Impact of the retreat of snow & glaciers in natural and human environments

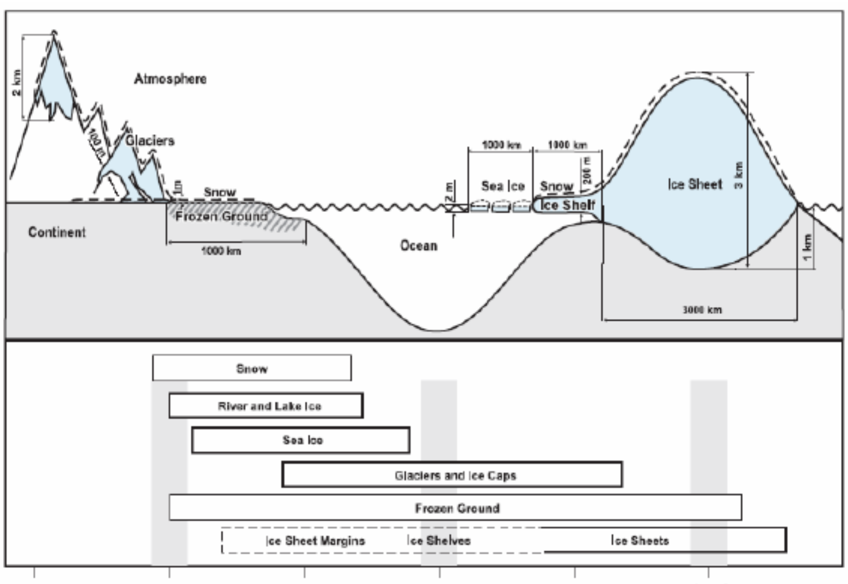
Gino Casassa et al.

CECs
CENTRO
DE ESTUDIOS
CIENTÍFICOS

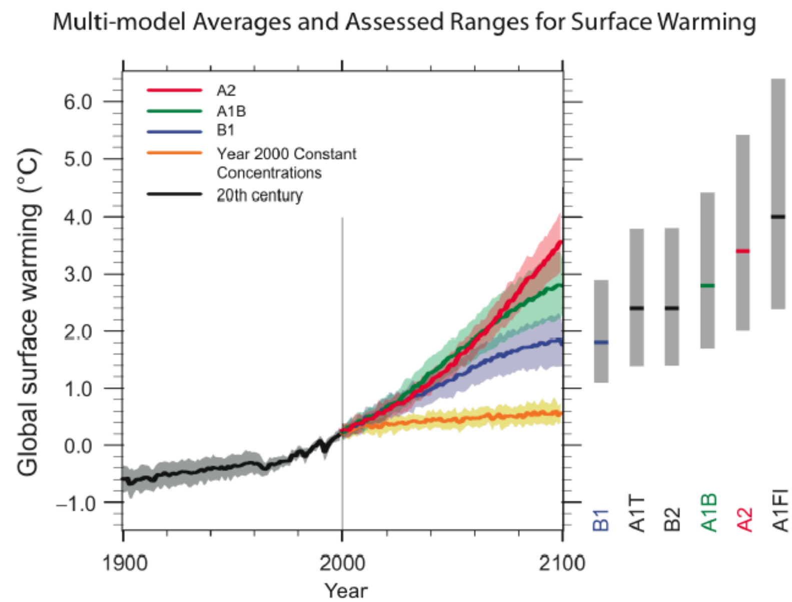
Valdivia, Chile

Taller "Derretimiento de Nieves y Glaciares: Ciencia, Tecnología y Políticas para Enfrentar los Desafíos de la Región Andina en un Contexto de Cambio Climático"
Santiago, Chile, 13-15 de septiembre de 2011

CRYOSPHERE



IPCC, 2007



IPCC, 2007

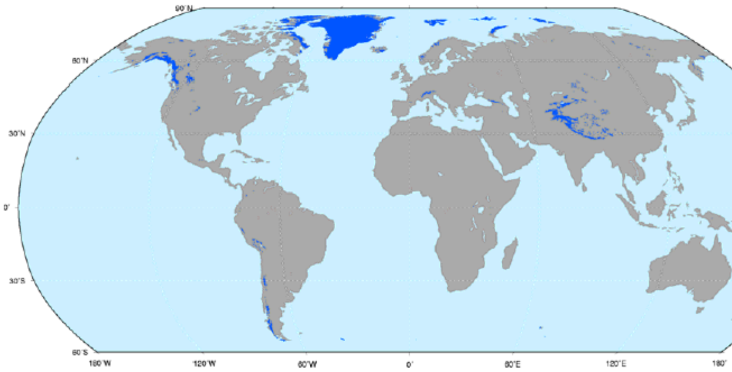
Temperate ice
(T=@ melting point)

vs.

Cold ice
(T< melting point)

Never put your tongue on a glacier.

GLIMS
WGMS
NSIDC

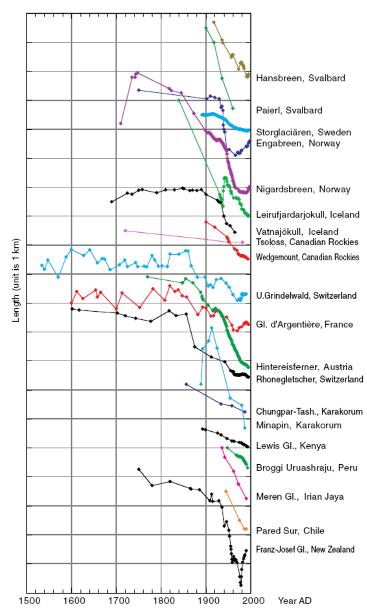


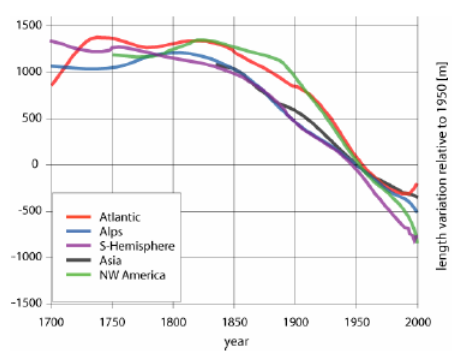
	Glaciers	Ice caps	Glaciers and ice caps [a]	Greenland ice sheet [b]	Antarctic ice sheet [b]
Number	>160 000	70			
Area (10^6 km^2)	0.43	0.24	0.68	1.71	12.37
Volume (10^6 km^3)	0.08	0.10	0.18 ± 0.04	2.85	25.71
Sea-level rise equivalent [d]	0.24	0.27	0.50 ± 0.10	7.2 [c]	61.1 [c]
Accumulation (sea-level equivalent, mm/yr) [d]			1.9 ± 0.3	1.4 ± 0.1	5.1 ± 0.2

IPCC, 2007

WGMS

GLACIER LENGTH

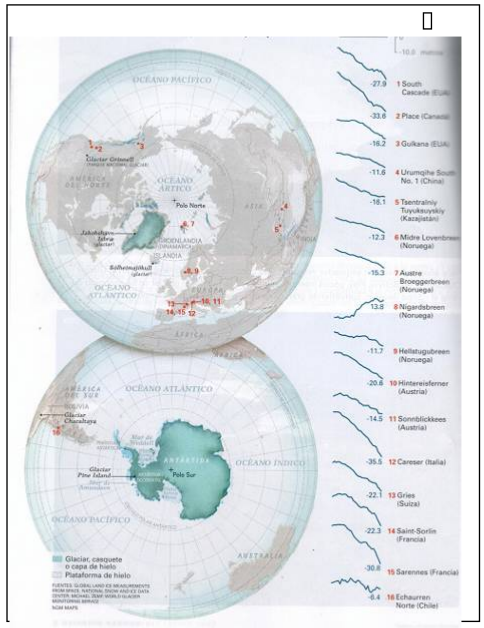




GLACIER MASS BALANCE

30 YEARS

10 METERS



Glacier Mass Balance

National Geographic, 2007

NATIONAL GEOGRAPHYC

GLACIERS in SOUTH AMERICA

Country	Region (s)	Area (km²)	References
Venezuela	Sierra Nevada de Mérida	0.1	Casassa (VICC 2010)
Colombia	3 Cordilleras	48	Ceballos (VICC 2010)
Ecuador	Cordillera Occidental and Oriental	39.61	Cáceres (VICC 2010)
Peru	20 Cordilleras	1,780	USGS, 1999
Bolivia	7 Cordilleras	534	IAHS(ICSI)-UNEP-UNESCO , 1989
Chile	Northern Patagonia Icefield (NPI)	3,953	Rivera et al., 2007
Chile/Argentina	Southern Patagonia Icefield (SPI)	12,500	Skvarca et al. (VICC 2010)
Chile	North, central, southern Chile, Patagonia other than NPI & SPI, Tierra del Fuego	7,365	Rivera et al., 2008 & Rivera et al., 2009
Argentina	North, central, southern Argentina, Patagonia (other than SPI)	2,000	Estimated from different published sources
Argentina	Tierra del Fuego	19.6	Iturraspe et al. (VICC 2010)
TOTAL	PREVIOUSLY 29,347 km²	**28,239**	

Casassa, 2010

GLACIERS IN SOUTH AMERICA: 28,239 km²

(~10% of all mountain glaciers)

*excluding glaciers in Antarctic Peninsula & Greenland

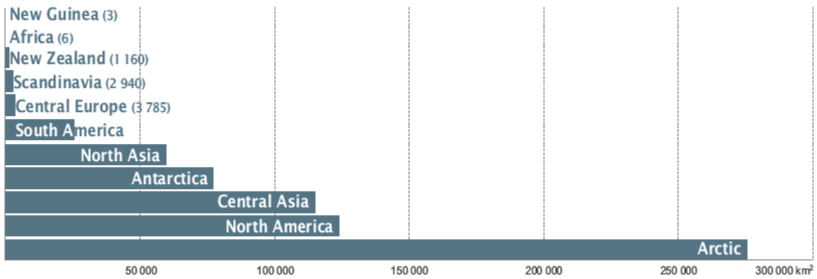
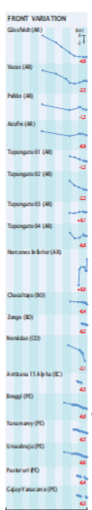


Fig. 3.7 Regional overview of the distribution of glaciers and ice caps

Global Glacier Changes: facts and figures, UNEP-WGMS, 2009

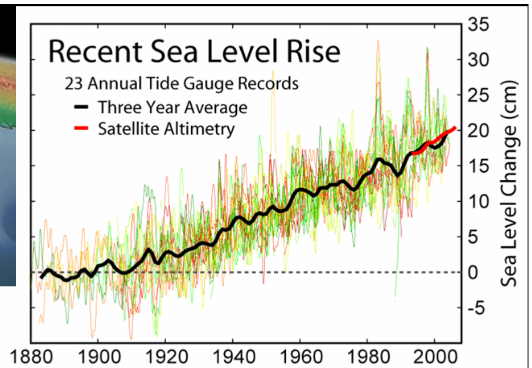
Glacier length

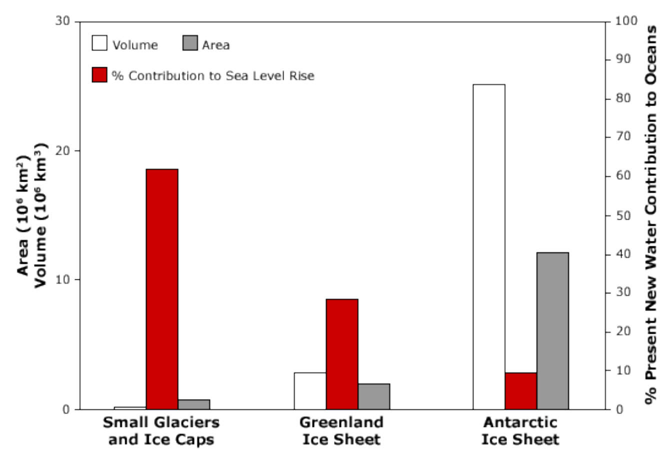


Mass balance

wgms

2009





Sea level rise contributors: Comparison of volume (white), area (grey) and percent contribution to sea level rise (red) by small glaciers and ice caps, and the Greenland and Antarctic Ice Sheets. Image courtesy (Meier et al., 2007). www.nsidc.org

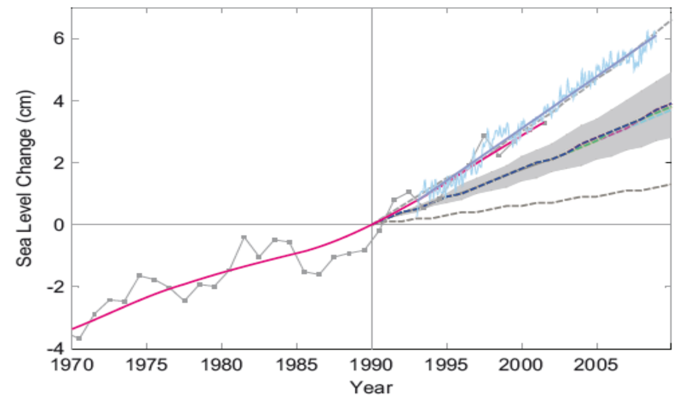
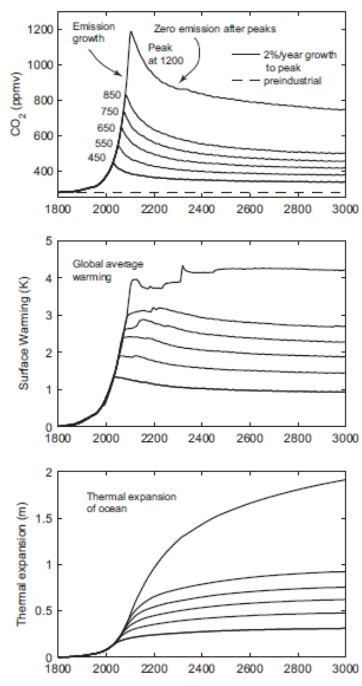


Figure 1
Change in sea level from 1970 to 2008, relative to the sea level at 1990. The solid lines are based on observations smoothed to remove the effects of interannual variability (light lines connect data points). Data in most recent years are obtained via satellite based sensors. The envelope of IPCC projections is shown for comparison; this includes the broken lines as individual projections and the shading as the uncertainty around the projections[3].

SYNTHESIS REPORT | CLIMATE**CHANGE**
Global Risks, Challenges & Decisions
COPENHAGEN 2009, 10-12 March
www.climatecongress.ku.dk



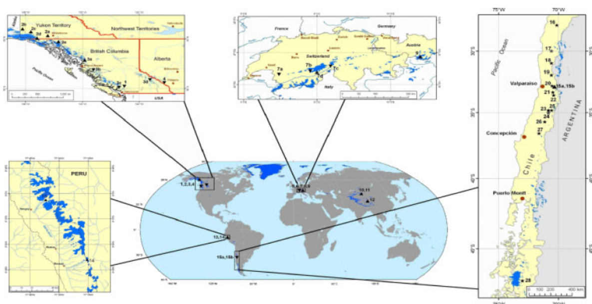
Salomon et al., 2009, PNAS

WATER RESOURCES

Greenland moulin

Steffen et al.

Univ. Colorado

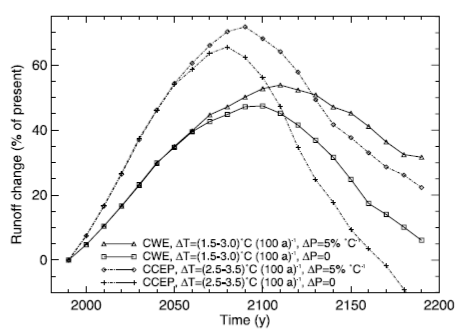


Casassa et al., 2009

CLIMATE WARMING & GLACIER RUNOFF

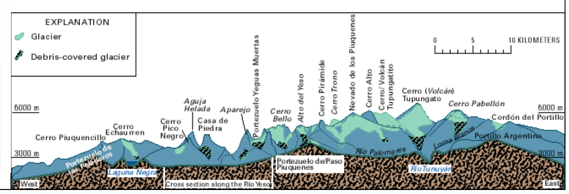
i. 1st stage: ELA rise, increased runoff. glacier melt mainly by thinning (albedo feedback relevant)
ii. critical point: reached after relevant glacier shrinkage & ELA reaches the upper areas
iii. 2nd stage: glacier melt no longer able to sustain runoff & runoff decreases to base level after glacier disappears

Response of Hofsjökull, Iceland, to climate change.
Aoalgeirsdottir,JGR, 2006

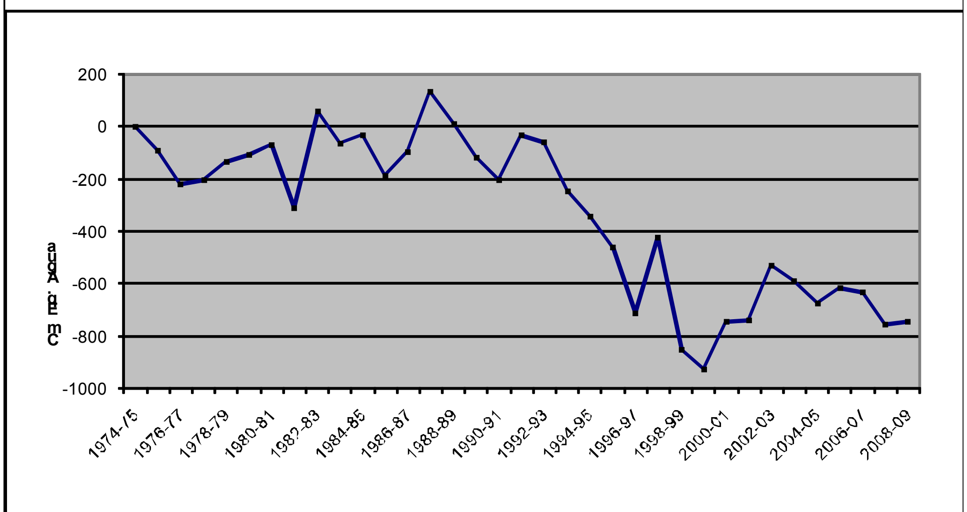


Job 6:17 When they (snow & ice) become warm, they go away; when it is hot, they vanish out of their place.
Job 6:17 <las aguas de deshielo> que al tiempo del calor se secan, y al calentarse desaparecen en su cauce.

ECHAURREN NORTE GLACIER



ANNUAL MASS BALANCE ECHAURREN NORTE GLACIER

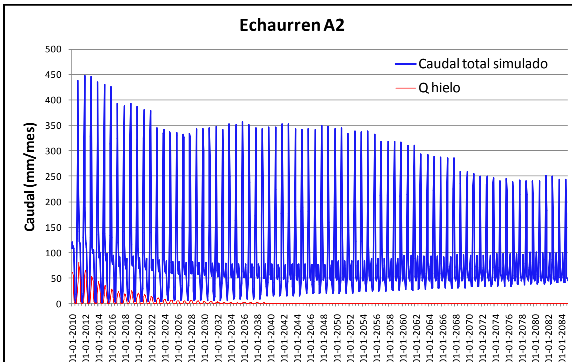


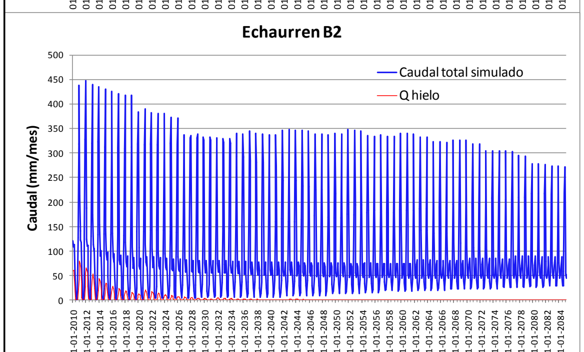
DGA 2010

FUTURE CLIMATE PROJECTIONS for ECHAURREN GLACIER

DGF, UCh, CONAMA, 2006

Escenario	Estación	T°C	pp%
A2	**DEF**	5	25-50
A2	**MAM**	4-5	100
A2	**JJA**	3-4	100
A2	**SON**	2-3	50-70
A2	**ANUAL**	4.0	75
B2	**DEF**	3-4	25-50
B2	**MAM**	3-4	100
B2	**JJA**	2-3	100
B2	**SON**	1-2	50-70
B2	**ANUAL**	3.0	75





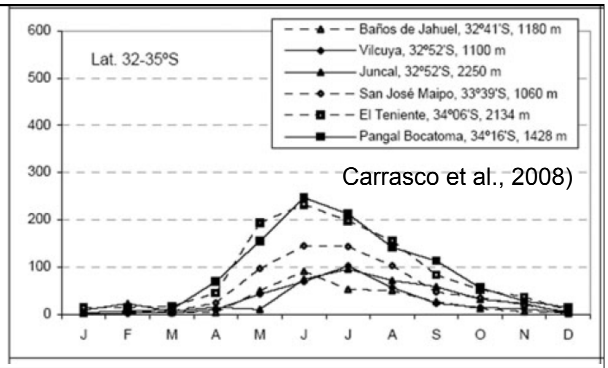
1	x	0,5
2	y	0,03
3	K_{Hielo}	0,5
4	K_{Nieve}	0,5
5	K_{Lento}	0,2
6	$A_{Hielo\ (sucio)}$	4,1
7	$A_{Hielo\ (limpio)}$	3,4
8	$A_{Nieve\ (sucia)}$	2,4
9	$A_{Nieve\ (limpia)}$	1,9

CECs-DGA, Estrategia Nacional de Glaciares, 2008

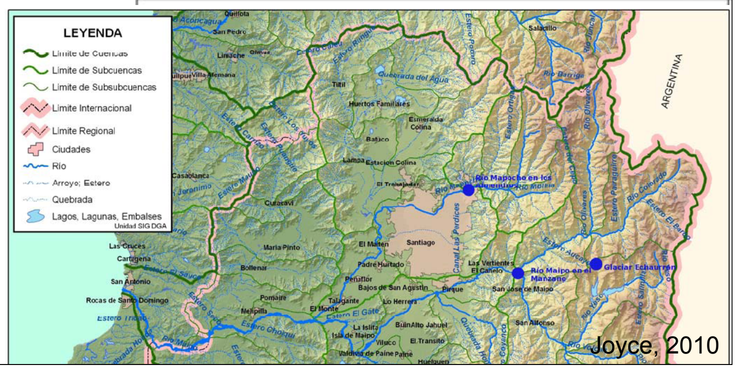
67% glacier runoff contribution to Maipo River at the end of the summer during extremely dry years

(Peña & Nazarala, 1987)

Peña, H. and Nazarala, B. (August 1987)"Snowmelt-Runoff Simulation Model of a Central Chile Andean Basin with Relevant Orographic Effects." Large Scale Effects of Seasonal Snow Cover: Proceedings of the Vancouver Symposium. IAHS Publ. no. 166.



Carrasco et al., 2008)



Joyce, 2010

COLLAPSE OF WATER STATIONARITY.
NEED TO CONSIDER CLIMATE CHANGE!

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Policy Forum, Science, 319, 573-574, 2008

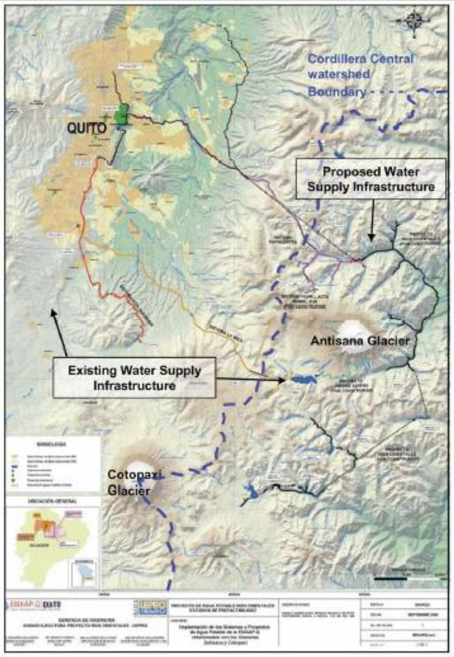


Figure 1.
Relative location of glaciers and moorlands surrounding Quito, Ecuador, as well as the location of infrastructure proposed to meet the city's water demand until 2040.

Table 2. Water Yields in Rios Orientales Project, With and Without the Impact of Glacier Retreat[a]

Rios Orientales Main creek system	Yield With Melting, m^3/s	Yield Without Melting, m^3/s
1. Papallacta-Tumiguina	1.975	1.167
2. Chalpi	1.885	1.225
3. Blanco Grande	0.410	0.267
4. Quiljos	0.324	0.211
5. Azufrado-Pucalpa	1.760	1.144
6. Cosanga	0.891	0.579
7. Antizana-Tambo	1.256	0.816
8. Reservoirs and minor creeks	2.479	1.611

[a]Data provided by Quito's Metropolitan Utility for Sewer Systems and Potable Water [*Institut de Recherche pour le Développement*, 1997]. The runoff estimates without melting from glaciers follow the same approach used for the Mica Project in Table 1.

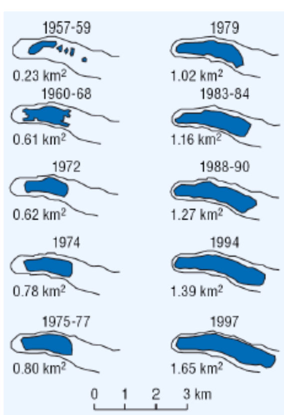
Table 3. Investment Needs: Rios Orientales With and Without Climate Change[a]

Year	Existing Conditions: Creek systems diverted	Investment, US$ million	Expected Conditions: Creek Systems Diverted	Investment, US$ million
2010	Papallacta, Chalpi, Blanco Grande, Quiljos, Azufrado	110	All creek systems are required	143
2011		110		143
2012		113		144
2021	Cosanga	10	Reservoirs and minor creeks	39
2022		11		40
2026	Antizana-Cosanga	22		
2027		22		
	Total NPV value	298		391

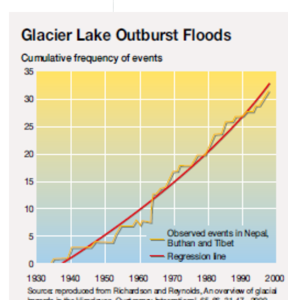
[a]Detailed scheduling of the water supply expansion needed for Quito for two scenarios (data from *Caceres et al.* [2004]). The existing expansion path is shown in second and third columns under the hypothesis of a stable climate (past records are good estimates of future hydrologic behavior). Fourth and fifth columns correspond to the infrastructure expansion path required to supply Quito with its water needs under the scenario of no glacier contribution to runoff.

EOS, Vergara et al., 2007

ENLARGEMENT OF GLACIAL LAKES & GLACIAL LAKE OUTBURST FLOODS (GLOFs)



Tsho Rolpa Lake, Nepal



Tsho Rolpa Lake, one of the largest glacial lakes in Nepal, has increased from 0.23 km2 in 1957/58 to 1.65 km2 in 1997.

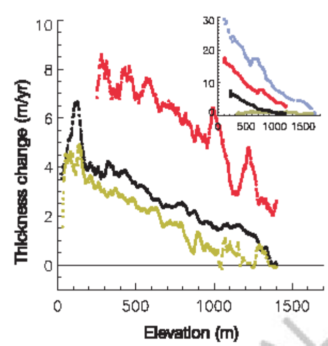
Adaptation project lowered lake level by 3 m in 2002.

Pokhrel 2003; Agrawala 2005

2010

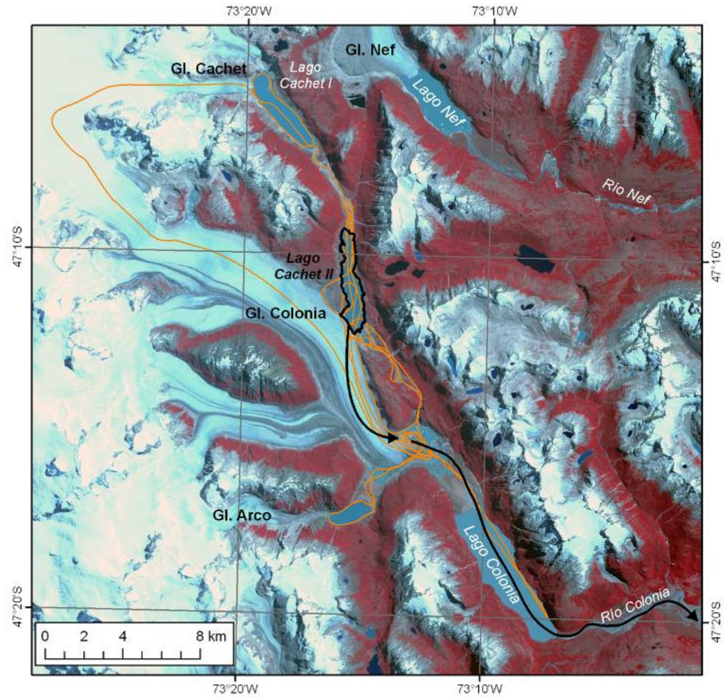
http://www.grida.no/publications/high-mountain-glaciers/

HOLLIN & SCHILLING (1981)



RIGNOT ET AL. (2003)

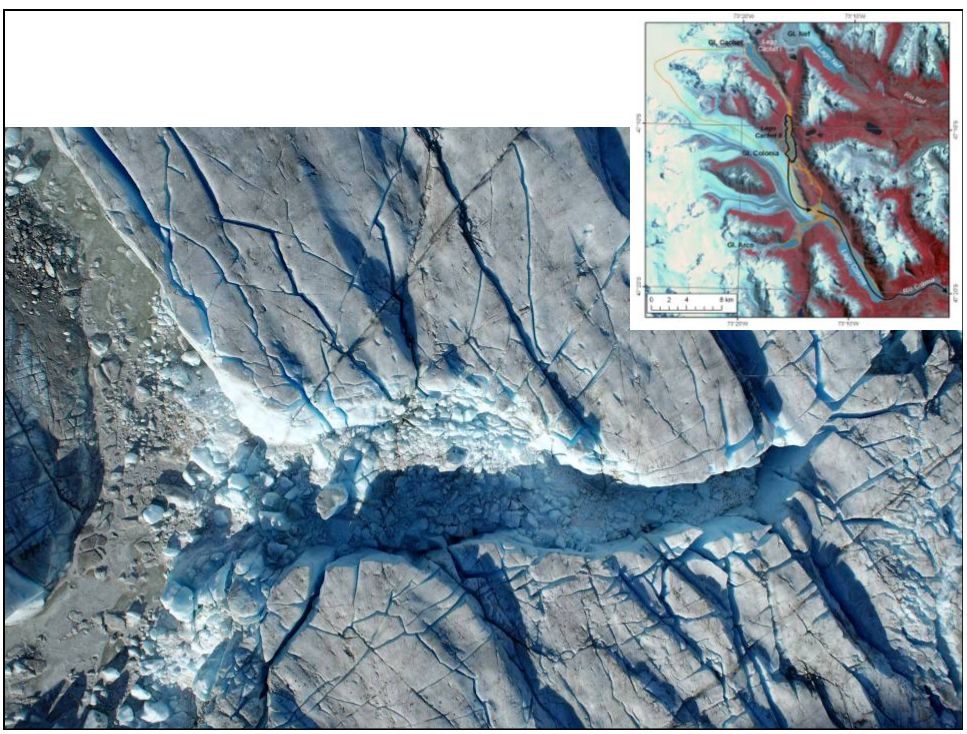
LAKE CACHET II More than 10 large GLOFs since April 2008



LAKE CACHET II

Photo: Jonathan Leidich

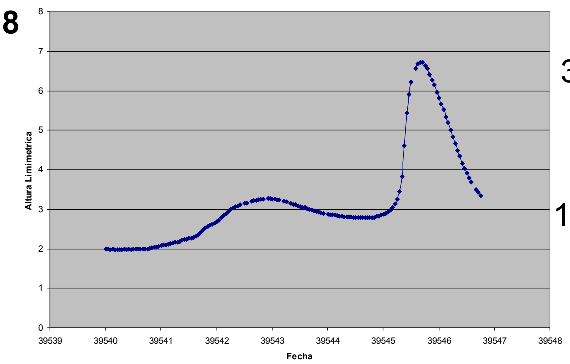

Photo: Jonathan Leidich


73°20'W
73°10'W
Gl. Cachet
Gl. Nef
Lago Cachet I
Lago Nef
Río Nef
Lago Cachet II
Gl. Colonia
Gl. Arco
Lago Colonia
Río Colonia
0 2 4 8 km

GLOF
07 April 2008

DGA Station Baker River below Colonia River

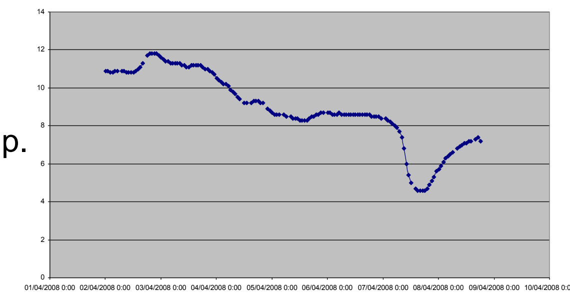
Runoff



3570 m^3/s

1200 m^3/s

Water temp.

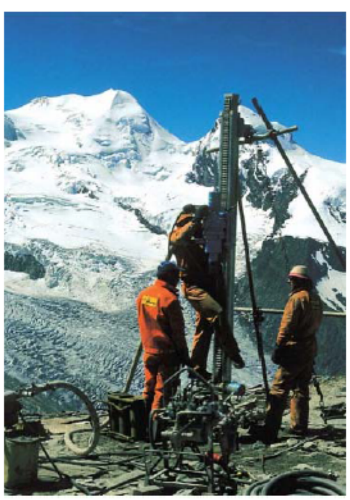


8 °C

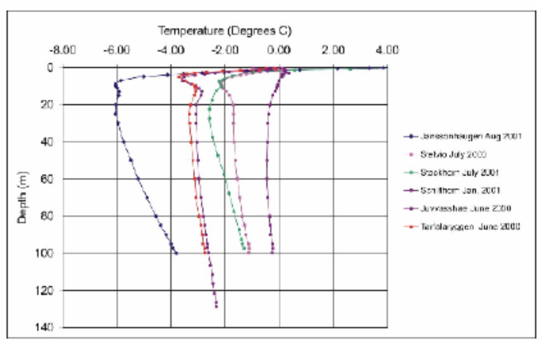
4 °C

Mountain Permafrost Warming

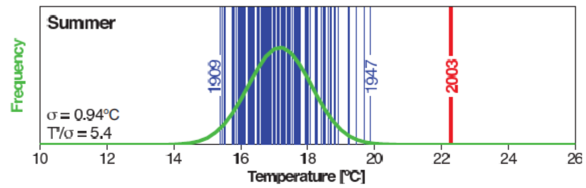
Alps, Southern Norway, Tibetan Plateau, Tianshan, Da Hinggan Mountains



Alps



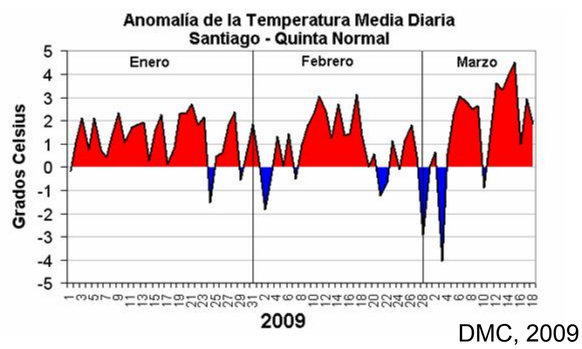
Harris, C., D. Vonder Mühll, K. Isaksen, W. Haeberli, J.L. Sollid, L. King, P. Holmlund, F. Dramis, M. Guglielmin, and D. Palacios, 2003
Vonder Mühll et al., 2004
Zhao et al., 2003
Wu and Liu, 2003; Zhao et al., 2004a
Qiu et al., 2000; Zhao et al., 2004
Zhou et al., 1996
Zhou et al., 1996
Isaksen et al., 2001



FAQ 9.1, Figure 1. *Summer temperatures in Switzerland from 1864 to 2003 are, on average, about 17°C, as shown by the green curve. During the extremely hot summer of 2003, average temperatures exceeded 22°C, as indicated by the red bar (a vertical line is shown for each year in the 137-year record). The fitted Gaussian distribution is indicated in green. The years 1909, 1947 and 2003 are labelled because they represent extreme years in the record. The values in the lower left corner indicate the standard deviation (σ) and the 2003 anomaly normalised by the 1864 to 2000 standard deviation (T'/σ). From Schär et al. (2004).*

2003 SUMMER HEAT WAVE IN EUROPE

IPCC, 2007

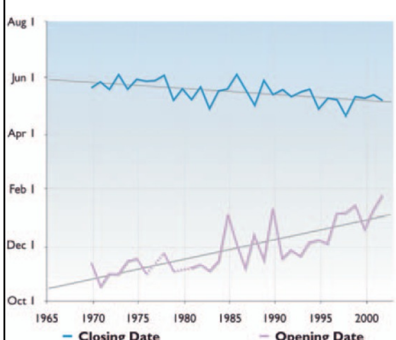


DMC, 2009

2008/2009: verano más cálido desde 1915

La temperatura máxima alcanzó este verano pasado 30.6°C, como promedio de la estación de verano. El valor medio histórico es de 28.9°C, es decir, representa un calentamiento del aire 1.7°C mayor que el valor medio histórico. La zona centro-sur, entre Curicó y Temuco, también se caracterizó por presentar unos de los veranos más cálidos en los últimas 5 décadas. Los promedios de la temperatura máxima fueron 30.7°C en Curicó, 29.7°C en Chillán y 26.1°C en Temuco, representado así una anomalía térmica que superó en casi 2°C el promedio histórico.

Thawing of frozen ground

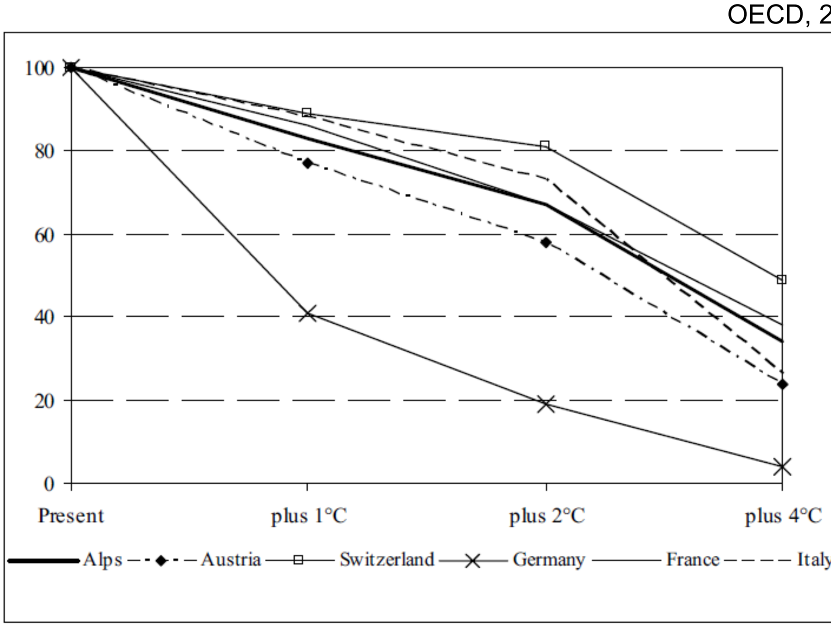


The number of travel days for oil exploration on Alaskan tundra has been decreasing over recent decades as the opening dates come later and the closing dates come earlier (ACIA 2003)

Thawing of frozen soil and rock in high-mountain areas can produce slope instability and rock falls. A reported case linked to warming is the exceptional rock fall activity in the Alps during the 2003 summer heat wave, when the active layer in the Alps deepened significantly, by 30% to 100% of the depth measured before the heat wave (Gruber, 2004, permafrost; Schär, 2004, role; Noetzli, 2003, permafrost).

Figure 5. **Sensitivity of Alpine ski areas to changes in the line of natural snow-reliability**
(in %, 100= present-day naturally snow-reliable ski areas)

OECD, 2007



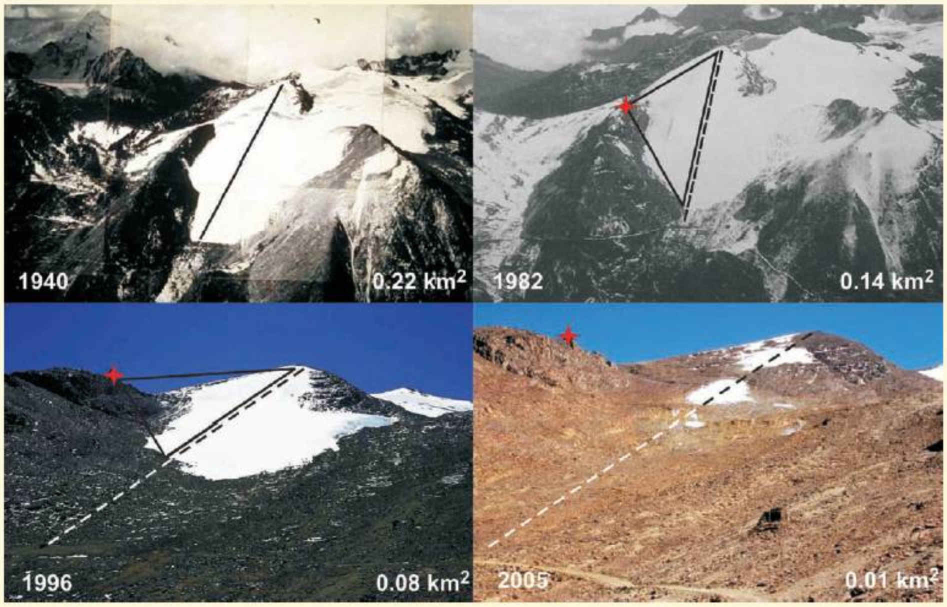
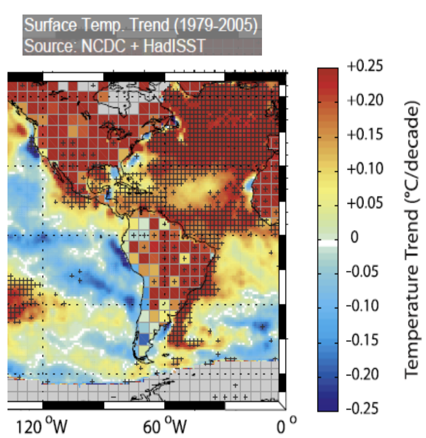


Figure 1.1. *Areal extent of Chacaltaya Glacier, Bolivia, from 1940 to 2005. By 2005, the glacier had separated into three distinct small bodies. The position of the ski hut, which did not exist in 1940, is indicated with a red cross. The ski lift, which had a length of about 800 m in 1940 and about 600 m in 1996, was normally installed during the summer months (precipitation season in the tropics) and covered a major portion of the glacier, as indicated with a continuous line. The original location of the ski lift in 1940 is indicated with a segmented line in subsequent epochs. After 2004, skiing was no longer possible. Photo credits: Francou and Vincent (2006) and Jordan (1991).* IPCC, 2007

Regional cooling in a warming world

Falvey & Garreaud, JGR, 2009



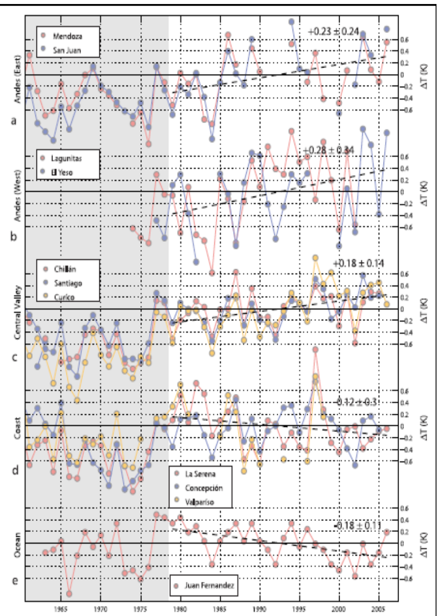
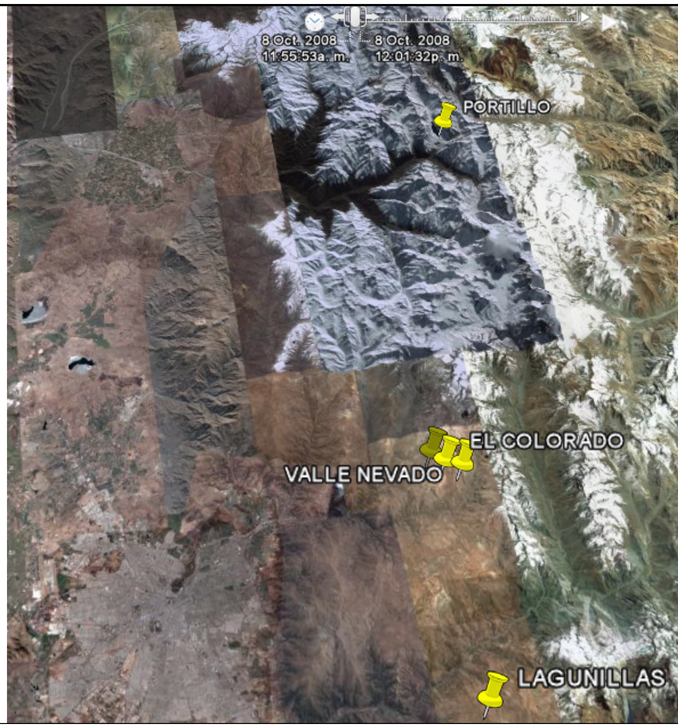
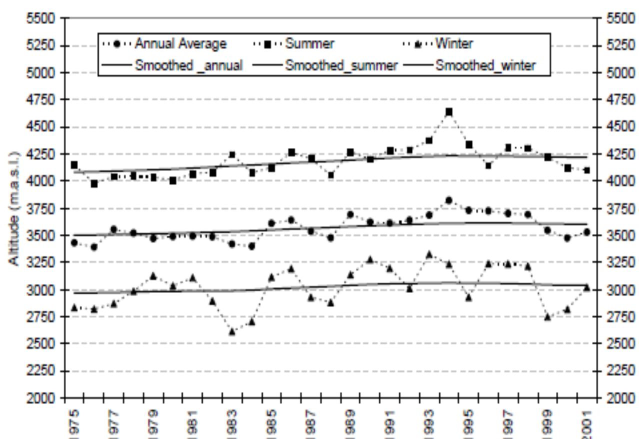


Figure 2. Time series of surface atmospheric temperature anomalies (ΔT) in central Chile (27.5°–37.5°S). Anomalies are calculated with respect to the period 1979–2006. Stations are divided into five geographic zones, which are (from bottom to top): (e) ocean, (d) coast, (c) central valley, (b) western Andes, and (a) eastern Andes. Data from a station at Valparaiso are included in the central plot, although due to the large amount of missing data trends they are not calculated for Valparaiso elsewhere. The dashed lines show the linear fit to the data in each group for the period 1979–2006, calculated from the annual mean ΔT from all stations in each group. The associated trends, along with the 90% confidence interval, are also provided. Gray shading identifies years prior to 1979.

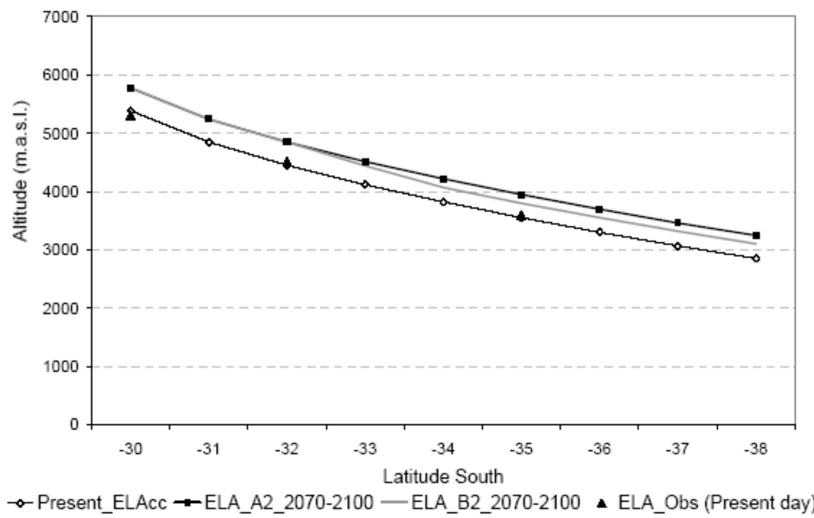


0°C isotherm altitude



Carrasco *et al.*, J. Glac., 2008

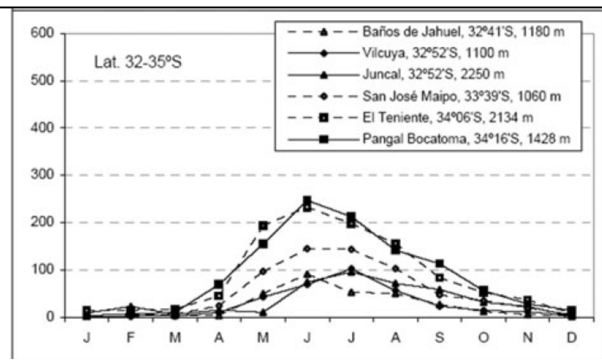
Ascenso de la línea de nieves – línea de equilibrio

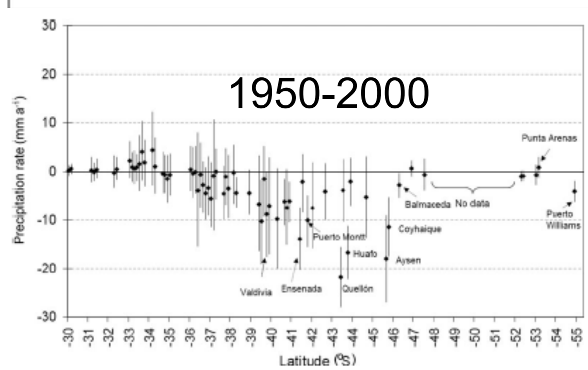


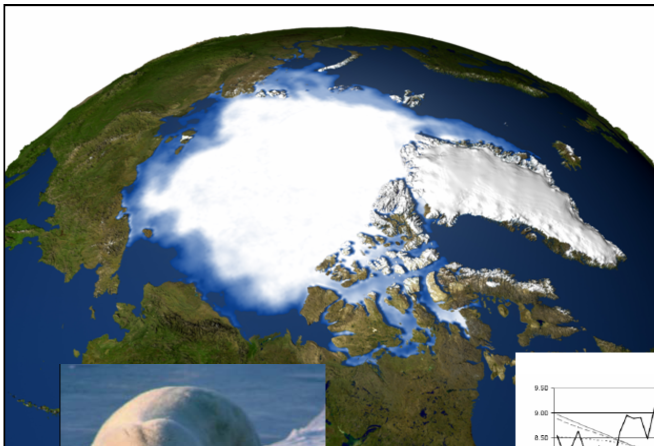
Carrasco, Casassa & Quintana, 2005

Precipitation Central Chile

Carrasco *et al.*, J. Glac., 2008







Warming 'opens Northwest Passage'

The most direct shipping route from Europe to Asia is fully clear of ice for the first time since records began.

14 Sep 2007

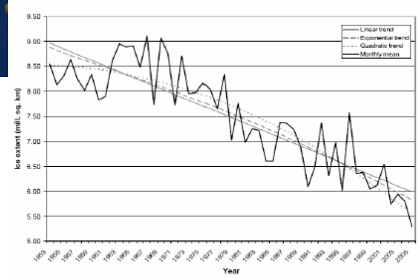


Figure 3. Adjusted Hadley September ice extent, 1953-2005 (black), with linear, exponential, and quadratic fit lines (gray).

Meier et al., 2008

Risks to Unique and Threatened Systems

Arctic Region
Human Systems

NARA, 2005

- Warming is disrupting indigenous hunting and food sharing as reduced sea ice causes the animals on which they depend to decline.
- Roads are sinking into melting permafrost, or being inundated by rising seas
- Reduced sea ice is a causing increases in coastal erosion.

ACIA 2004

QOYLLUR RITI: ETHNOGRAPHY OF A RITUAL PEREGRINATION OF INCA ORIGIN IN THE HIGH MOUNTAINS OF SOUTHERN PERU

M.C. Ceruti. 2007. Scripta Ethnologica, Vol. XXIX, 9-35.

Summary: The sanctuary *Señor de la Estrella de Nieve (Star of Snow Lord -Qoyllur Riti) is located* 4700 meters above sea level, in the Vilcanota Range of the Peruvian Andes. The festivity of *Qoyllur Ritti is one of the most important mountain pilgrimages in the modern Andean world, congregating* thousands of native Quechuas devotees every year, in late May or early June. The pilgrims engage in austerities such as purification by water, ritual dancing, whipping and ice climbing, in addition to completing a procession of over 30 kilometers on abrupt mountain terrain. Ritual activities also involve the presentation of offerings to the mountain spirits, as well as collecting sacred ice, which is believed to have healing properties. Based on the participant observations by the author, this paper studies the festivity of the *Estrella de Nieve (Star of Snow), analyzing its ritual and symbolic elements (of probable* ncient origin) which seem to echo some aspects of the ceremonies performed by the Inca civilization five centuries ago.

Mount Colquepunku

Air temp. N of 65ºN

NH sea ice

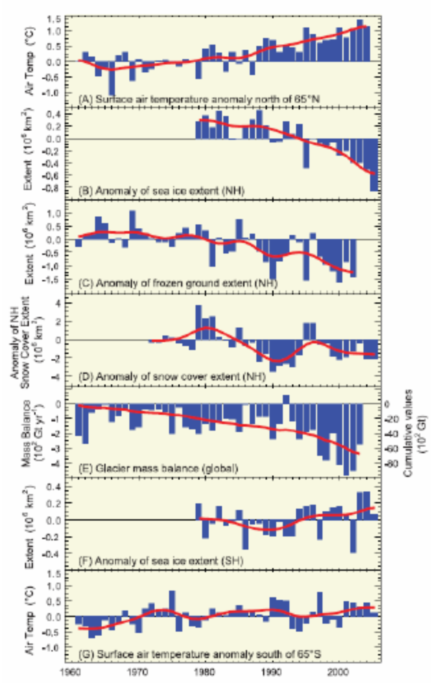
NH frozen ground

NF snow cover

Global glacier mass balance

SH sea ice

Air temp. S of 65ºS



IPCC. 2007

CONCLUSIONS

1. A significant melting and reduction of all cryospheric components has been observed globally, including snow, ice and frozen ground.
2. The present glacier retreat is unprecedented within the last 1000 years and cannot be explained by natural climate variability or by glacier dynamics, it is in fact largely due to warming driven by the anthropogenic greenhouse effect.
3. In turn the snow and ice retreat is producing relevant impacts in the environment, water resources, in indigenous livelihoods in the Arctic, and in human activities such as sport and tourism in alpine areas.
4. Future warming scenarios will result in an amplification of all these effects, leading possibly to major impacts such as reduced polar/high altitude species, destruction of infrastructure in permafrost terrain, destructive rock avalanches, increased glacial lake outburst floods, short-term increase in glacial runoff and long-term decrease of snow & ice runoff. Critical natural feedbacks can be severely enhanced as well due to global warming, such as the albedo feedback and the carbon release to the atmosphere from permafrost storage.