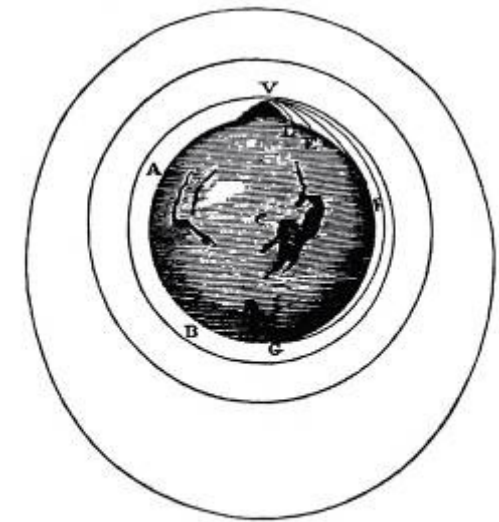


# Snow and Ice on Planet Earth: Present State, Impacts and Projections

Gino Casassa

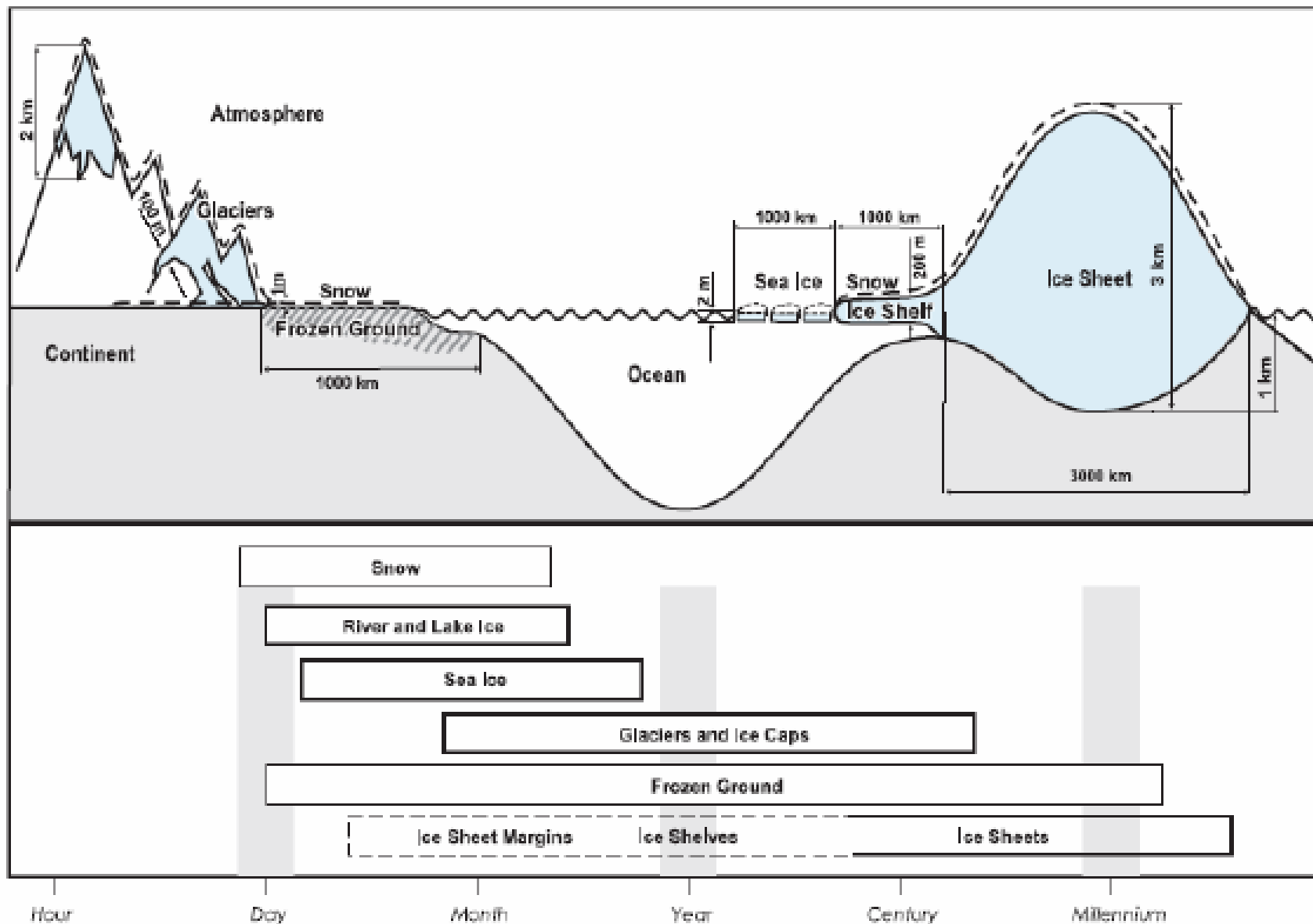


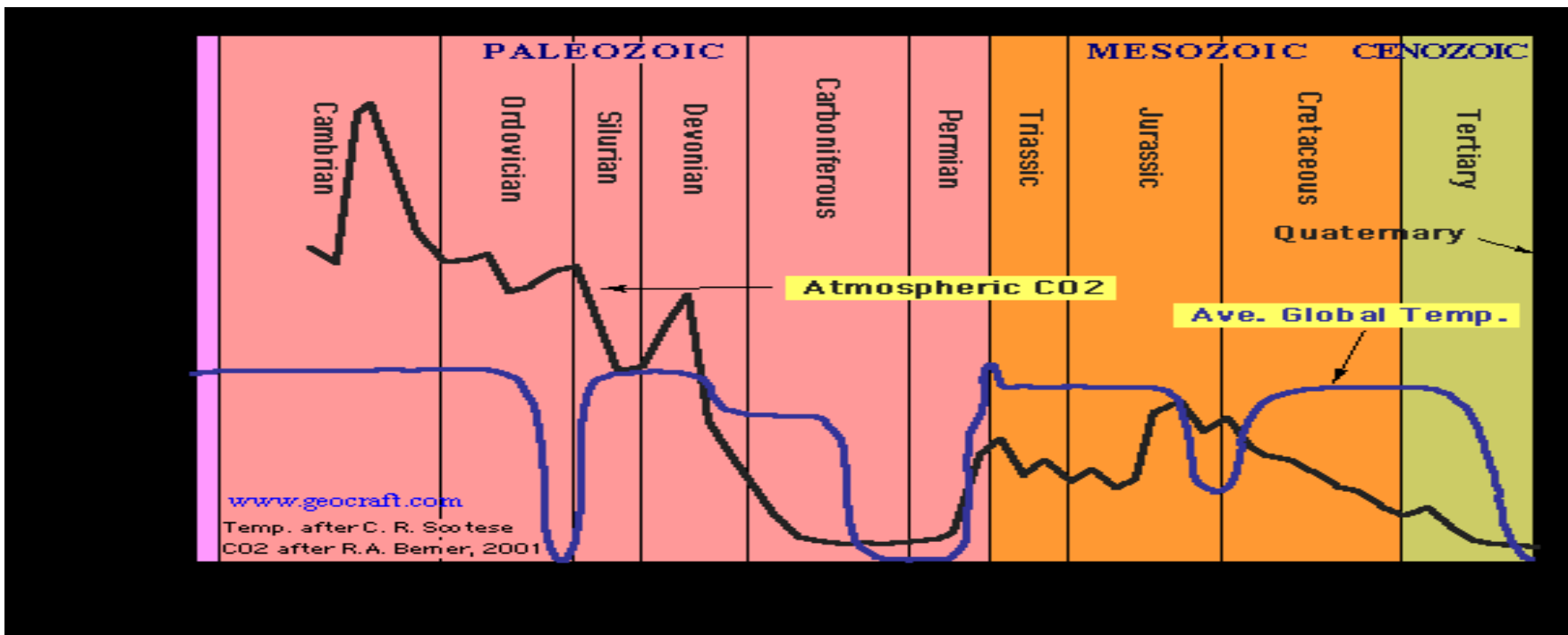
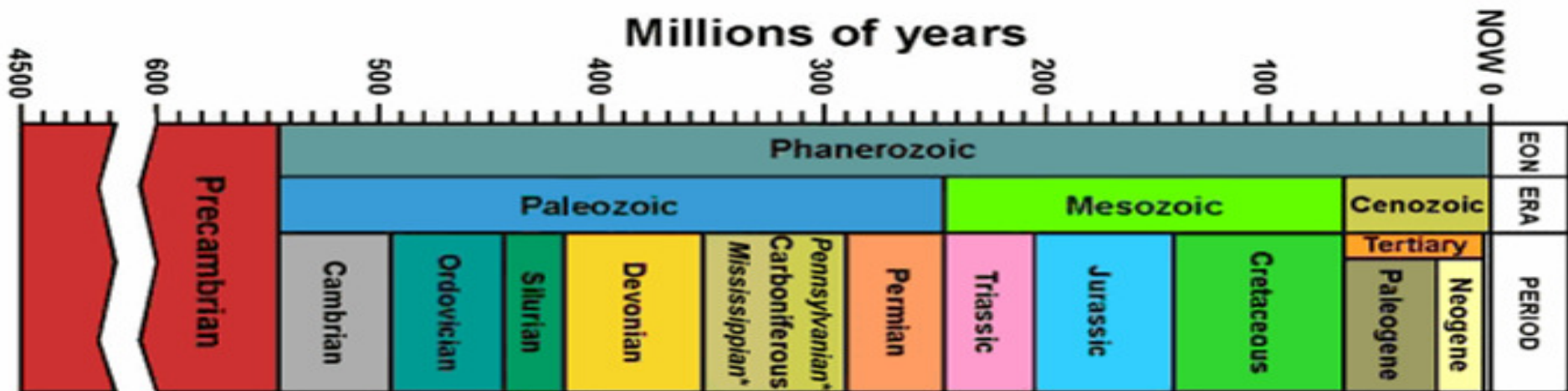
CECS

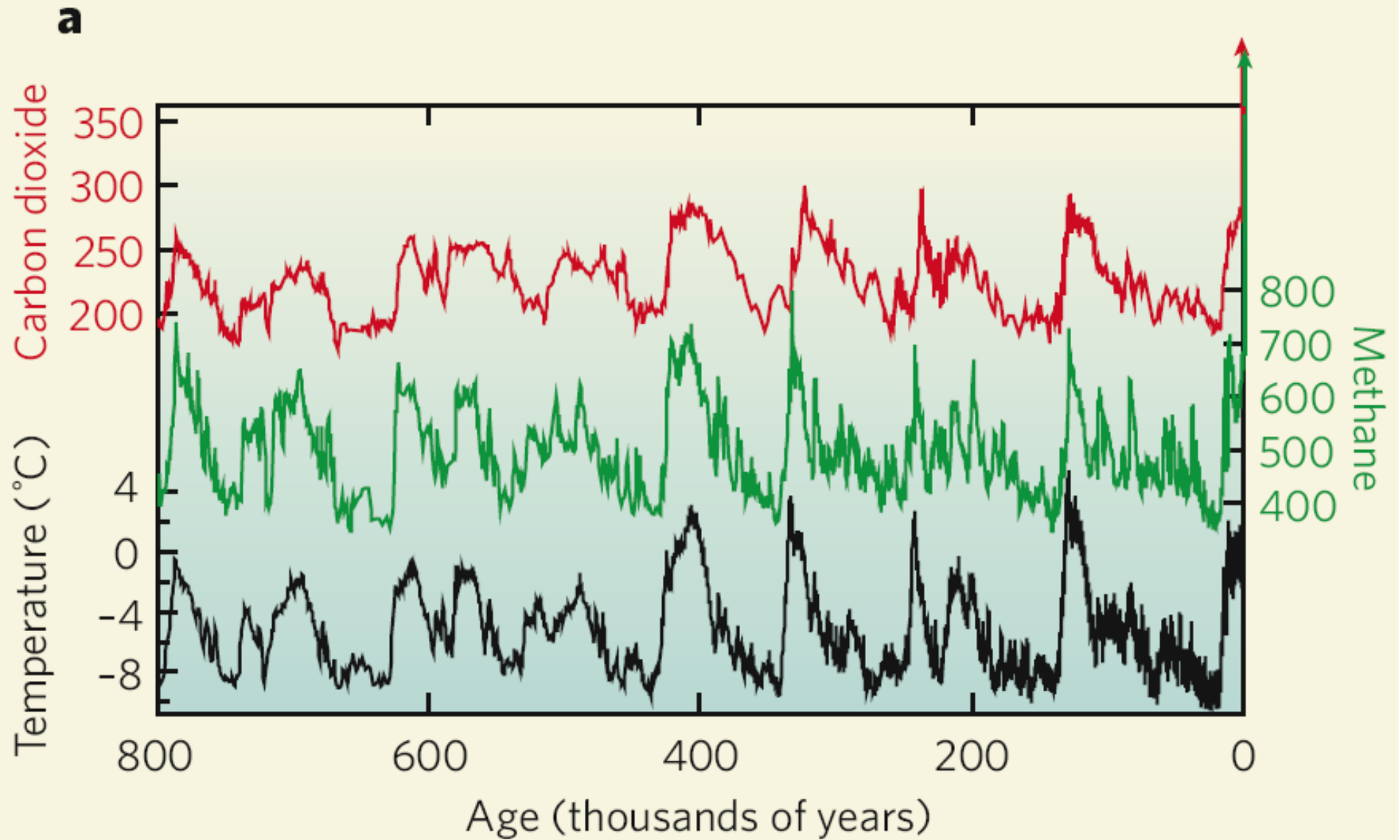
Centro de  
Estudios  
Científicos,  
Valdivia

*Climate Change and Water Extremes  
Water and Sustainability  
Expo Zaragoza 2008, Zaragoza, 21 July 2008*

# CRYOSPHERE

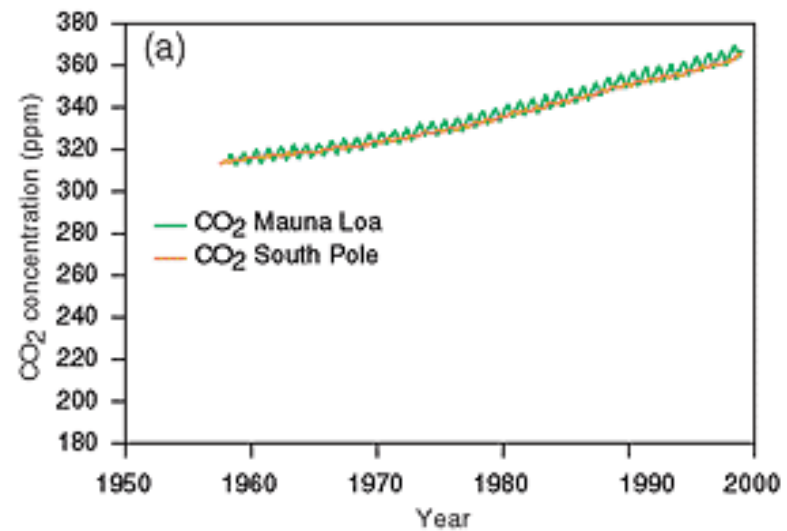
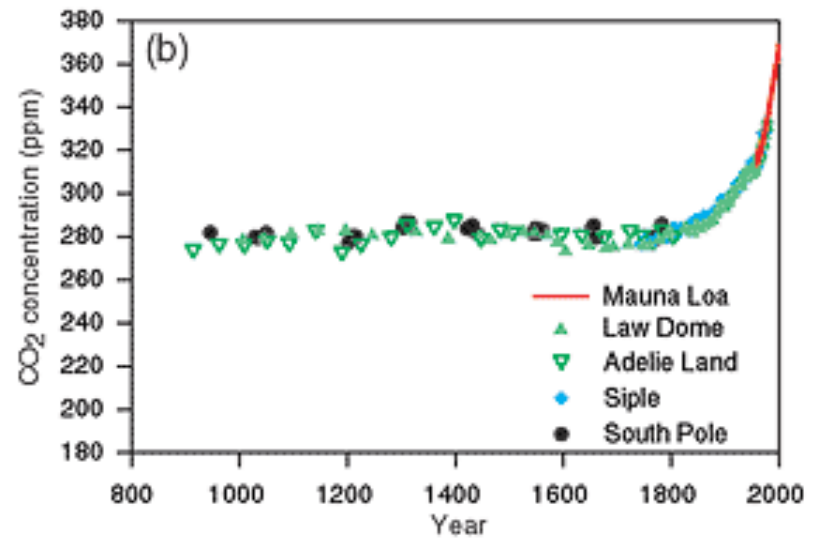
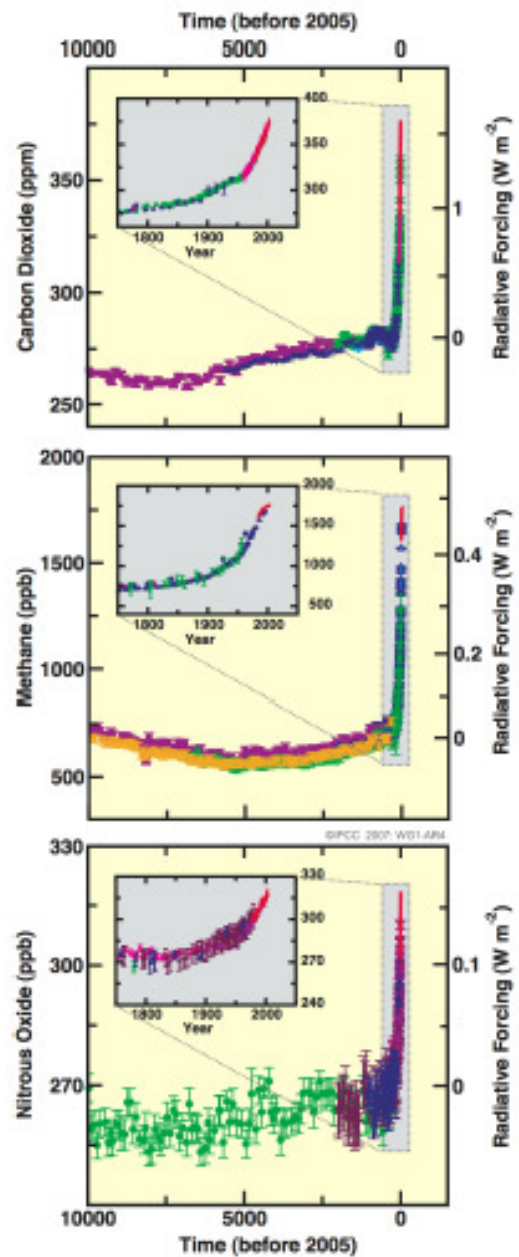


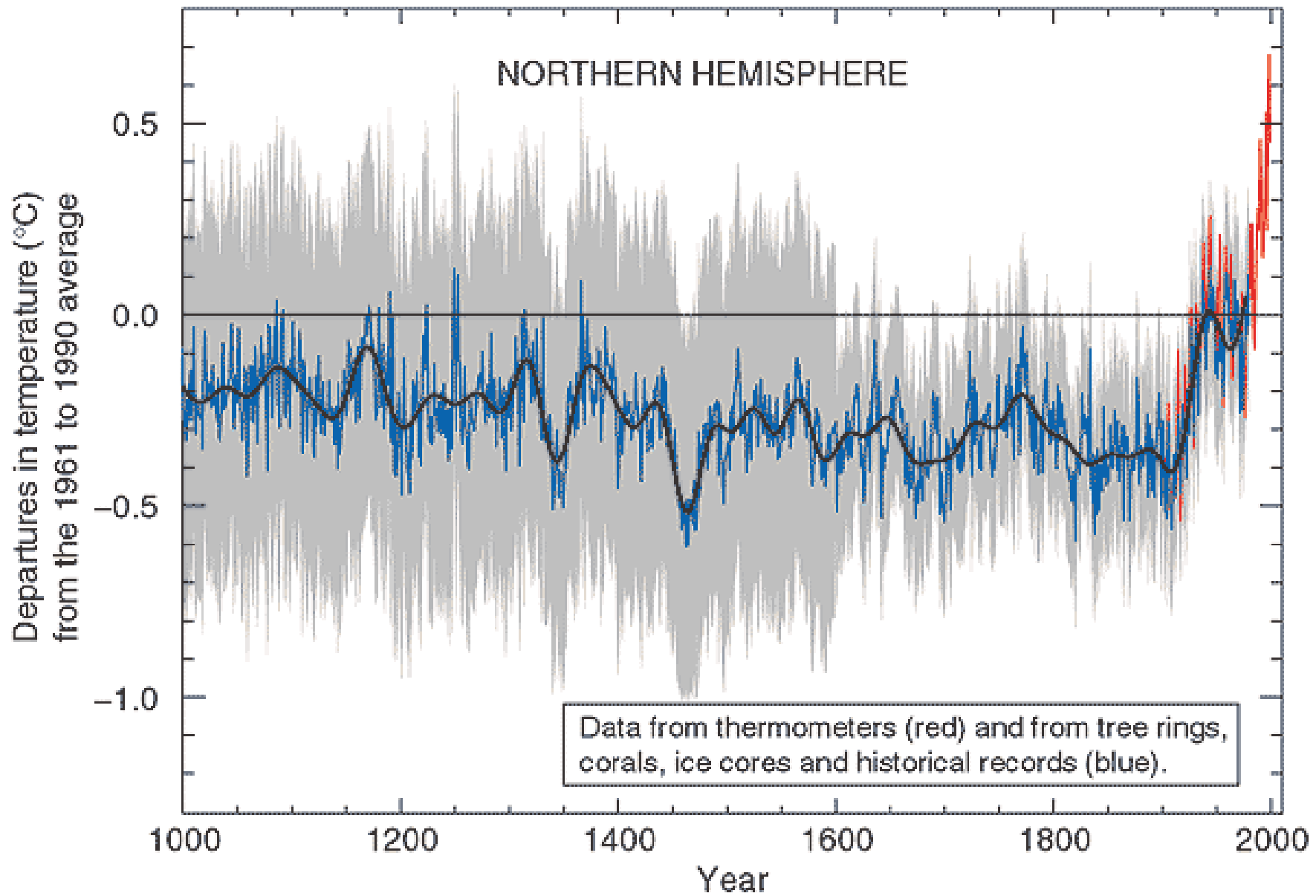




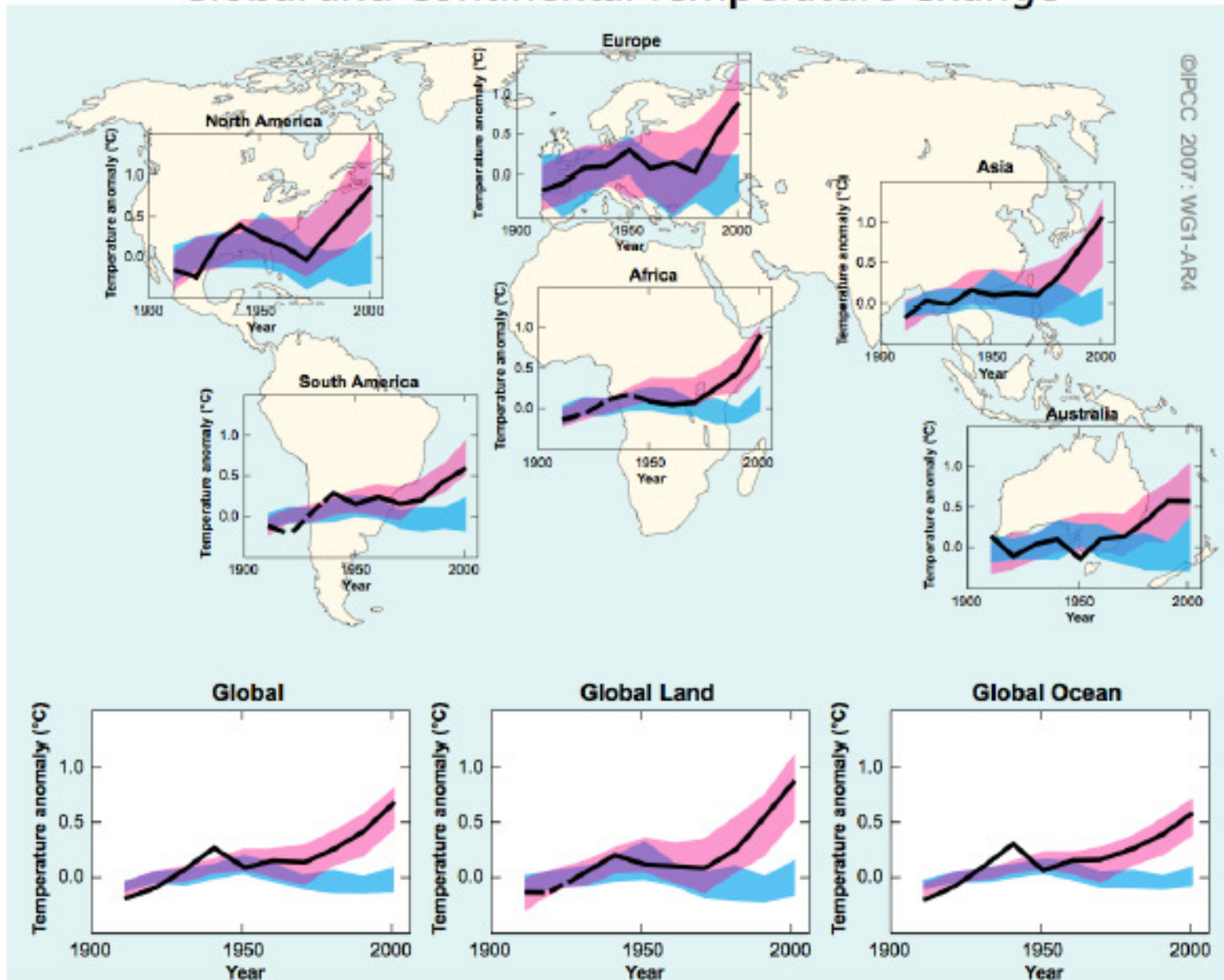
Lüthi et al. & Loulergue et al., 2008. Nature, 15 May 2008

## Changes in Greenhouse Gases from ice-Core and Modern Data





# Global and Continental Temperature Change



Temperate Ice

( $T=0^{\circ}\text{C}$ )

vs.

Cold Ice

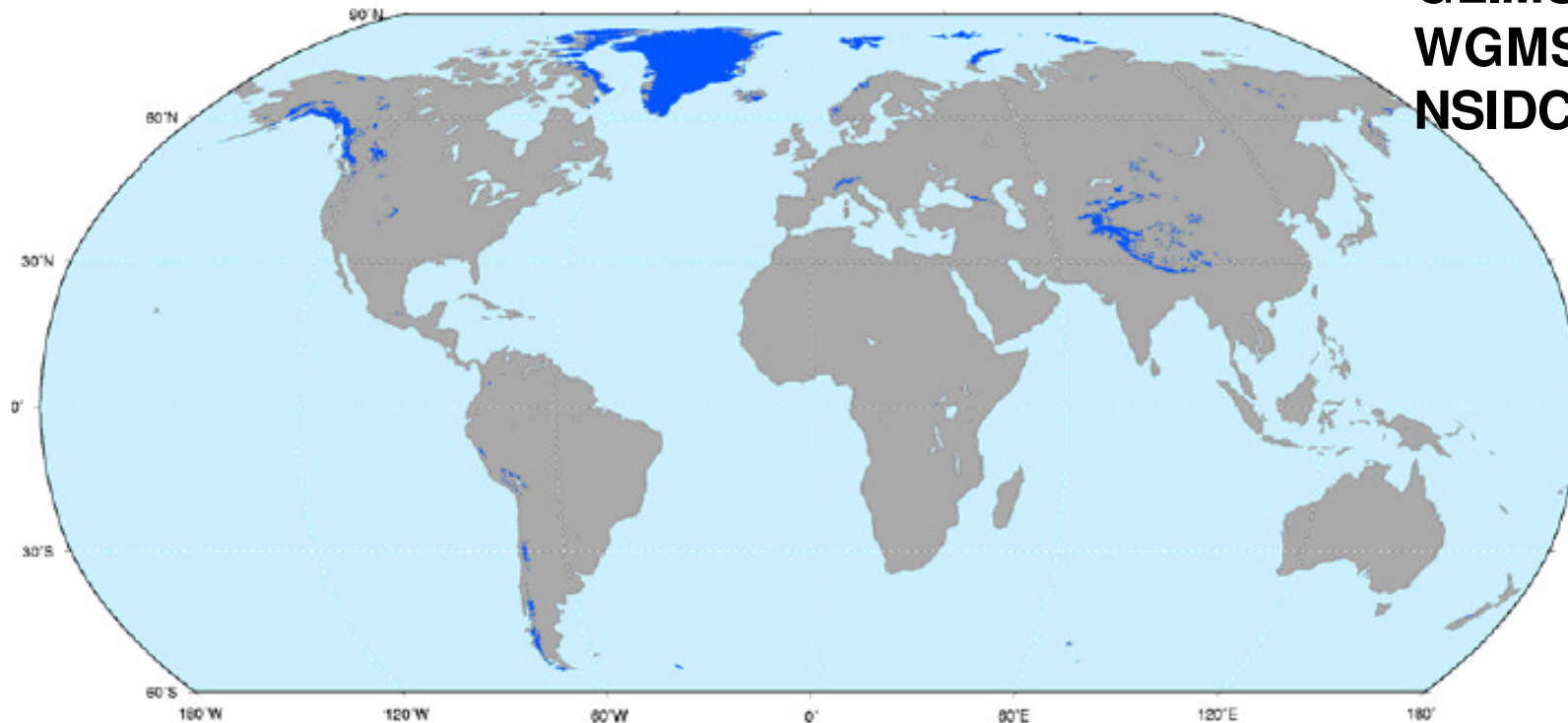
( $T<0^{\circ}\text{C}$ )



Never put your tongue on a glacier.

Gary Larson, The Far Side

**GLIMS  
WGMS  
NSIDC**



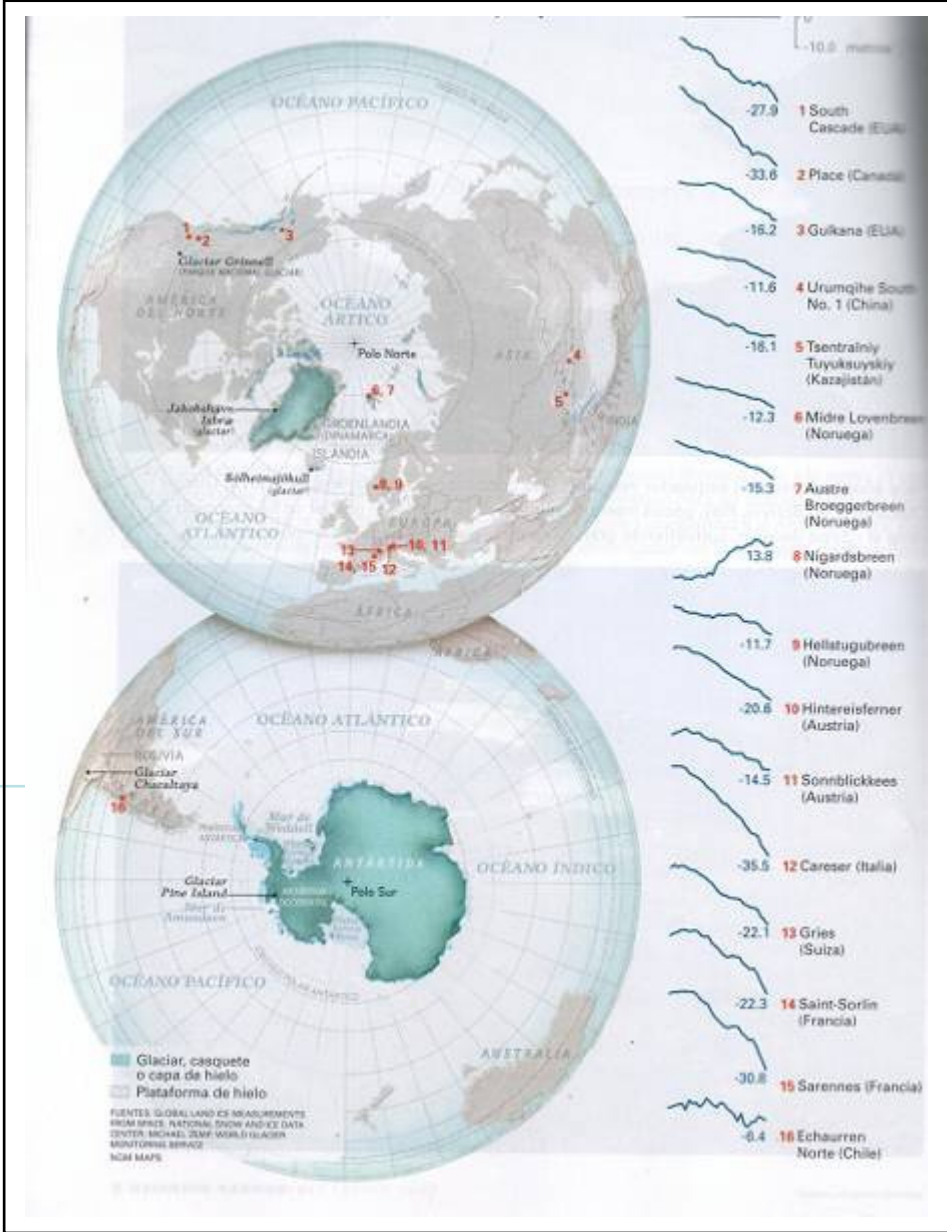
	<b>Glaciers</b>	<b>Ice caps</b>	<b>Glaciers and ice caps<sup>a</sup></b>	<b>Greenland ice sheet<sup>b</sup></b>	<b>Antarctic ice sheet<sup>b</sup></b>
Number	>160 000	70			
Area (10 <sup>6</sup> km <sup>2</sup> )	0.43	0.24	0.68	1.71	12.37
Volume (10 <sup>6</sup> km <sup>3</sup> )	0.08	0.10	0.18 ± 0.04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

Antarctica: 13,586,400 km<sup>2</sup>; Greenland 1,736,095 km<sup>2</sup>; Canadian Arctic islands: 151,057 km<sup>2</sup>; Central Asia: 114,800 km<sup>2</sup>; North America 76,880 km<sup>2</sup>; South America 29,347 km<sup>2</sup> (Chile 75%); Europe: 5,759 km<sup>2</sup>; Africa: 10 km<sup>2</sup>

30 YEARS

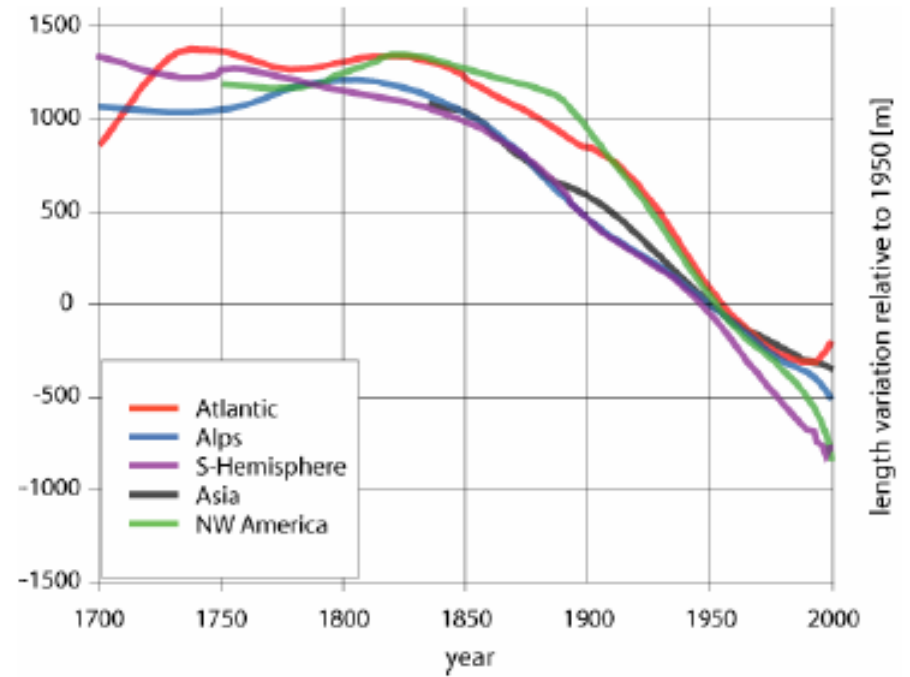
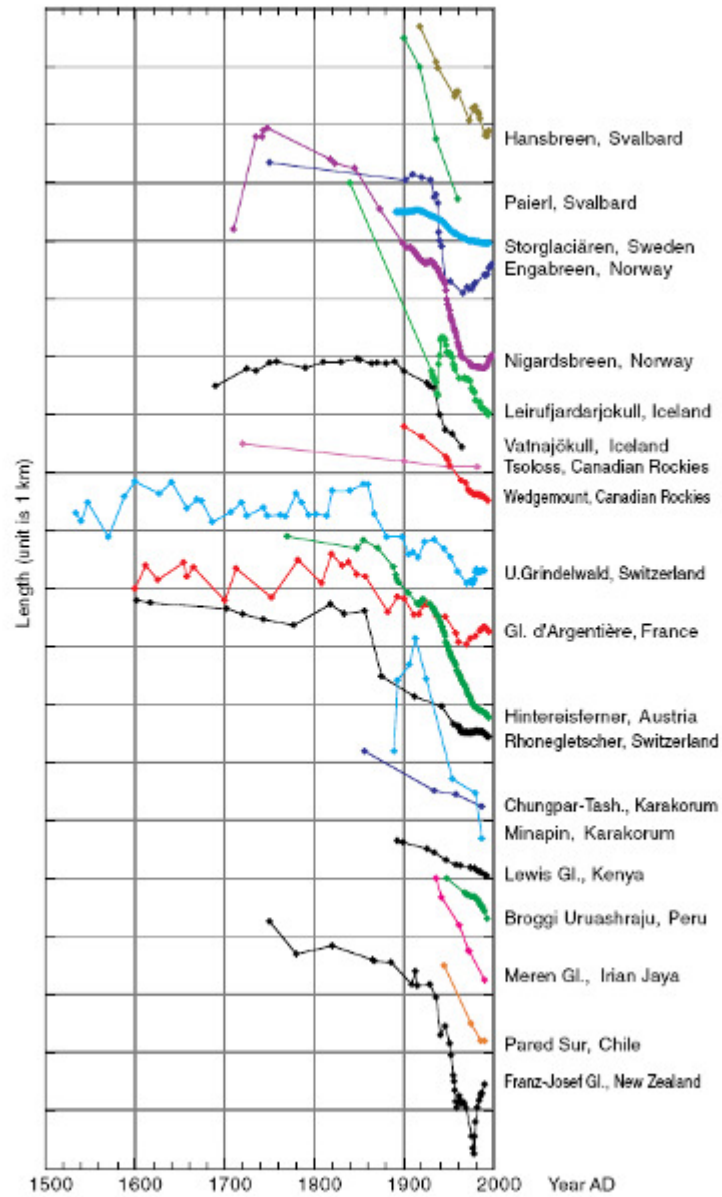
10 METERS

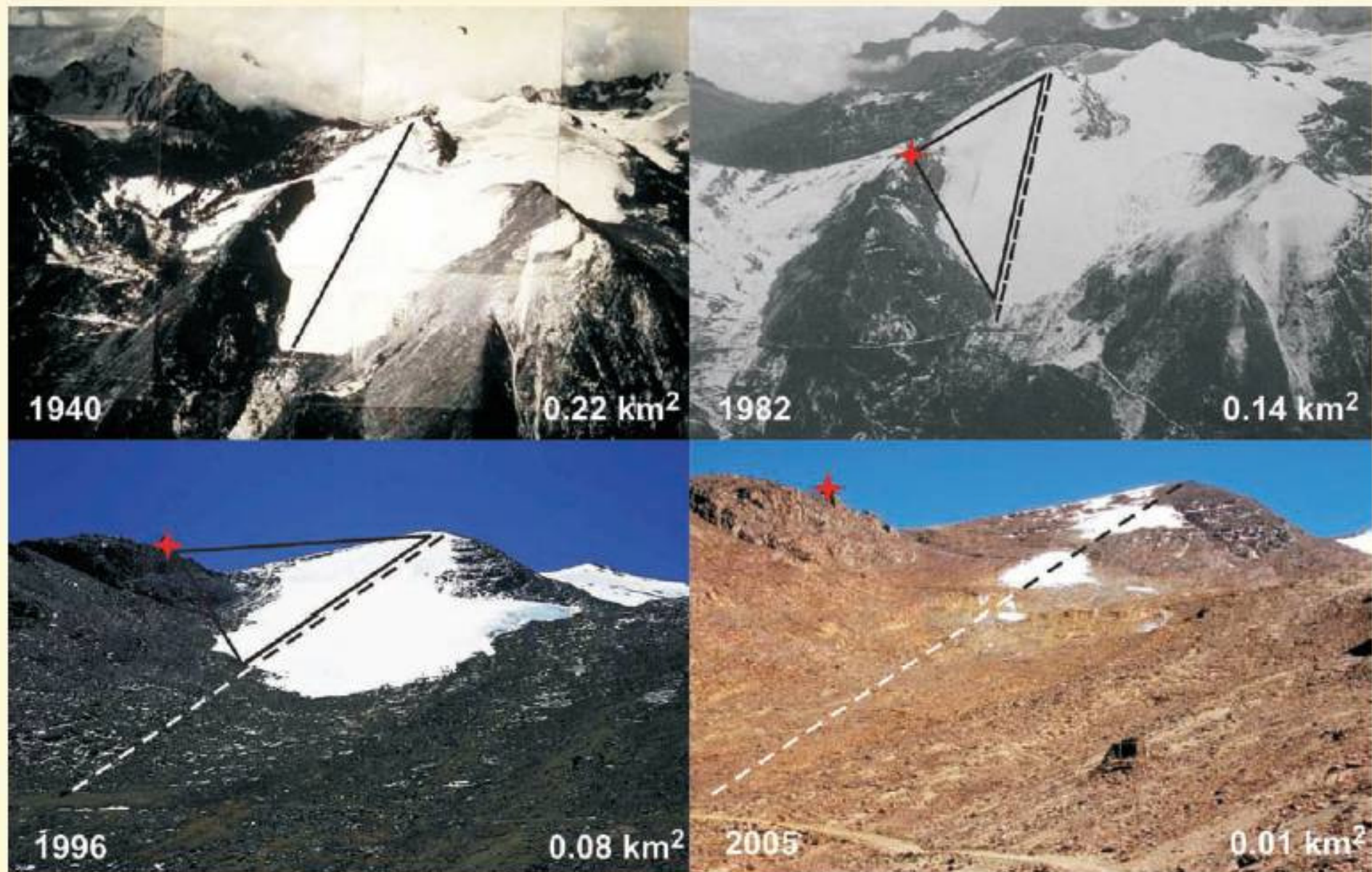
# Glacier Mass Balance



National Geographic, 2007

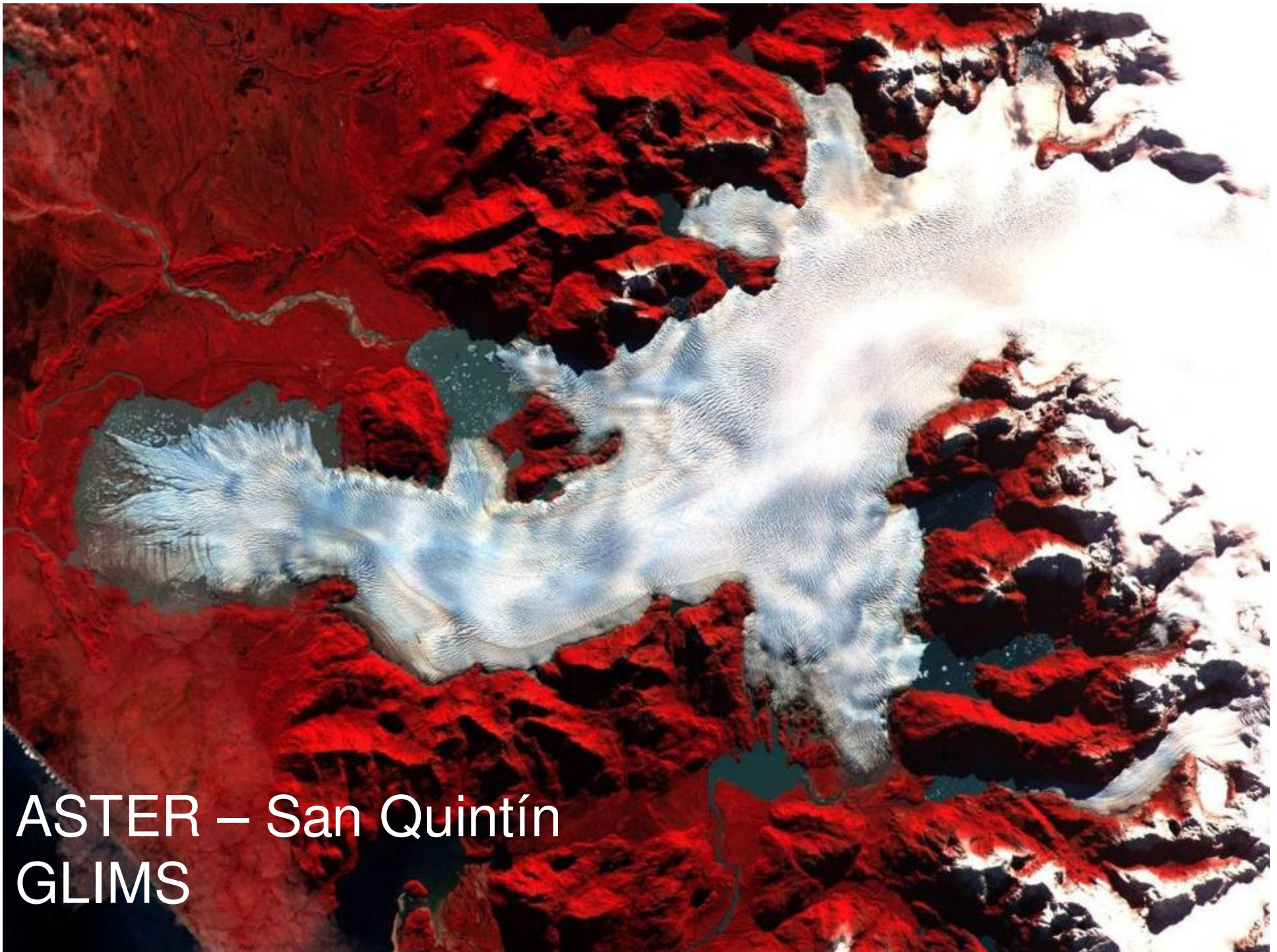
# WGMS





**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).

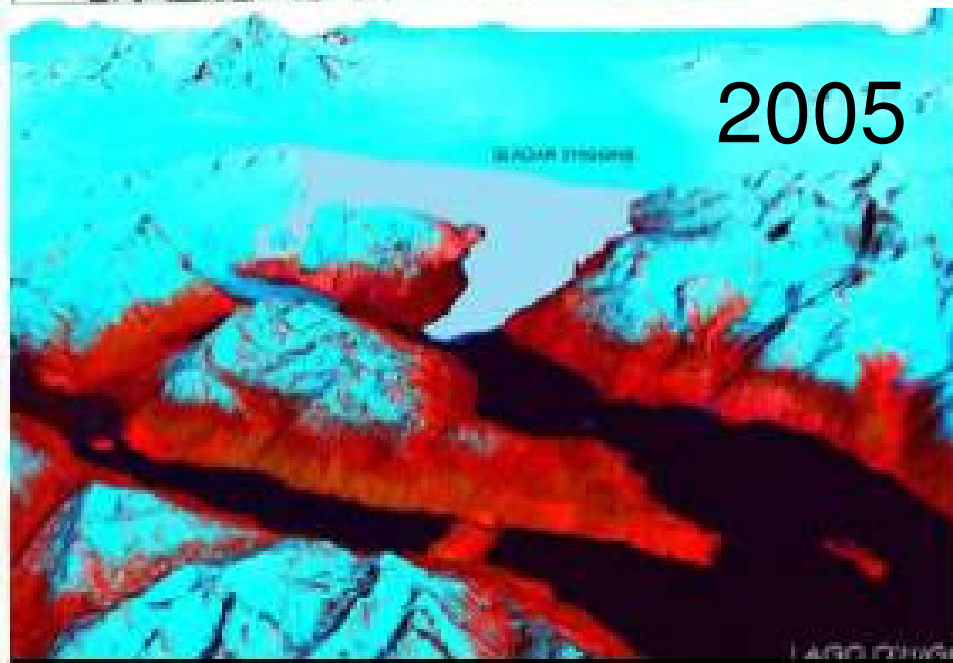
IPCC, 2007



ASTER – San Quintín  
GLIMS

# O'Higgins Glacier, Patagonia

(Casassa, 2008)

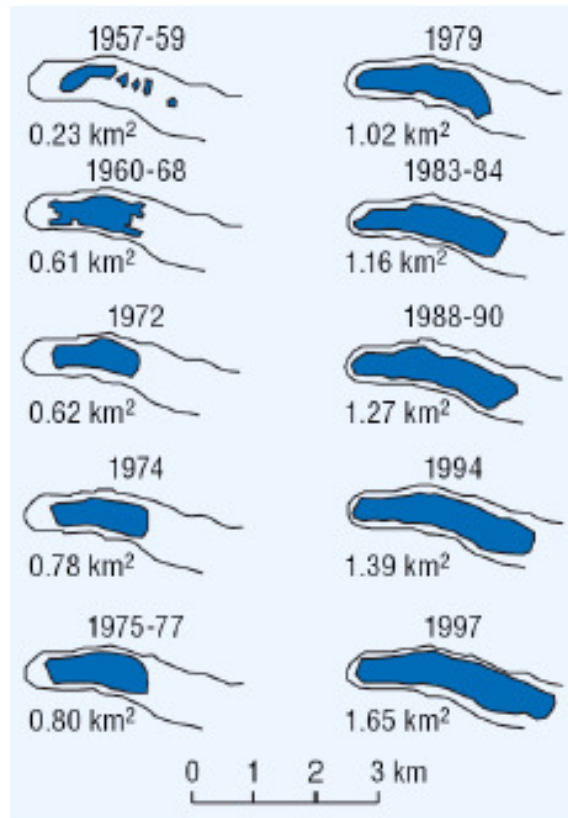


# Muir Glacier, Alaska

(NSIDC/WDC, 2006)



# Enlargement of Glacial Lakes

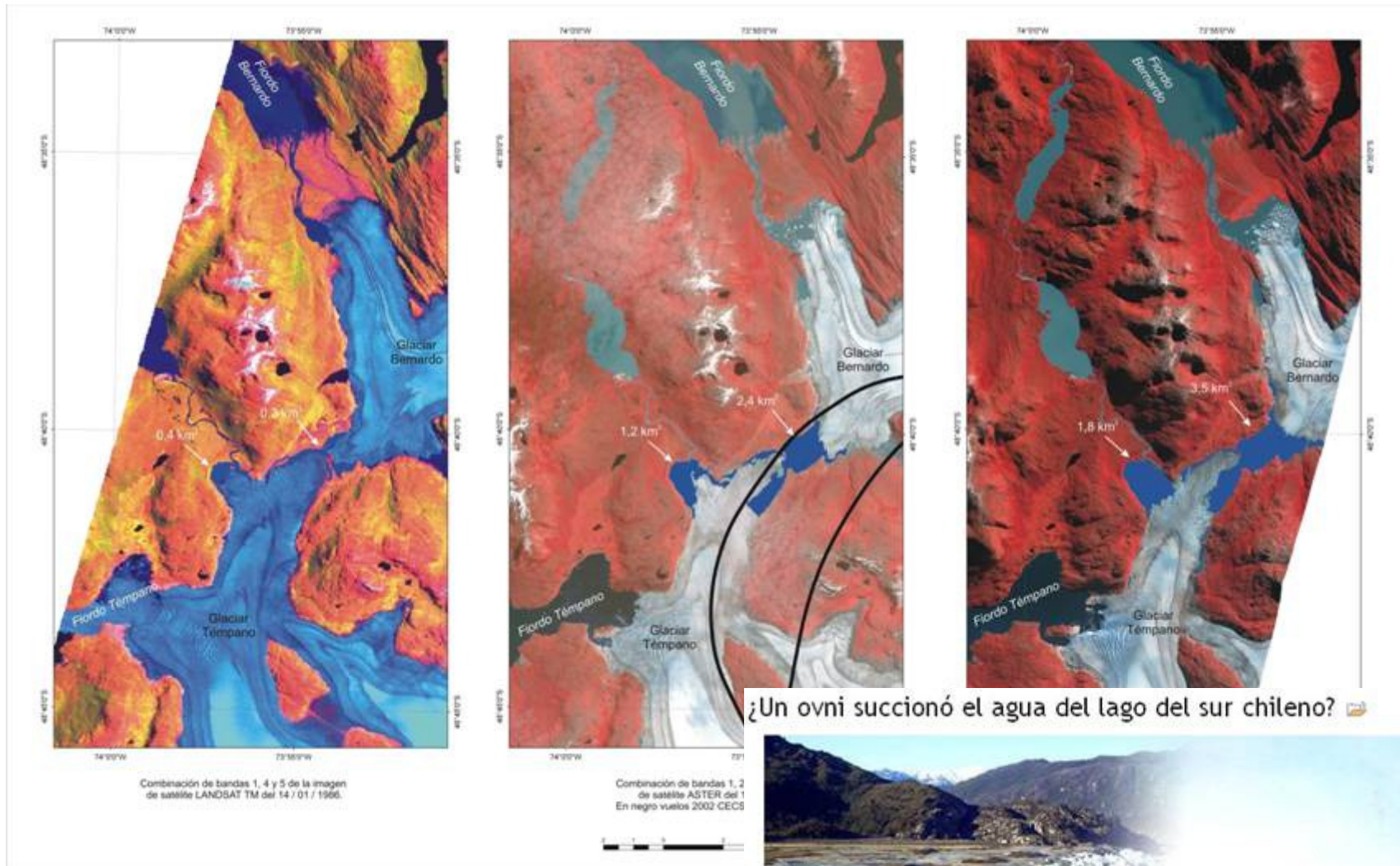


Tsho Rolpa Lake, Nepal

**Tsho Rolpa Lake, one of the largest glacial lakes in Nepal, has increased from 0.23 km<sup>2</sup> in 1957/58 to 1.65 km<sup>2</sup> in 1997.**

**Adaptation project lowered lake level by 3 m in 2002.**

**Pokhrel 2003; Agrawala 2005**

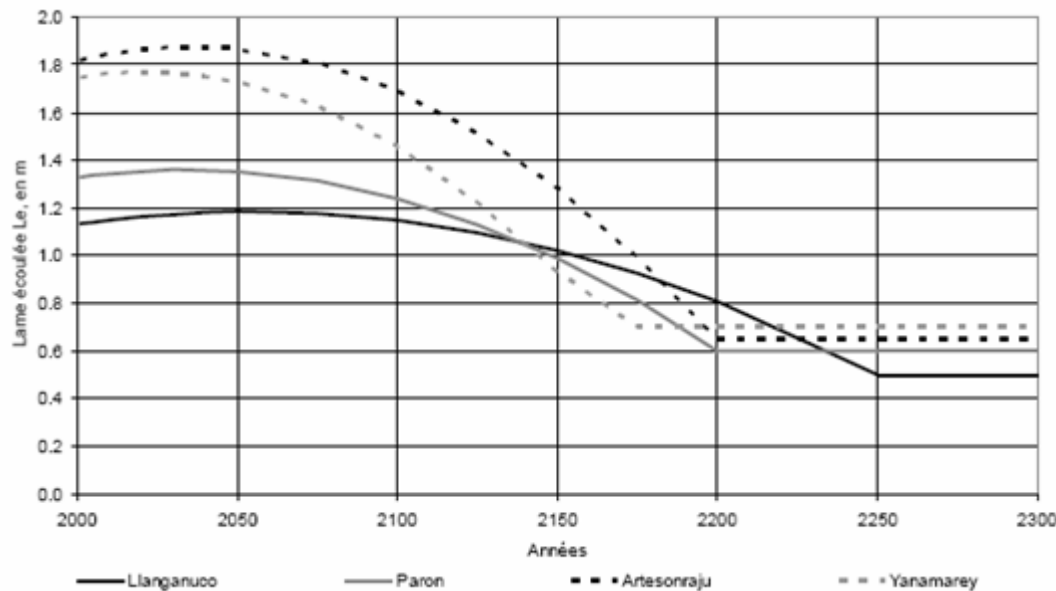
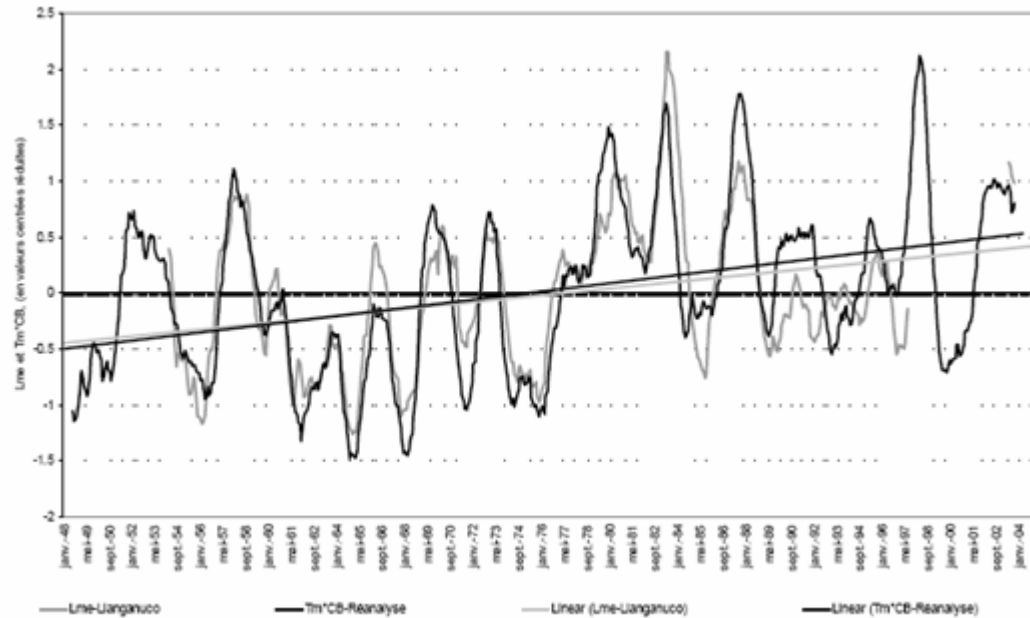


Lago Témpano, Patagonia,  
April-May 2007



# WATER RESOURCES

Job 6:17 <las aguas de deshielo> que al tiempo del calor se secan, y al calentarse desaparecen en su cauce.



Pouyaud et al., 2005, HSJ

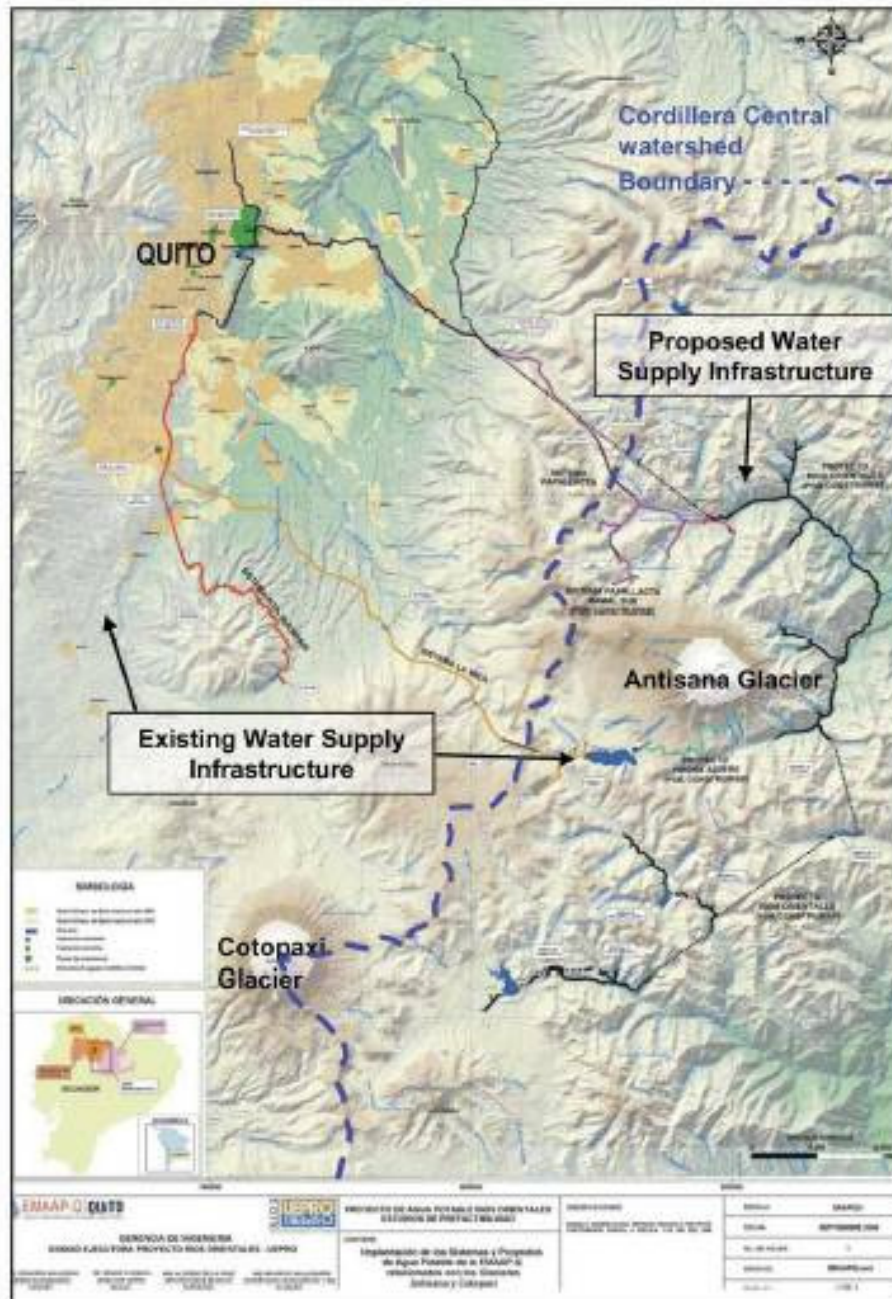


Figure 1. Relative location of glaciers and moorlands surrounding Quito, Ecuador, as well as the location of infrastructure proposed to meet the city's water demand until 2040.

**Table 2. Water Yields in Rios Orientales Project, With and Without the Impact of Glacier Retreat\***

Rios Orientales Main creek system	Yield With Melting, m <sup>3</sup> /s	Yield Without Melting, m <sup>3</sup> /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

\*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<sup>a</sup>**

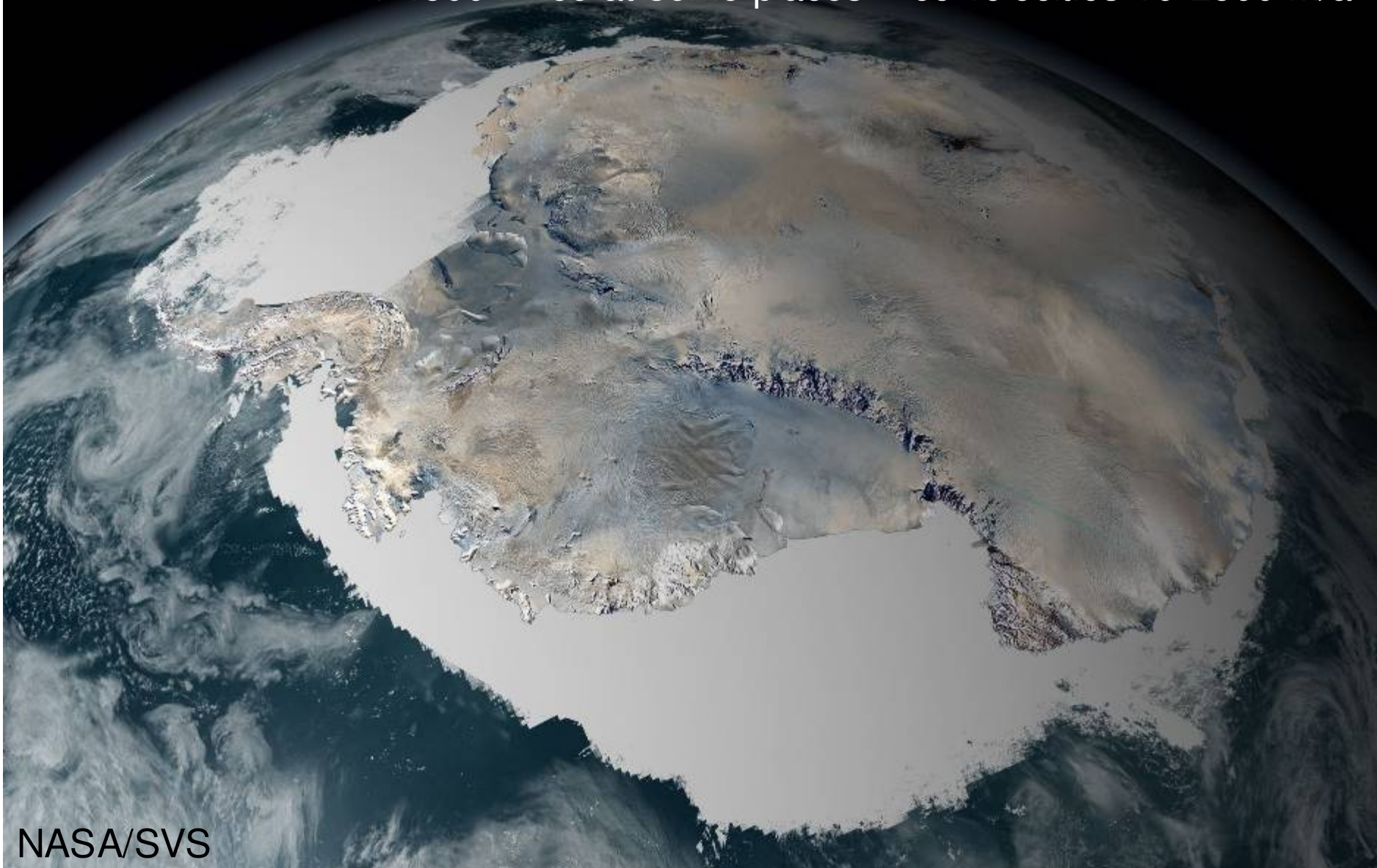
Year	Existing Conditions: Creek systems diverted	Investment, US\$ million	Expected Conditions: Creek Systems Diverted	Investment, US\$ million
2010	Papallacta, Chalpi, Blanco Grande, Quiljos, Azufrado	110	All creek systems are required	143
2011		110		143
2012		113		144
2021	Cosanga	10	Reservoirs and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

<sup>a</sup>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

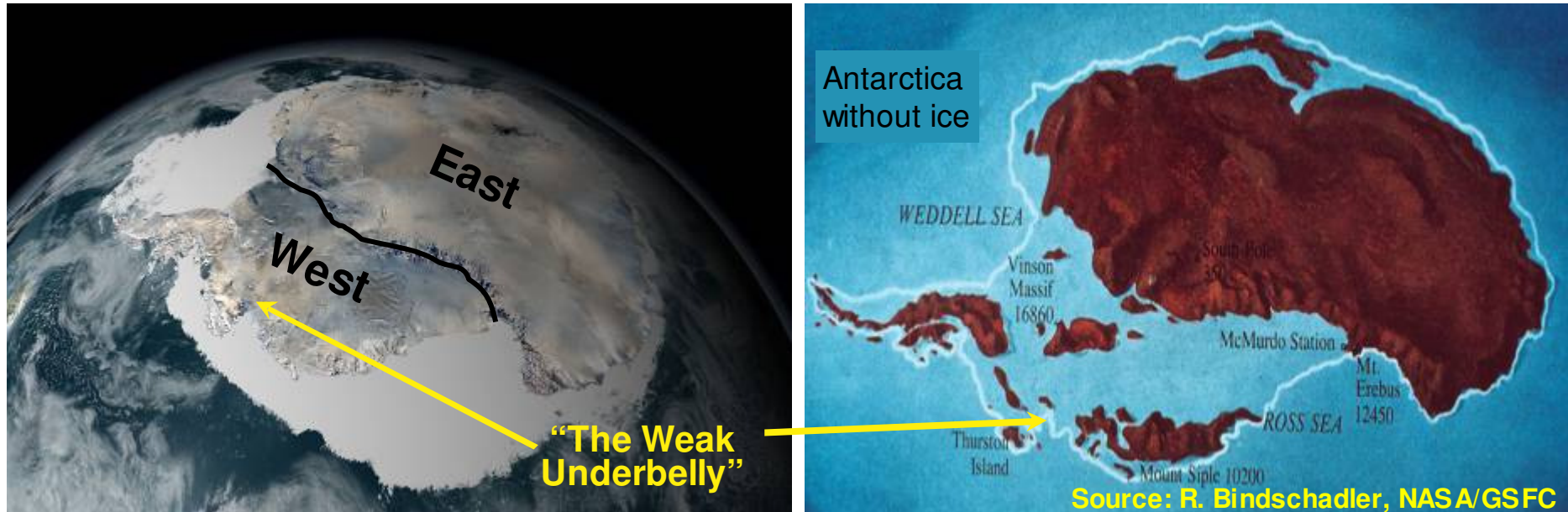
Antarctica,  
the seventh  
continent...

13.5 million km<sup>2</sup> (10% of the Earth) - 98% covered by ice  
70% of the Earth's fresh water - 91% of the ice on Earth  
Stores 55 m of sea level - 2000 m average ice thickness  
>4500 m ice at some places - Ice velocities 10-2500 m/a



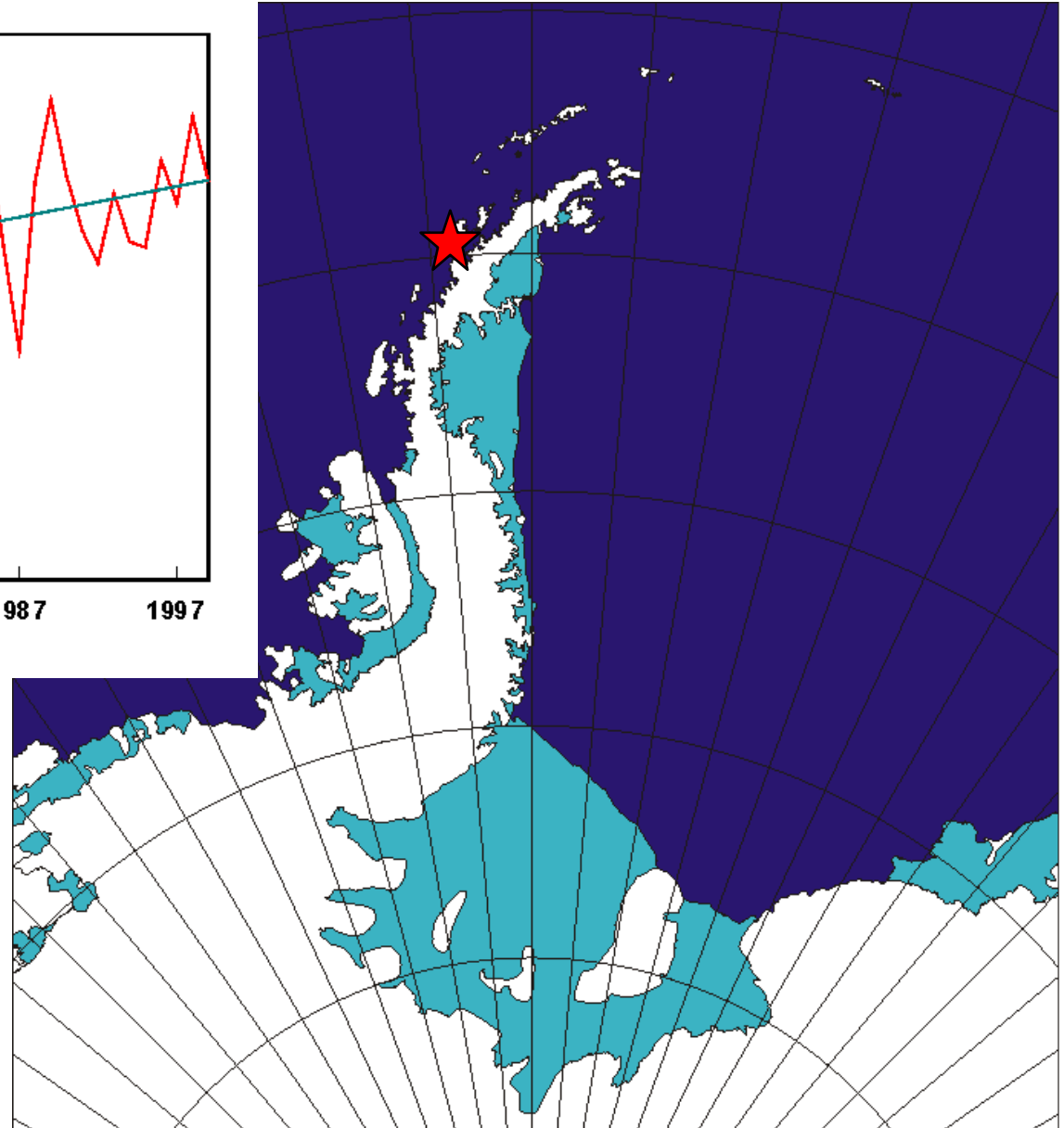
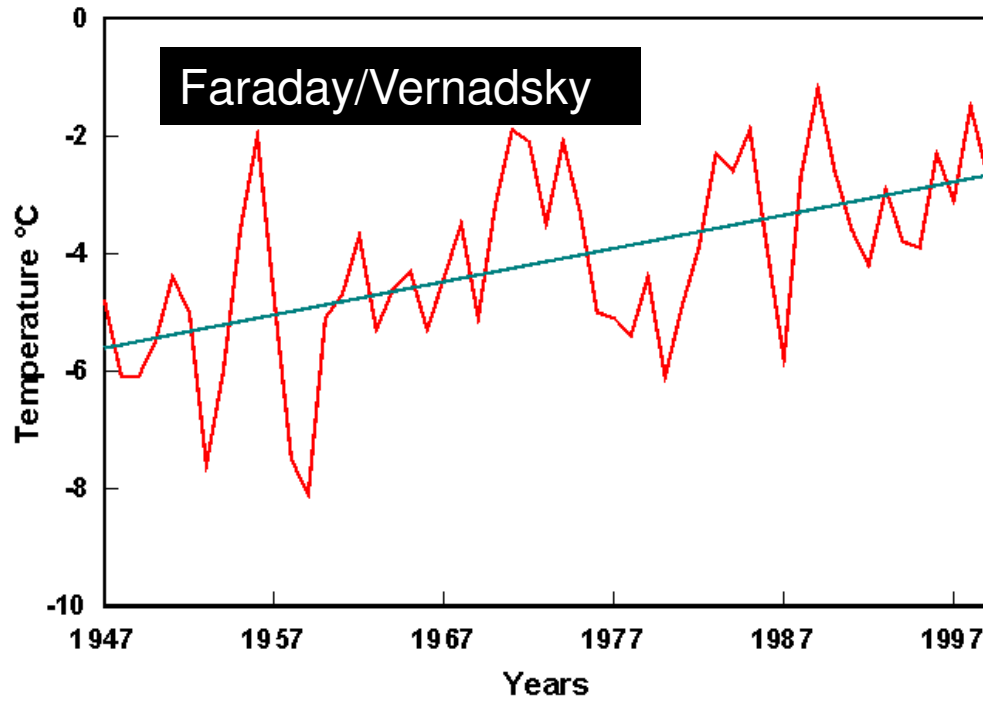
NASA/SVS

# The Antarctic Ice Sheet



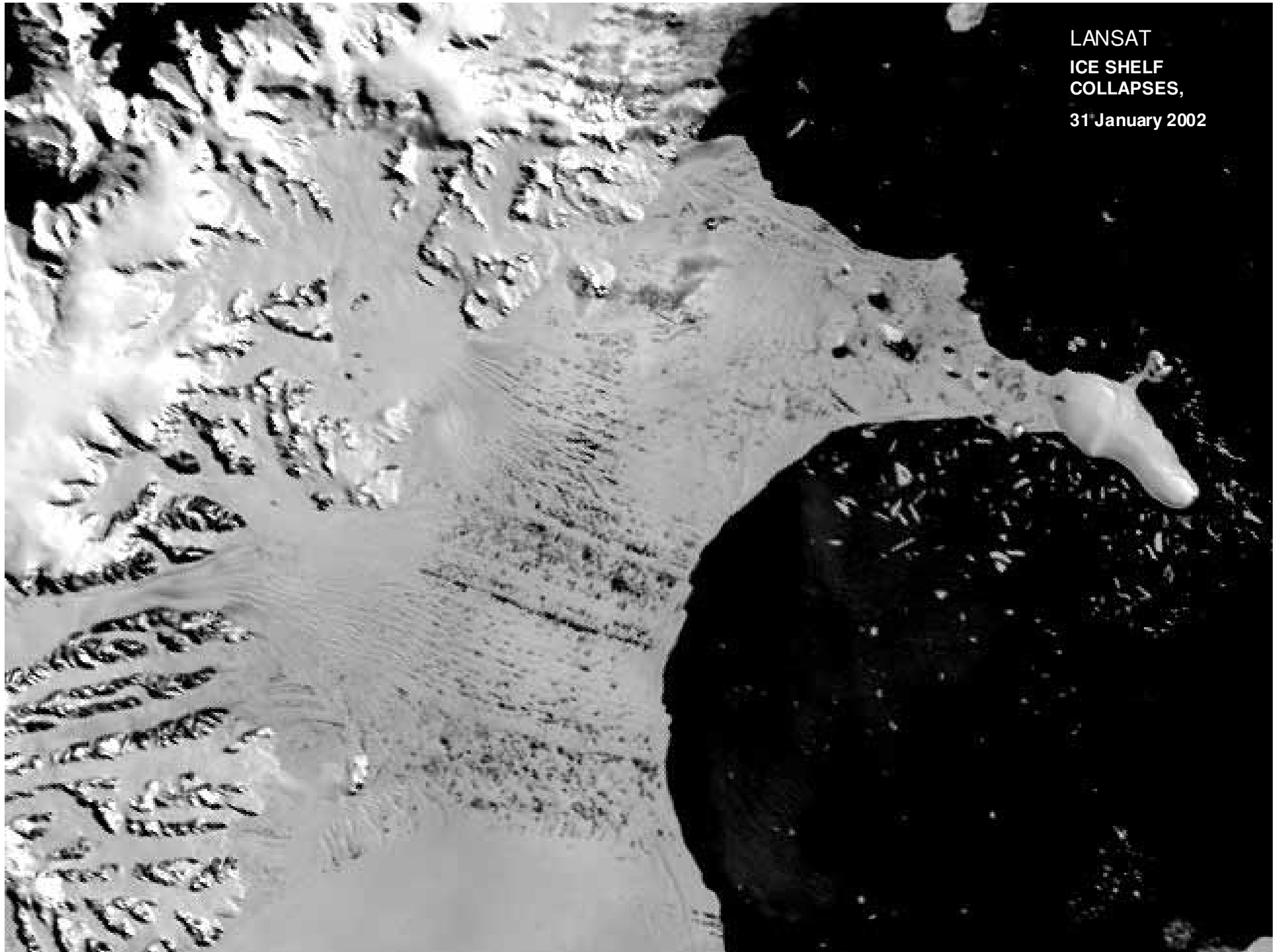
- 56.6 m sea level equivalent (SLE)
- Temperatures well below freezing
- West Antarctic ice sheet (5 m SLE) rests on a soft bed that is below sea level
- **Inherently unstable?**

# Warming on the Antarctic Peninsula



BAS

LANSAT  
ICE SHELF  
COLLAPSES,  
31<sup>st</sup> January 2002

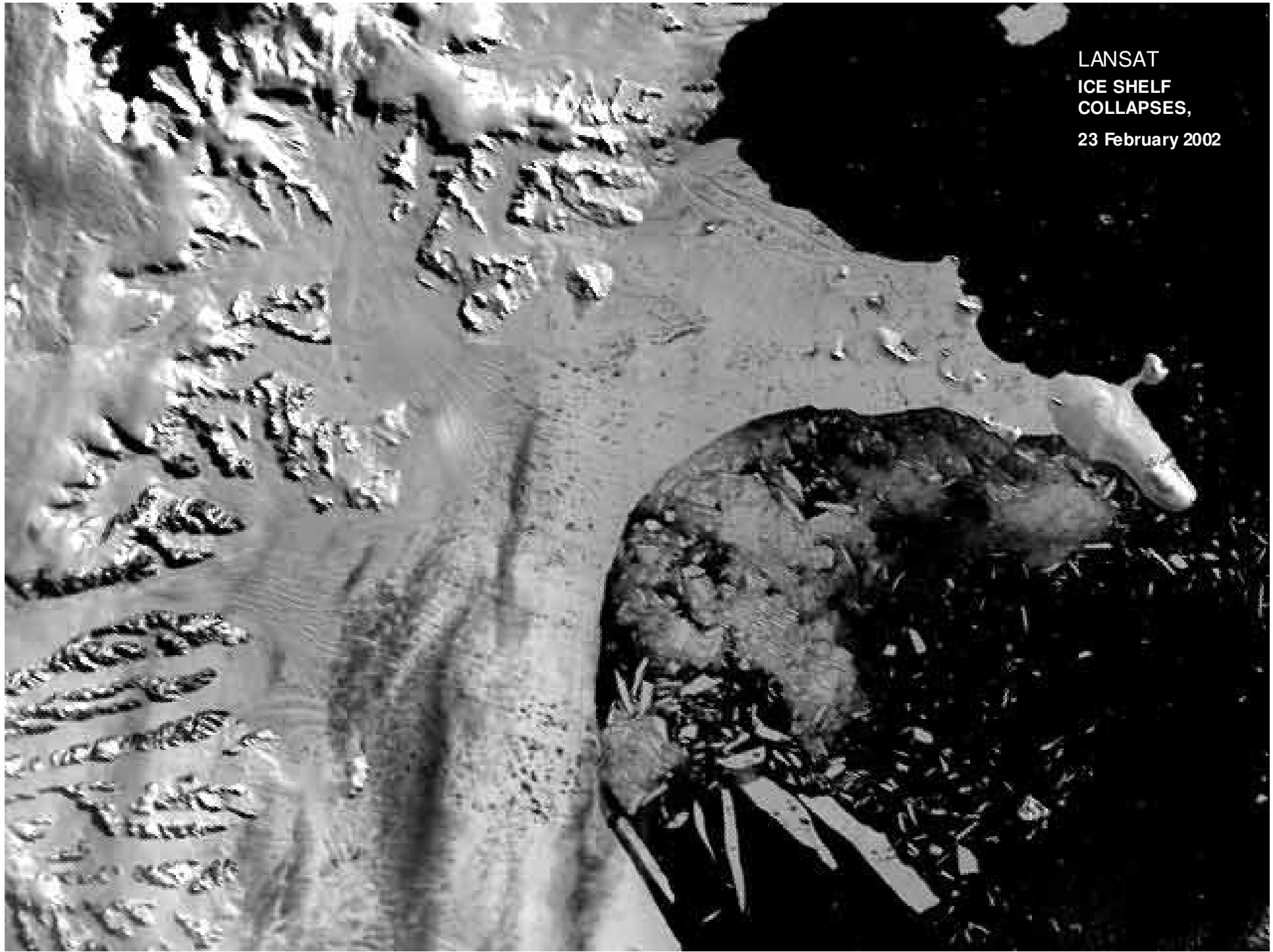


A satellite image showing a large ice shelf that has collapsed. The image is in grayscale. The top left portion shows a relatively smooth, light-colored ice surface. A dark, irregular shape in the center-right represents the collapsed ice, which has broken into many smaller, dark fragments. The surrounding ocean is dark. The text 'LANSAT ICE SHELF COLLAPSES, 17 February 2002' is in the top right, and a URL is in the bottom right.

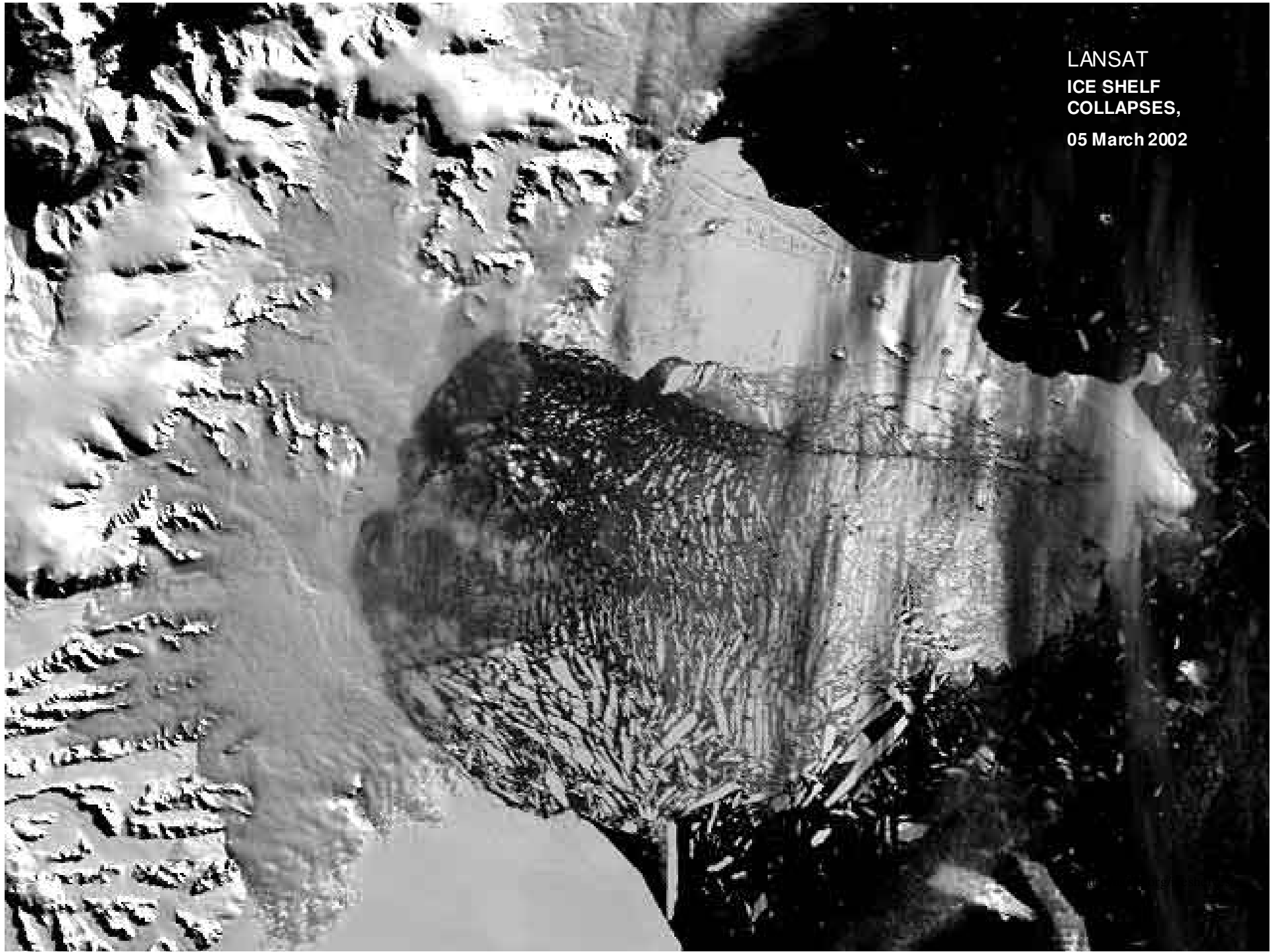
LANSAT  
ICE SHELF  
COLLAPSES,  
17 February 2002

<http://nsidc.org/>

LANSAT  
ICE SHELF  
COLLAPSES,  
23 February 2002



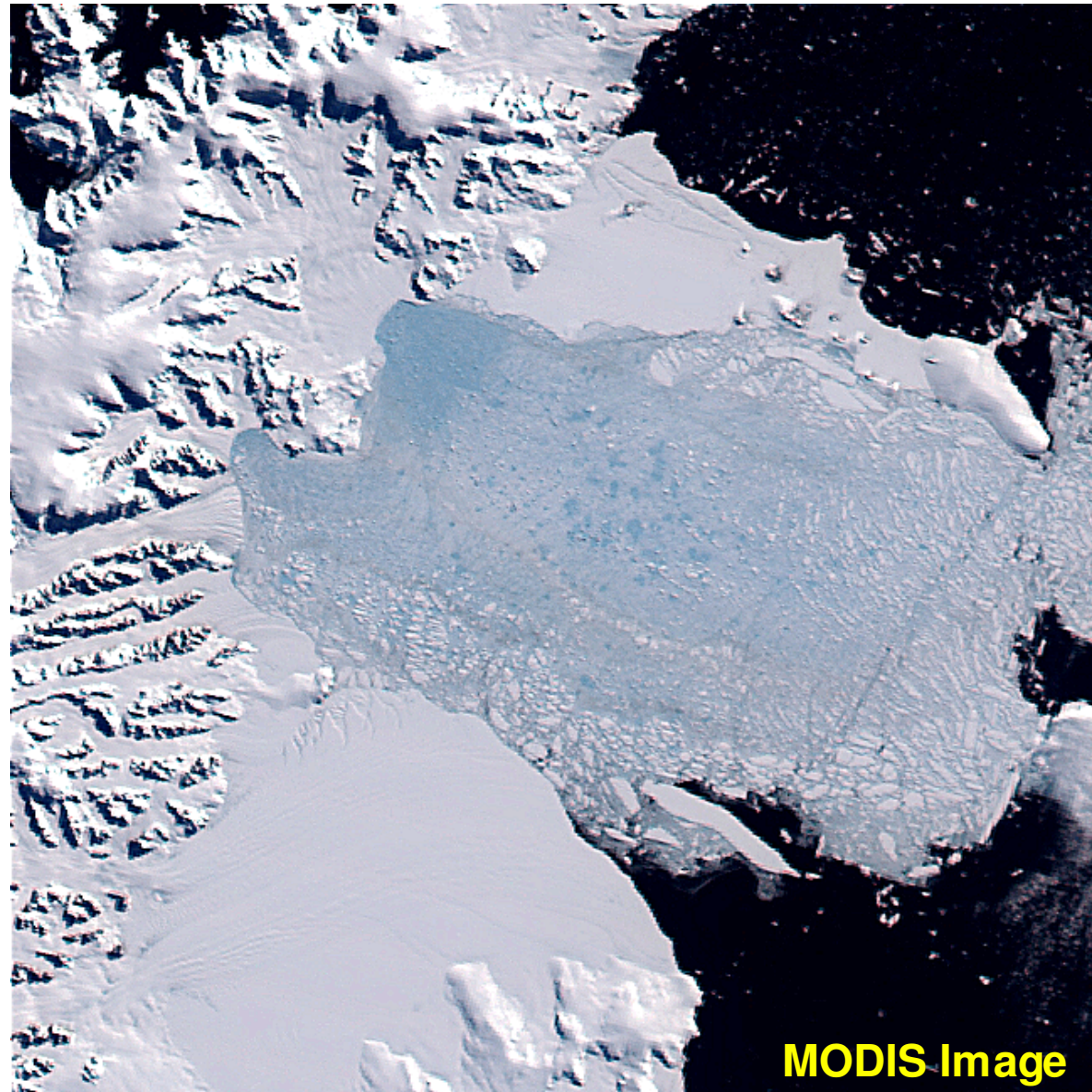
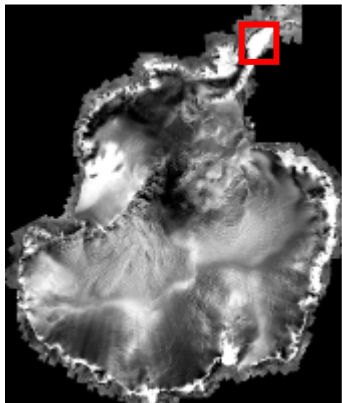
LANSAT  
ICE SHELF  
COLLAPSES,  
05 March 2002



# Larsen B Break-up 2002

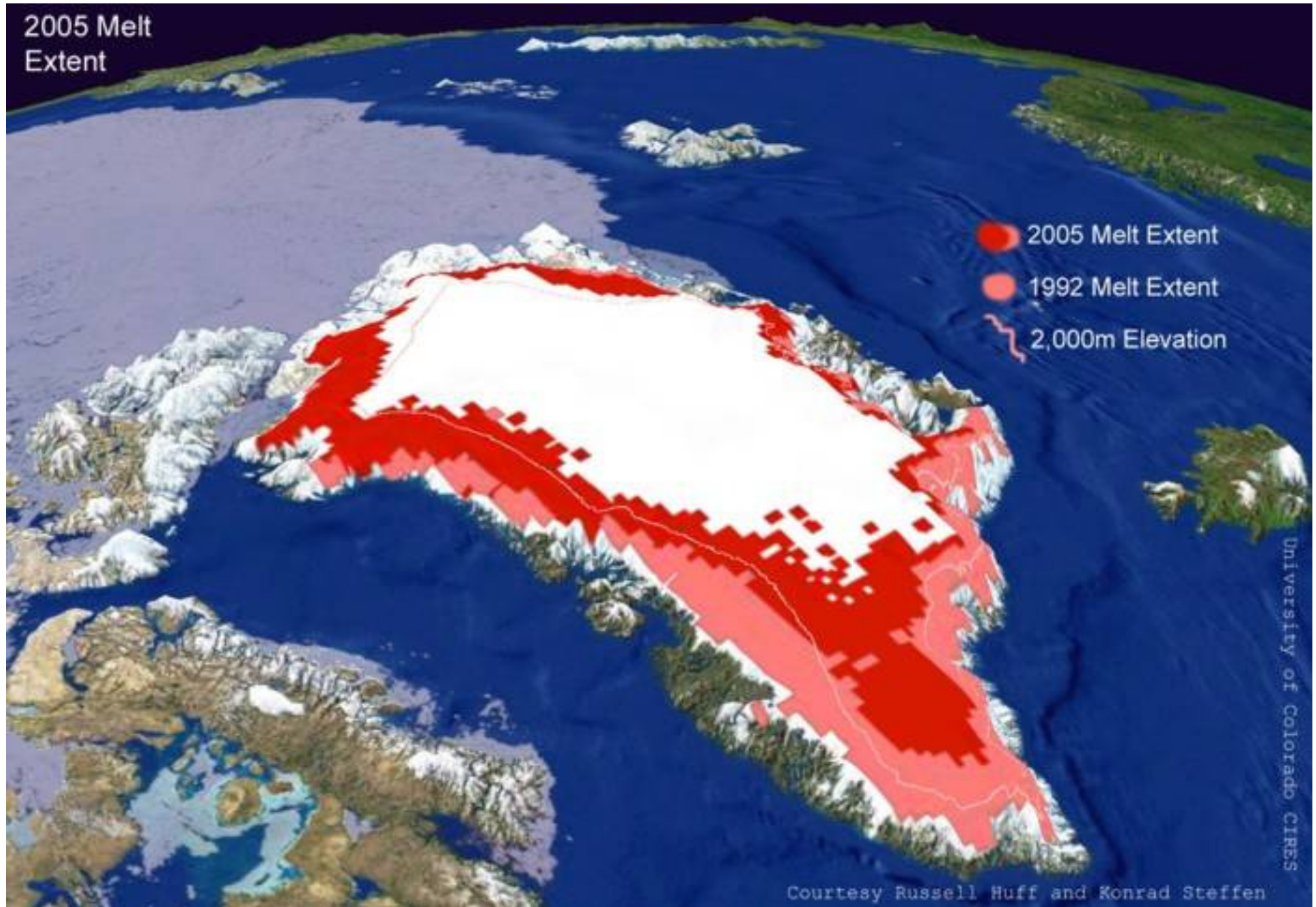
March 17

10,000  
years of ice  
gone in one  
month!



Ted Scambos, NSIDC

# Greenland: 7.3 m SLE



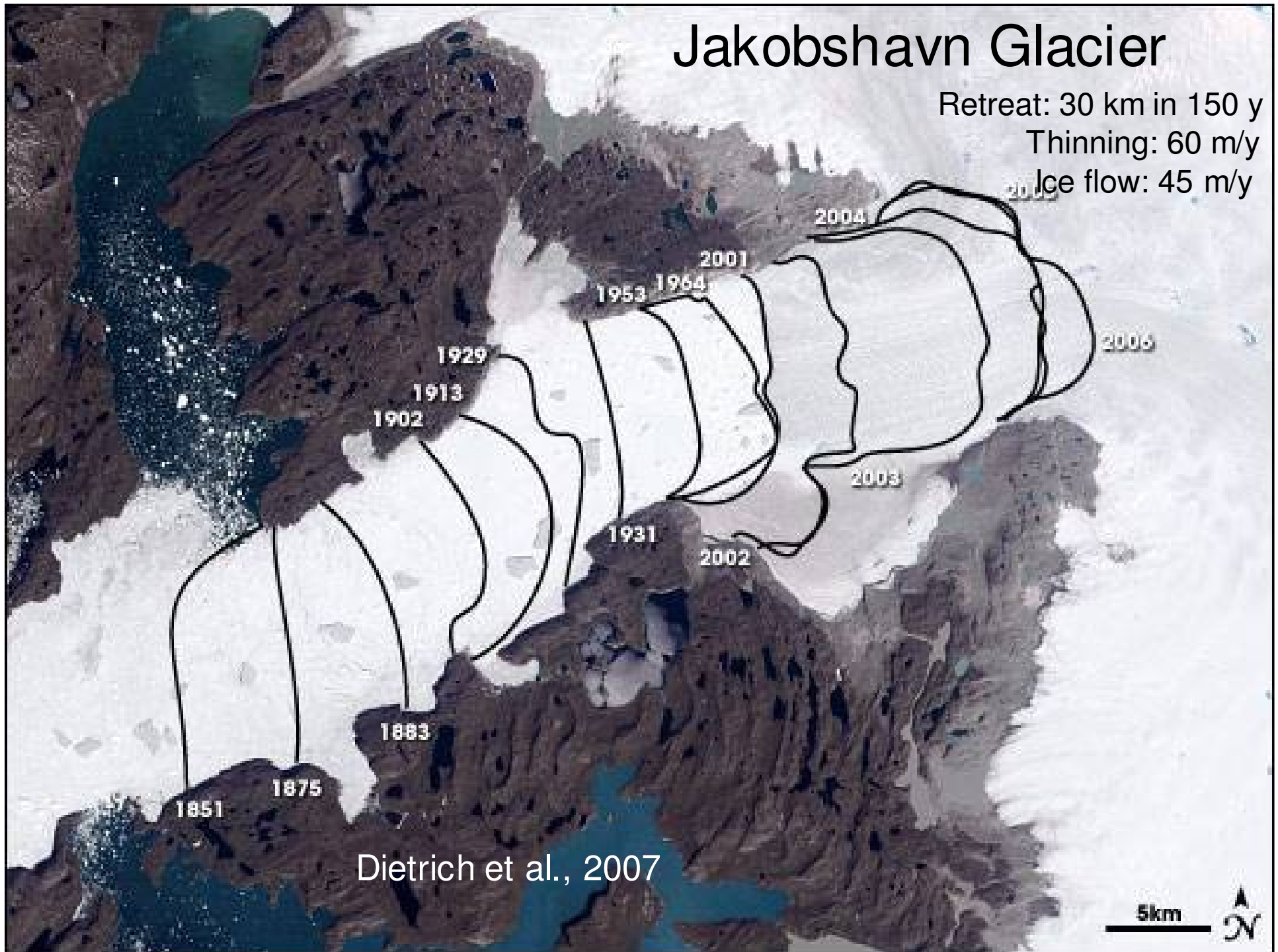
Steffen et al.  
Univ. Colorado

# Greenland moulin

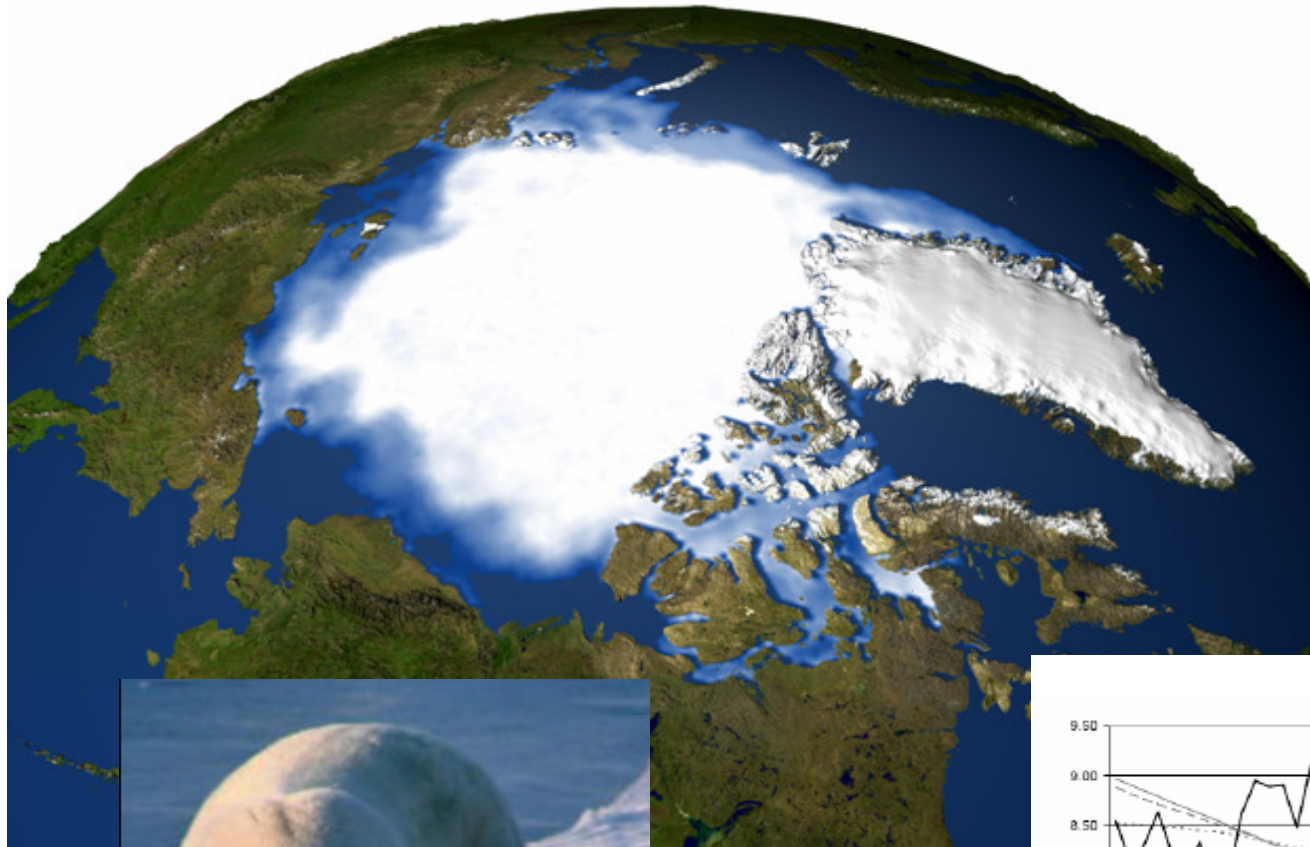


# Jakobshavn Glacier

Retreat: 30 km in 150 y  
Thinning: 60 m/y  
Ice flow: 45 m/y



Dietrich et al., 2007



## 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

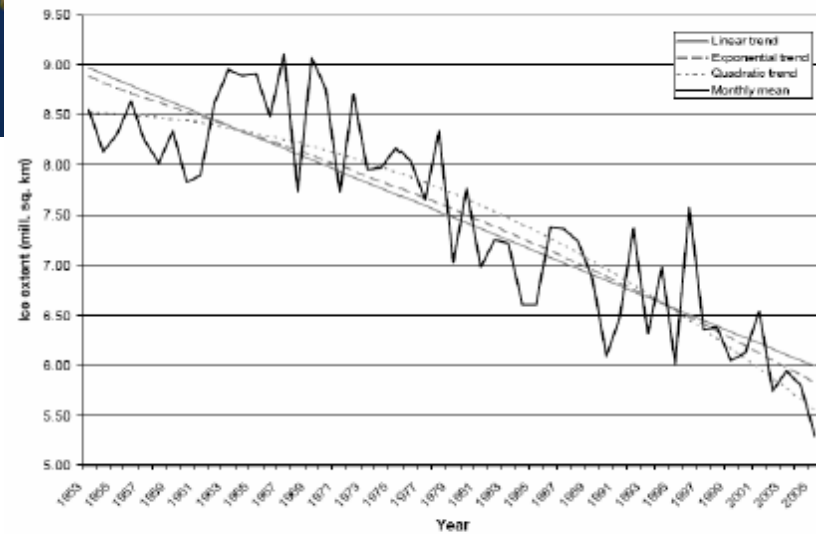


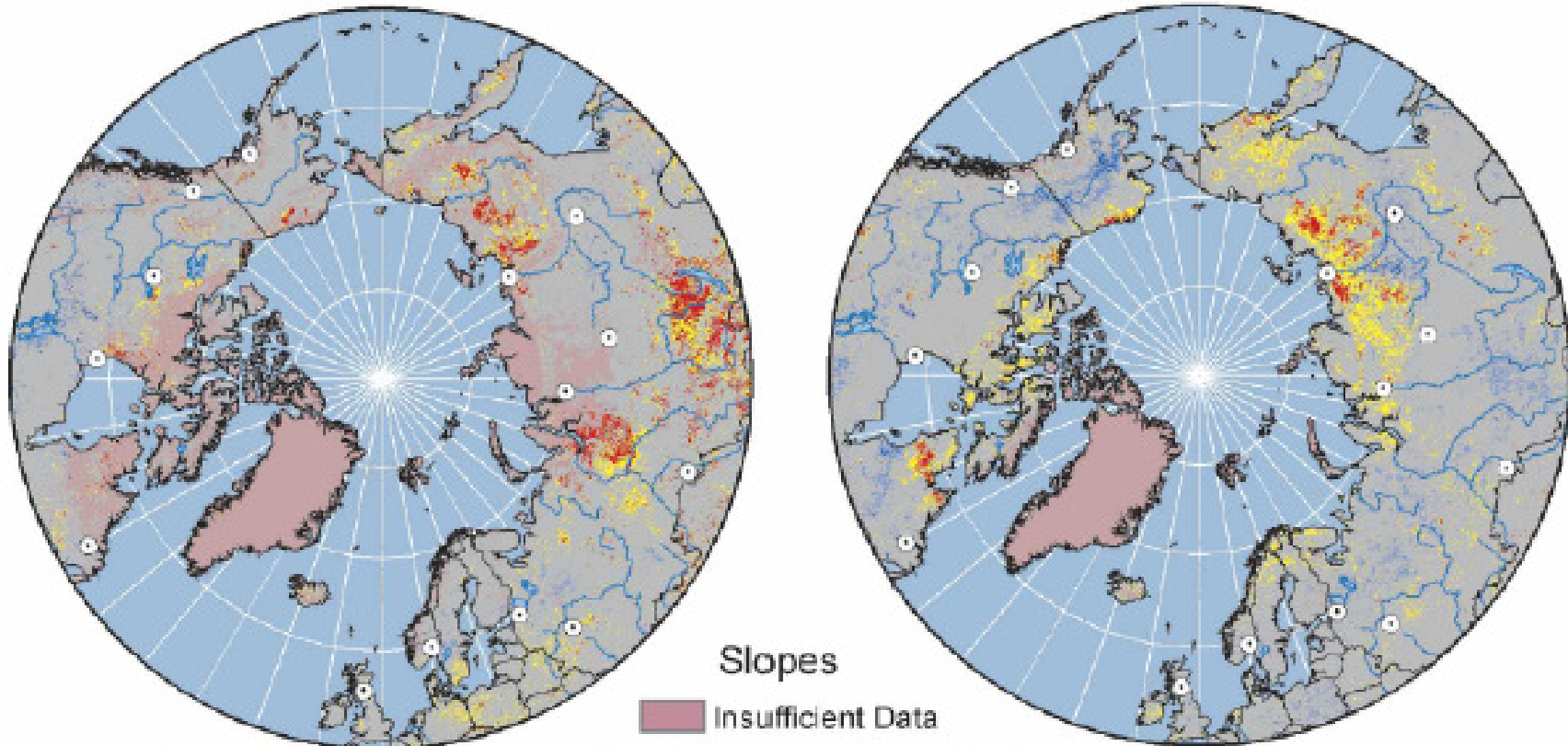
Figure 3. Adjusted Hadley September ice extent, 1953-2005 (black), with linear, exponential, and quadratic fit lines (gray).

Meier et al., 2008

# Changes in Arctic Plants

May and June

July and August



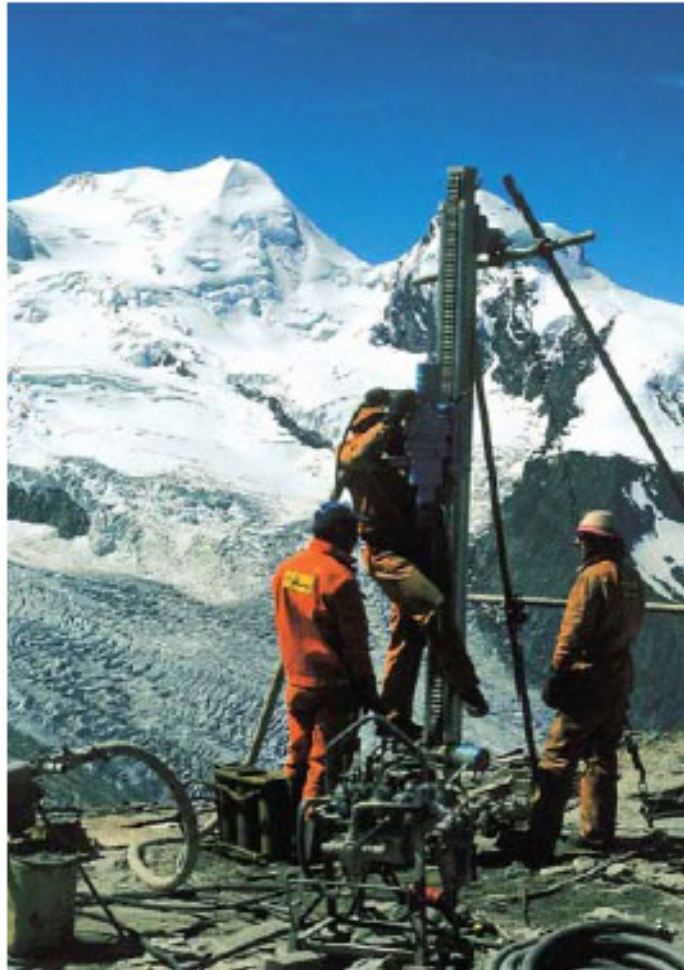
**Tundra areas consistently and predominantly showed greening trends.**

Greening of the Arctic

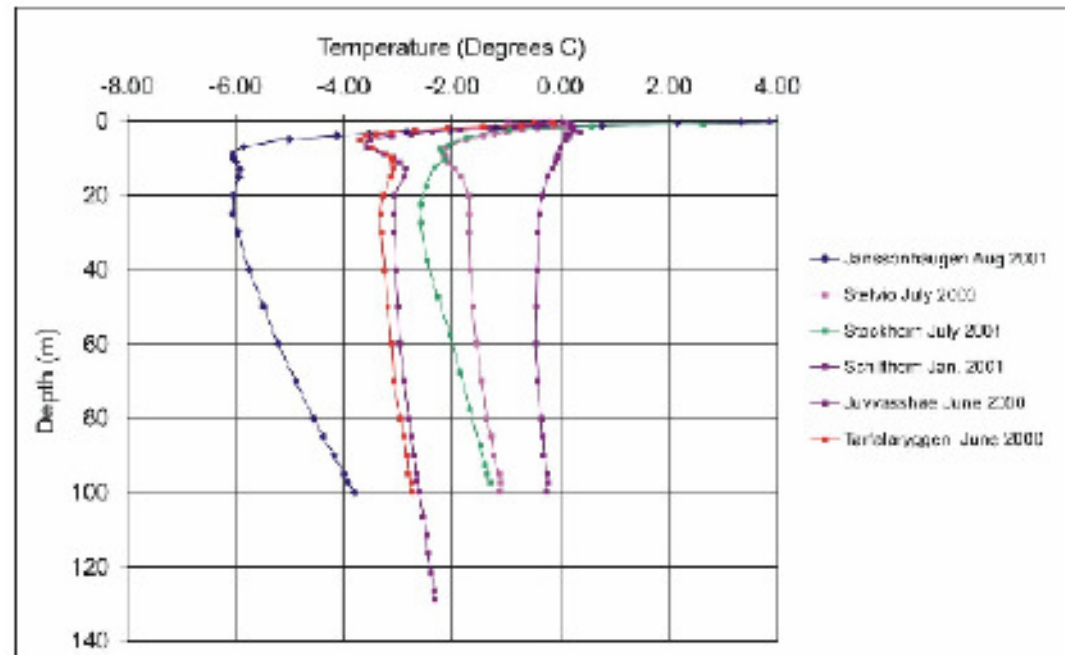
IPCC, 2007

# Mountain Permafrost Warming

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



Alps



Harris, C., D. Vonder Mühl, K. Isaksen, W. Haeberli, J.L. Sollid, L. King, P. Holmlund, F. Dramis, M. Guglielmin, and D. Palacios, 2003

Vonder Mühl et al., 2004

Zhao et al., 2003

Wu and Liu, 2003; Zhao et al., 2004a

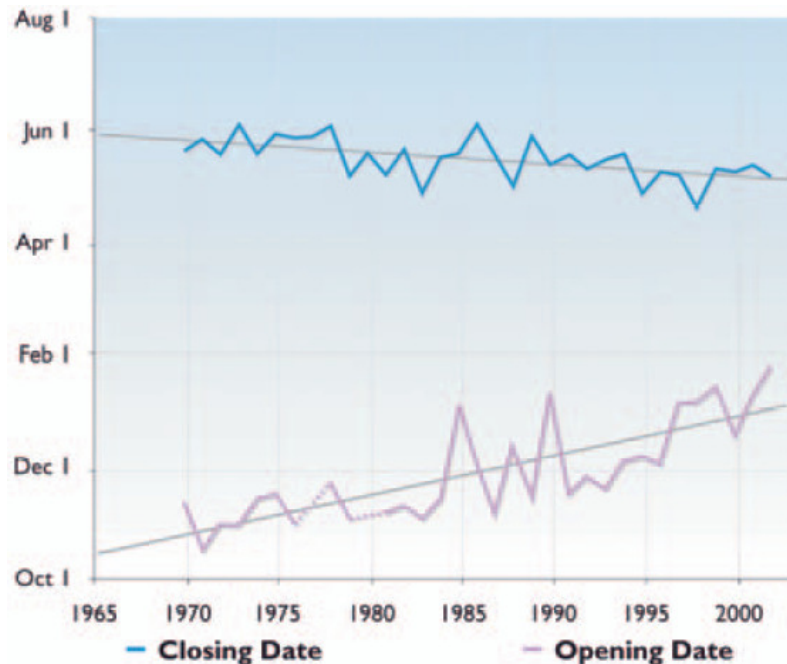
Qiu et al., 2000; Zhao et al., 2004

Zhou et al., 1996

Zhou et al., 1996

Isaksen et al., 2001

# 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).



Air temp. N of 65°N

NH sea ice

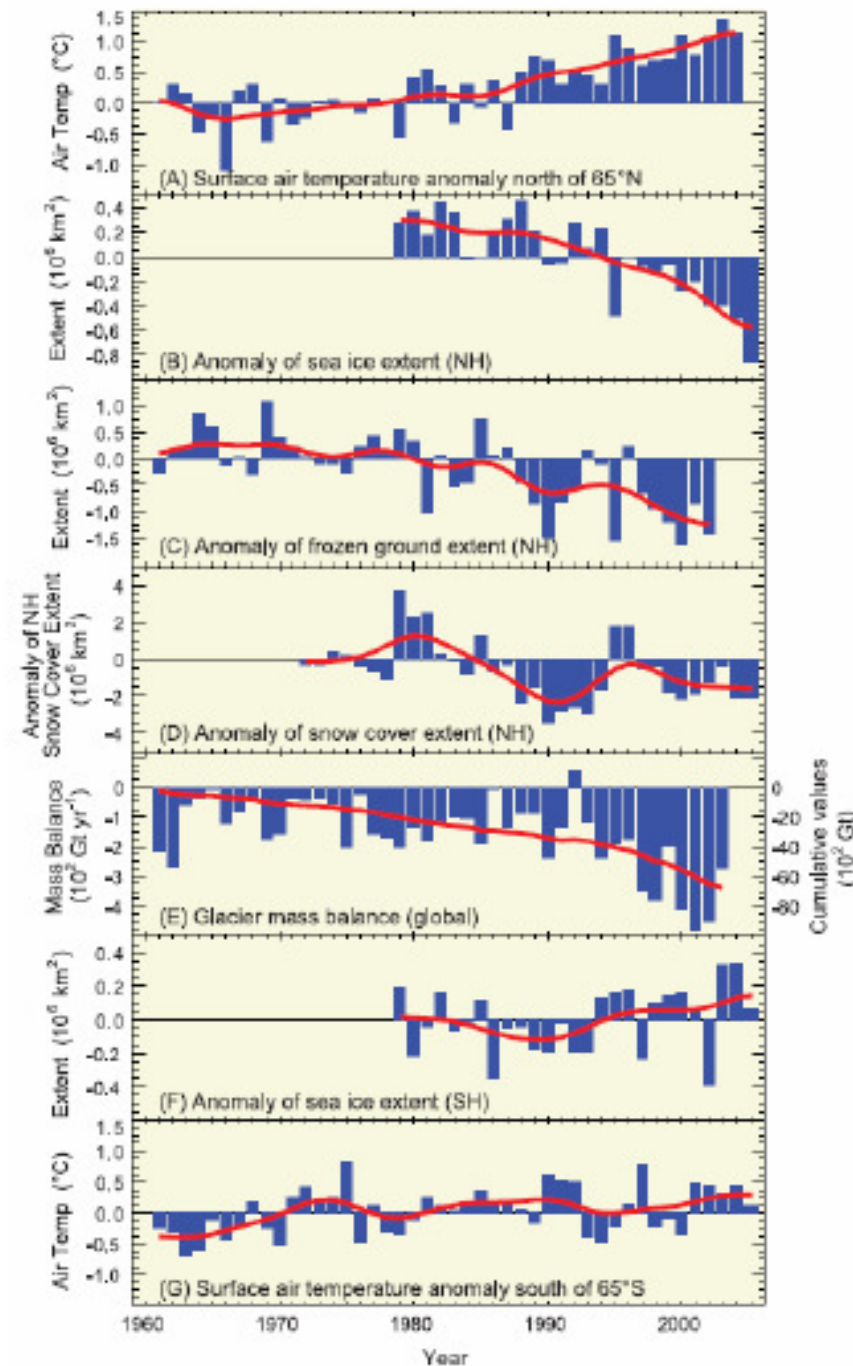
NH frozen ground

NF snow cover

Global glacier  
mass balance

SH sea ice

Air temp. S of 65°S



IPCC. 2007

Cryospheric Component	Area (10 <sup>6</sup> km <sup>2</sup> )	Ice Volume (10 <sup>6</sup> km <sup>3</sup> )	Potential Sea Level Rise (m)	Sea Level Contribution	
				mm/year	
				1961-2003	1993-2003
Northern Hemisphere (NH) snow on land	1.9-45.2	0.0005-0.005	0.001-0.01	~0	~0
Sea ice	19-27	0.019-0.025	~0	~0	~0
Glaciers and ice caps <sup>a,b</sup>	0.51-0.54	0.05-0.13	0.15-0.37	+0.32 to +0.68	+0.55 to +0.99
Ice shelves <sup>c</sup>	1.5	0.7	~0	~0	~0
Greenland ice sheet <sup>d</sup>	1.7	2.9	7.3	-0.07 to +0.17	+0.14 to +0.28
Antarctic ice sheet <sup>c</sup>	12.3	24.7	56.6	-0.28 to +0.55	-0.14 to +0.55
Seasonally frozen ground (NH) <sup>e</sup>	5.9-48.1	0.006-0.065	~0	~0	~0
Permafrost (NH) <sup>f</sup>	22.8	0.011-0.037	0.03-0.10	~0	~0
<b>CRYOSPHERE CONTRIBUTION</b>	<b>66-159</b>	<b>28.4-28.6</b>	<b>64.1-64.4</b>	<b>0.69 ± 0.47</b>	<b>1.19 ± 0.42</b>
<b>TOTAL SEA LEVEL RISE</b>				<b>1.8 ± 0.5</b>	<b>3.1 ± 0.7</b>
<b>% CRYOSPHERE CONTRIBUTION</b>				<b>38%</b>	<b>38%</b>

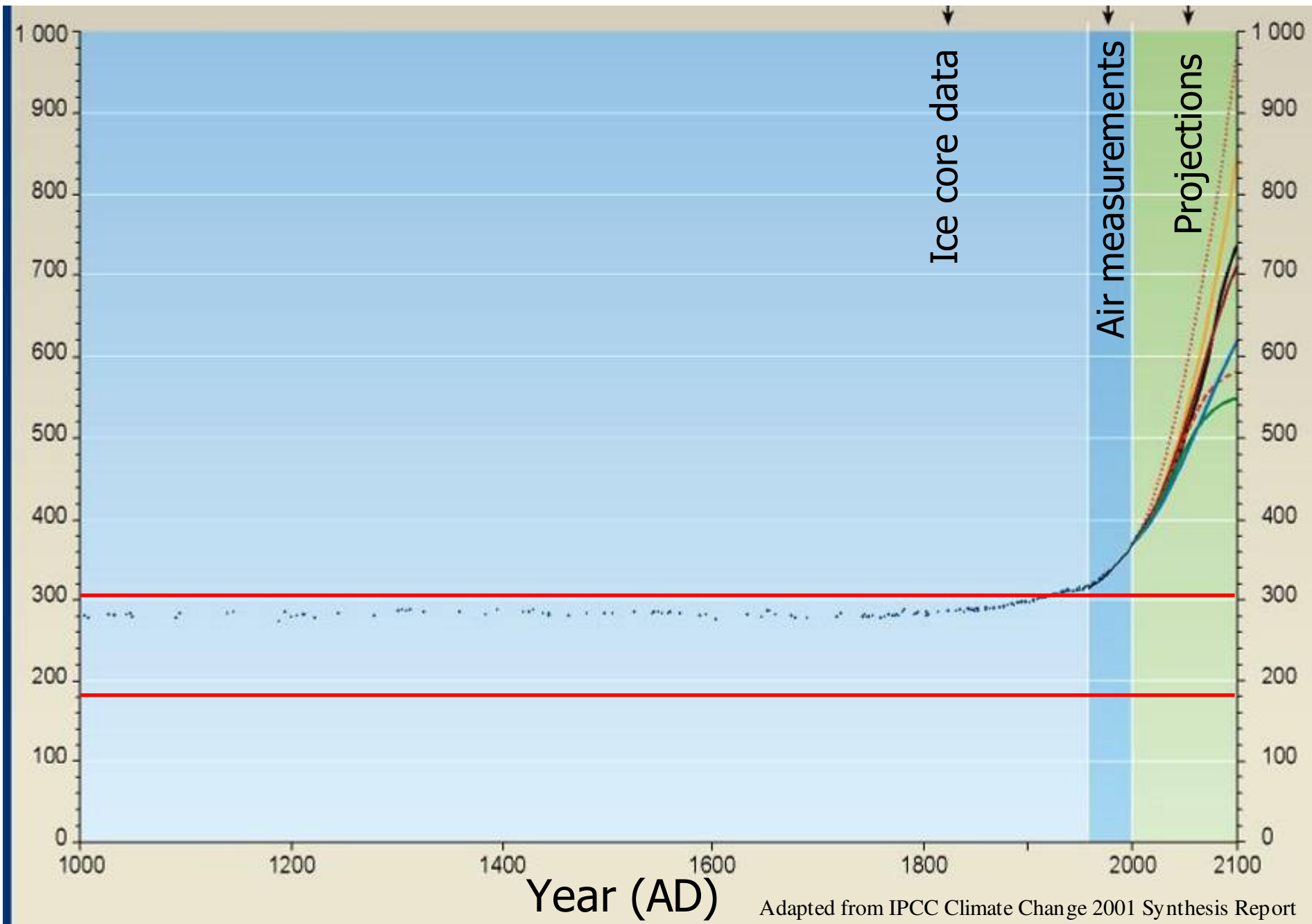
# SEA LEVEL RISE

(IPCC, 2007)

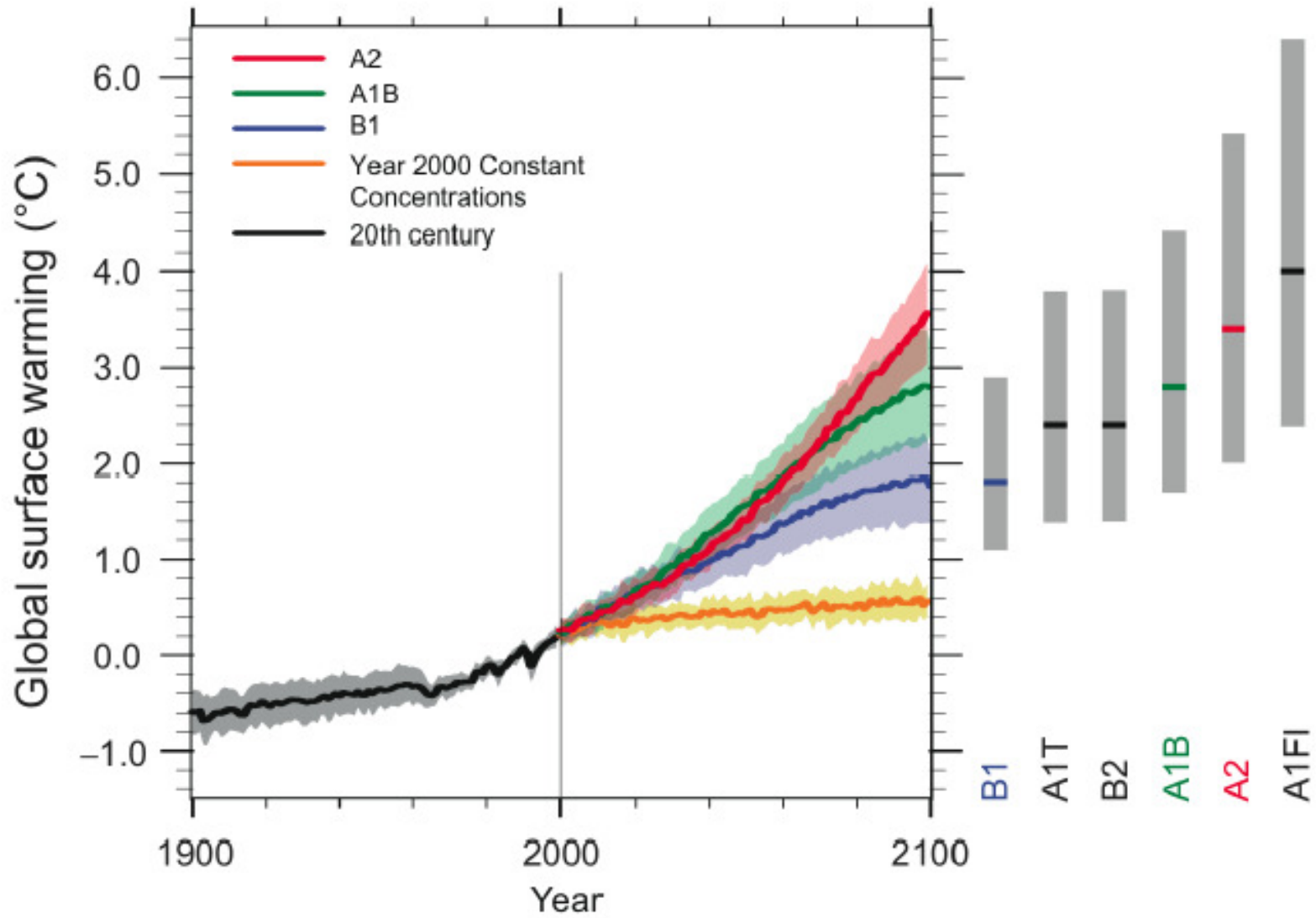
# PROJECTIONS

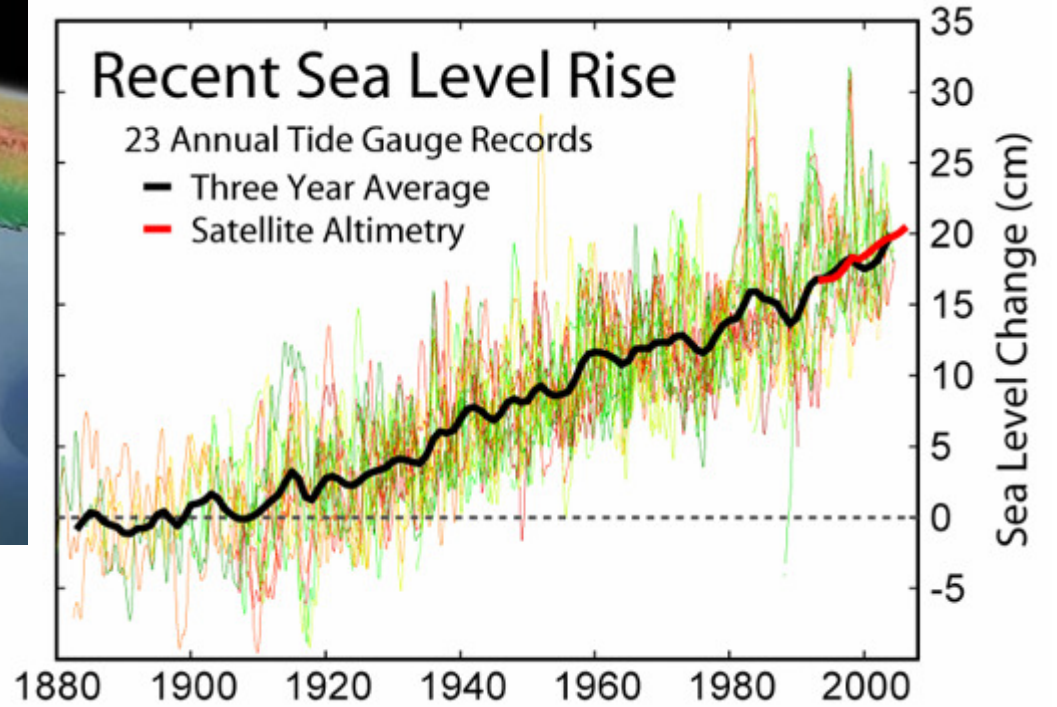


# Past and future CO<sub>2</sub> atmospheric concentrations



## Multi-model Averages and Assessed Ranges for Surface Warming







Bob Thomas, Chincoteague Island, Va, USA

# CONCLUSIONS

1. A significant melting and reduction of all cryospheric components has been observed globally, including snow, ice and frozen ground.
2. In turn this has produced relevant impacts in physical, biological, and chemical systems, in indigenous livelihoods in the Arctic, and in human activities such as sport and tourism in alpine areas.
3. Future warming scenarios will result in an amplification of all these effects, leading possibly to major impacts such as the extinction of polar/high altitude species, destruction of infrastructure in permafrost terrain, destructive rock avalanches, and increased glacial lake outburst floods.
4. Positive effects such as increased sea traffic and offshore oil operations will probably be offset by enhanced contamination.

Gracias!

