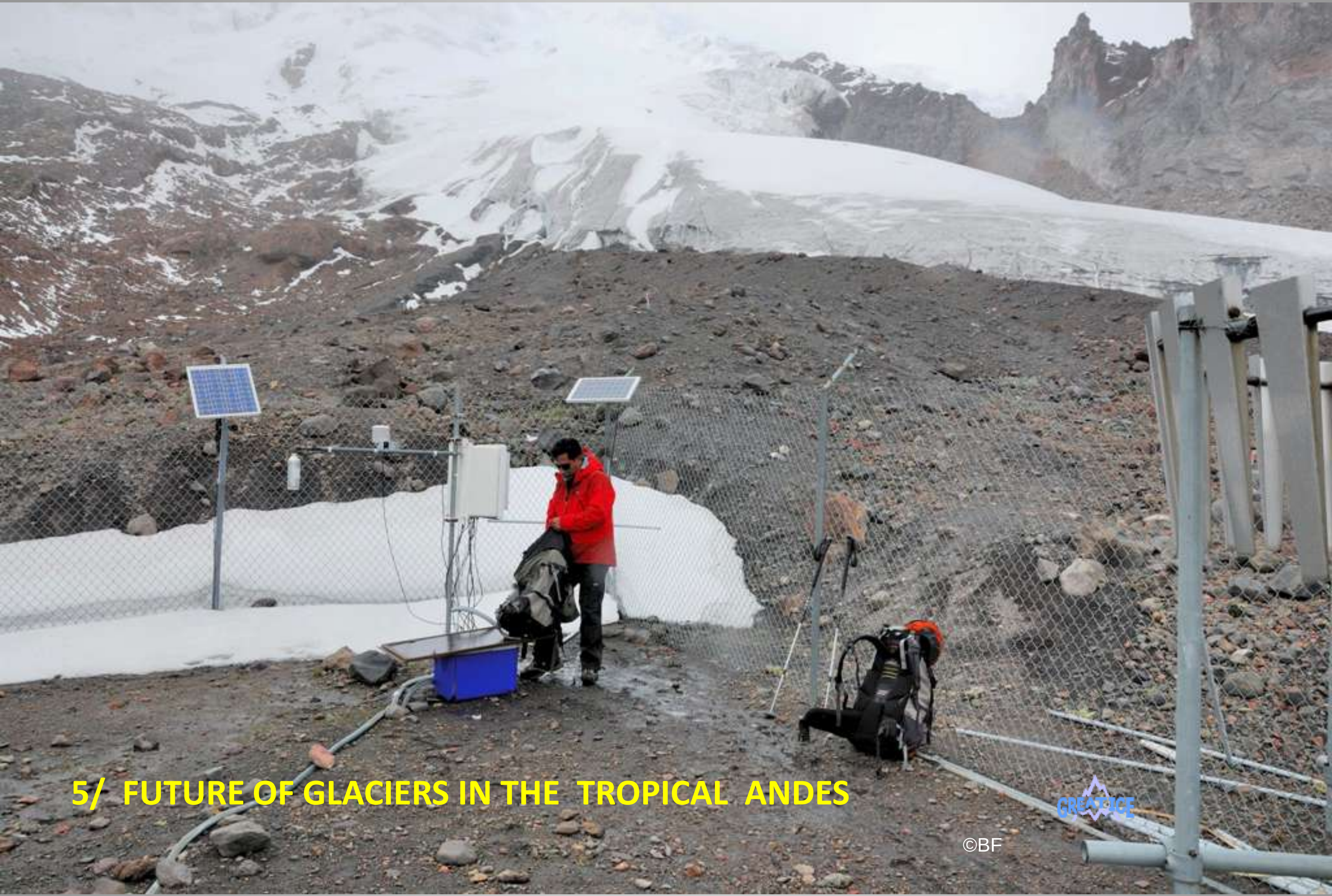


From Juen, Kaser

Fig. 12. Simulated change in monthly runoff in 2050 and 2080 (in %, compared with 1961–90 average) in 5 different catchments of the Cordillera Blanca based on the IPCC climate change scenarios B1 and A2. The catchments exhibit a decreasing degree of glaciation (1990 values): Paron 40.9%; Llanganuco 31.0%; Chancos 24.1%; Quillcay 17.4%; Pachacoto 9.7%.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G. & Bradley, R.S., 2008. Climate change and tropical Andean glaciers – Past, present, future. *Earth Science Reviews, 89 (2008): 79-96.*

5/ FUTURE OF GLACIERS IN THE TROPICAL ANDES



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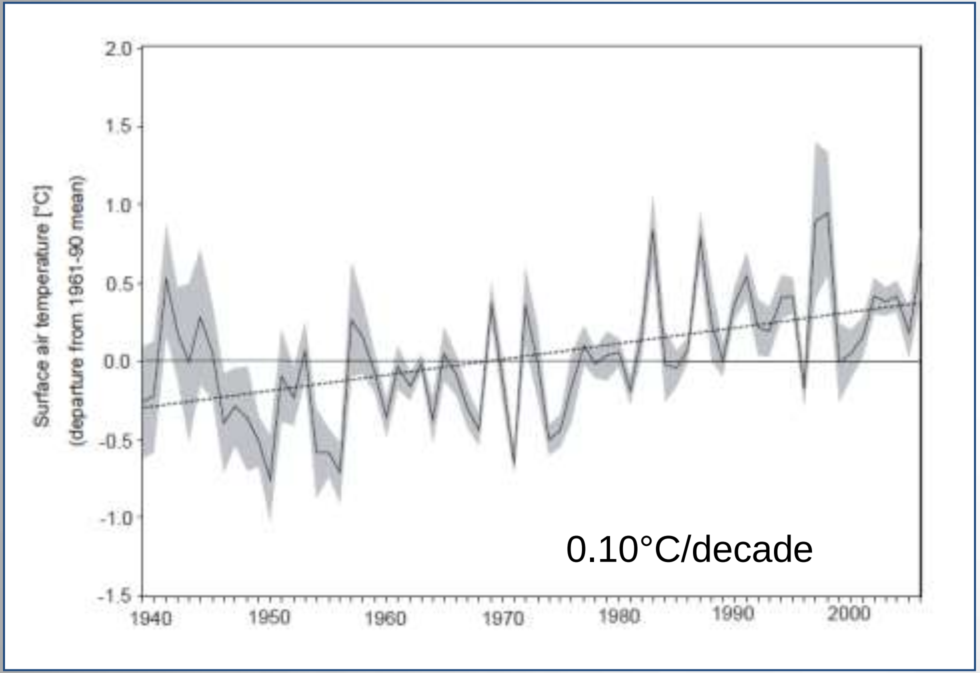
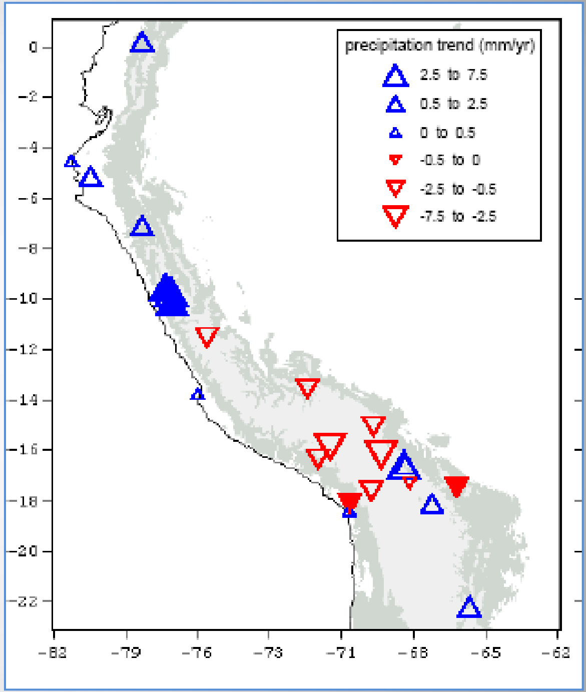
Since the 1950s, temperature has increased by ~0.7°C in the Tropical Andes, mainly after 1976



Annual temperature deviation from 1961-90 average
(1°N -23°S) between 1939 and 2006. Compilation of 279 station records. Black line: long-term variation (0.10°C/decade).
(Vuille et al., 2008)



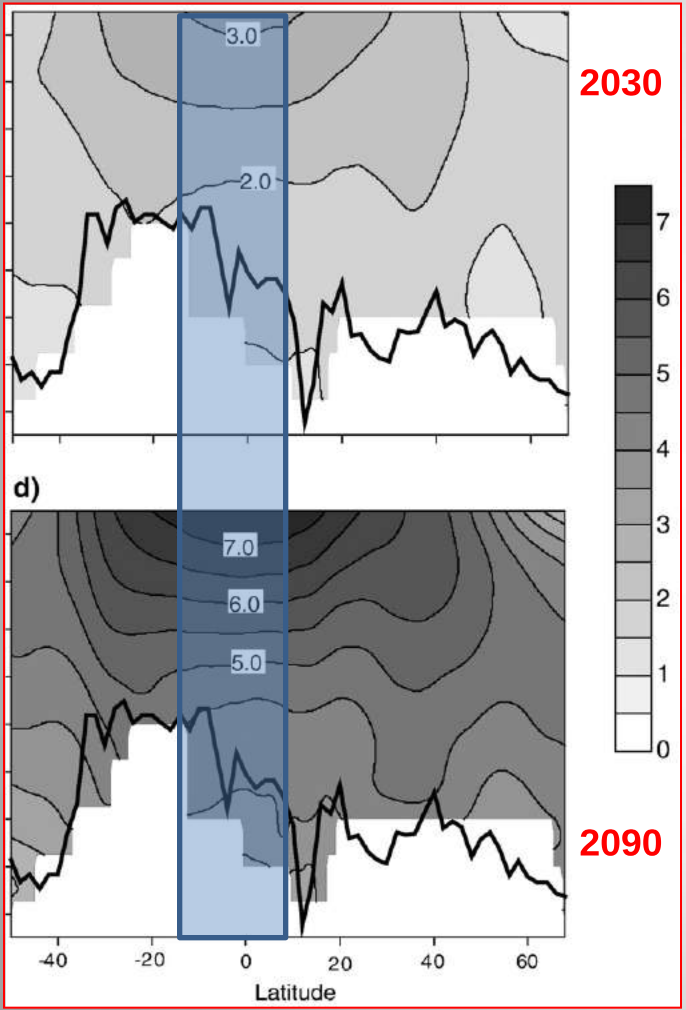
Precipitation trend from 1950 to 1994
(42 station records)

▲ increase

▼ decrease

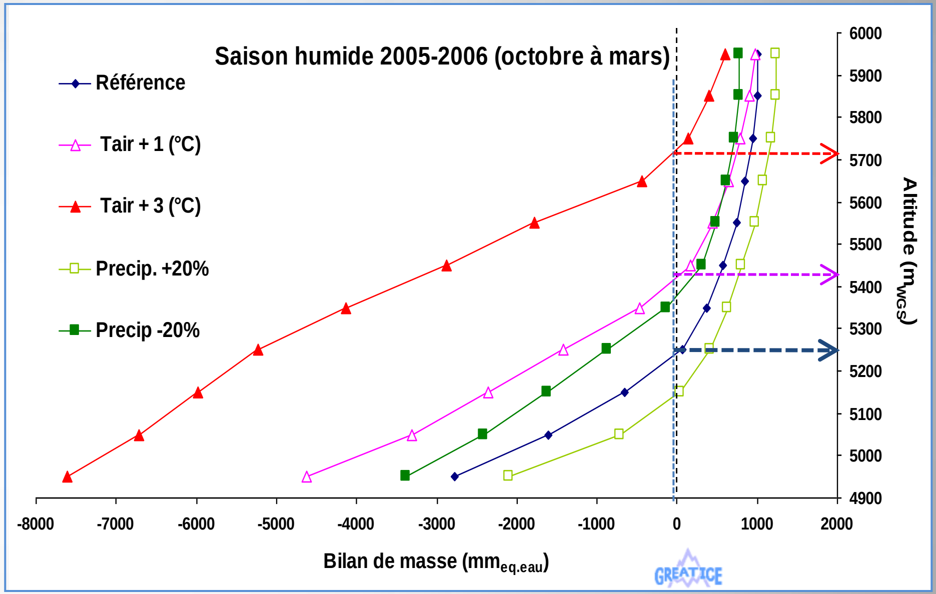
Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G. & Bradley, R.S., 2008. Climate change and tropical Andean glaciers – Past, present, future. *Earth Science Reviews, 89 (2008): 79-96.*

Future…



SRES A2
Mean simulation of 8 models
Alaska (+68°N – Patagonia (-50°N)
Vuille et al., 2008

Models/Simulations



Sensibility of mass balance of Glaciar Zongo at temperature and precipitation variations. Reference : wet season 2005-2006
CROCUS model Lejeune, 2009

ELA$_{wet}$ = 5230 m (Present)

ELA$_{wet}$ = 5430 m (+1°C)

ELA$_{wet}$ = 5700 m (+3°C)

+1°C ≈ ELA +200m

Synthetic papers since the IPCC 2007

Jomelli, V., Favier, V., Rabatel, A., Brunstein, D., Hoffmann, G., & Francou, B., 2009. Fluctuations of glaciers in the tropical Andes over the last millennium and palaeoclimatic implications: A review. In: *Palaeogeography, Palaeoclimatology, Palaeoecology, Vol. 281, Issues 3-4, Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives: 269-282.*

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