Ice Dynamics and the Accelerating Glacier and Ice Sheet Contributions to Rising Sea Level

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Outline

I. Sea level is rising, but how fast? Data from satellite altimetry

II. Where is the water coming from? The main contributors

III. Glaciers in a warming climate: do they "just melt," or is there more to it?

IV. Why is rising sea level tracking the extreme upper limit predicted by the IPCC? Possible glaciological reasons

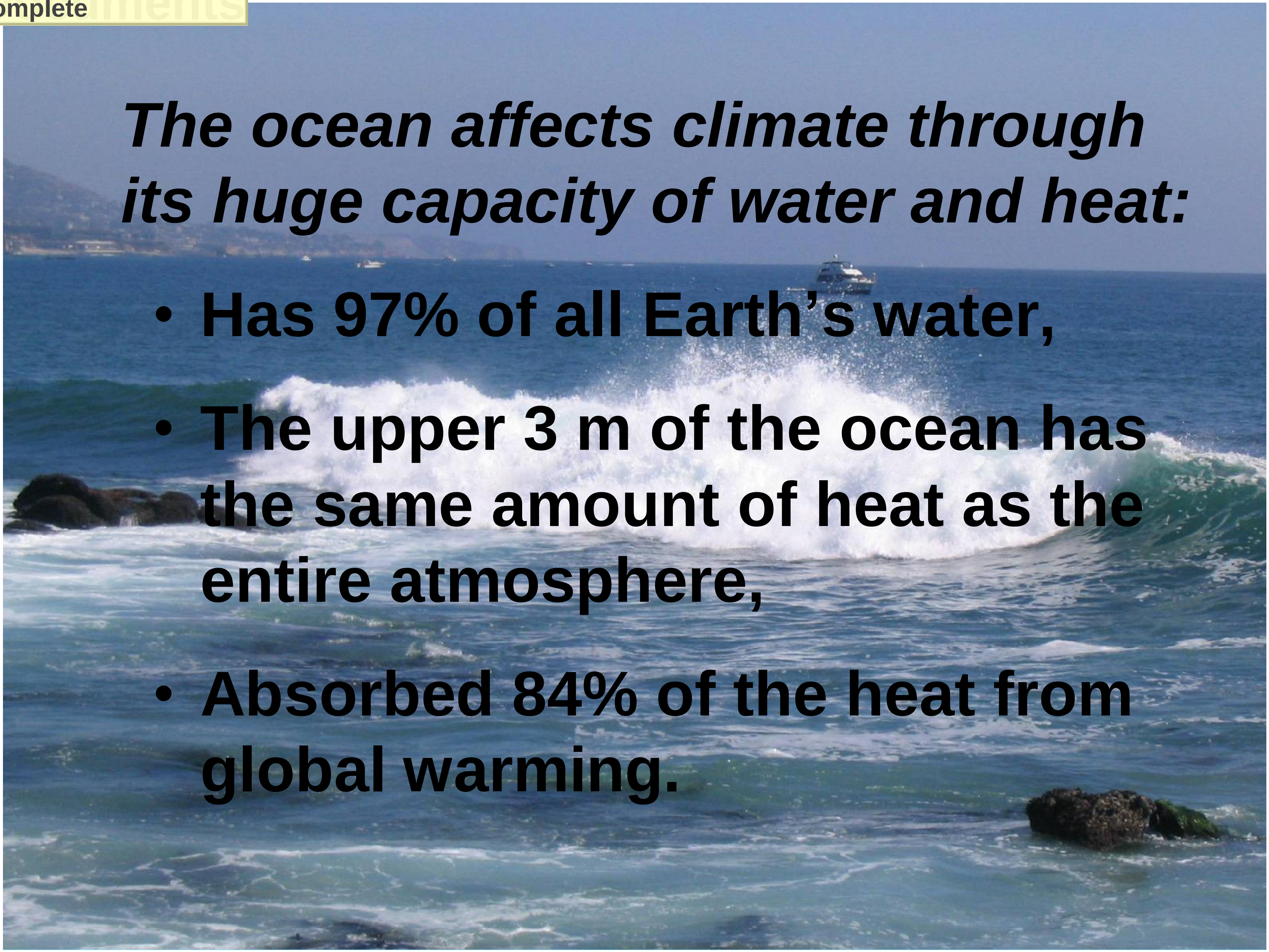
V. The challenge of prediction: developing a model that can simulate the dynamic responses of the ice sheets to a warming ocean

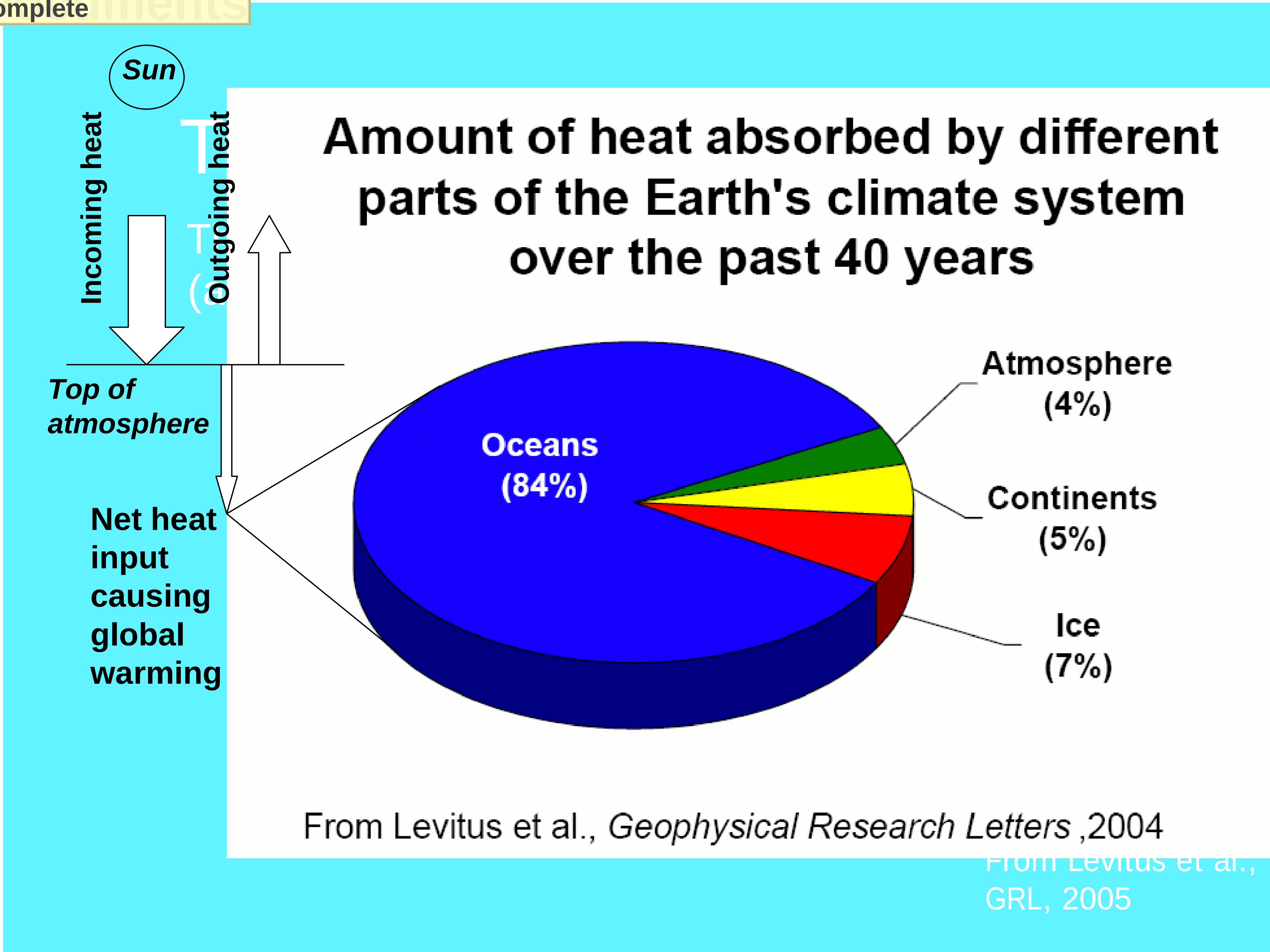
Sea level is rising, but how fast?

Data from satellite radar altimetry

Topex / Poseidon / Jason world ocean slides (next 11) are courtesy of

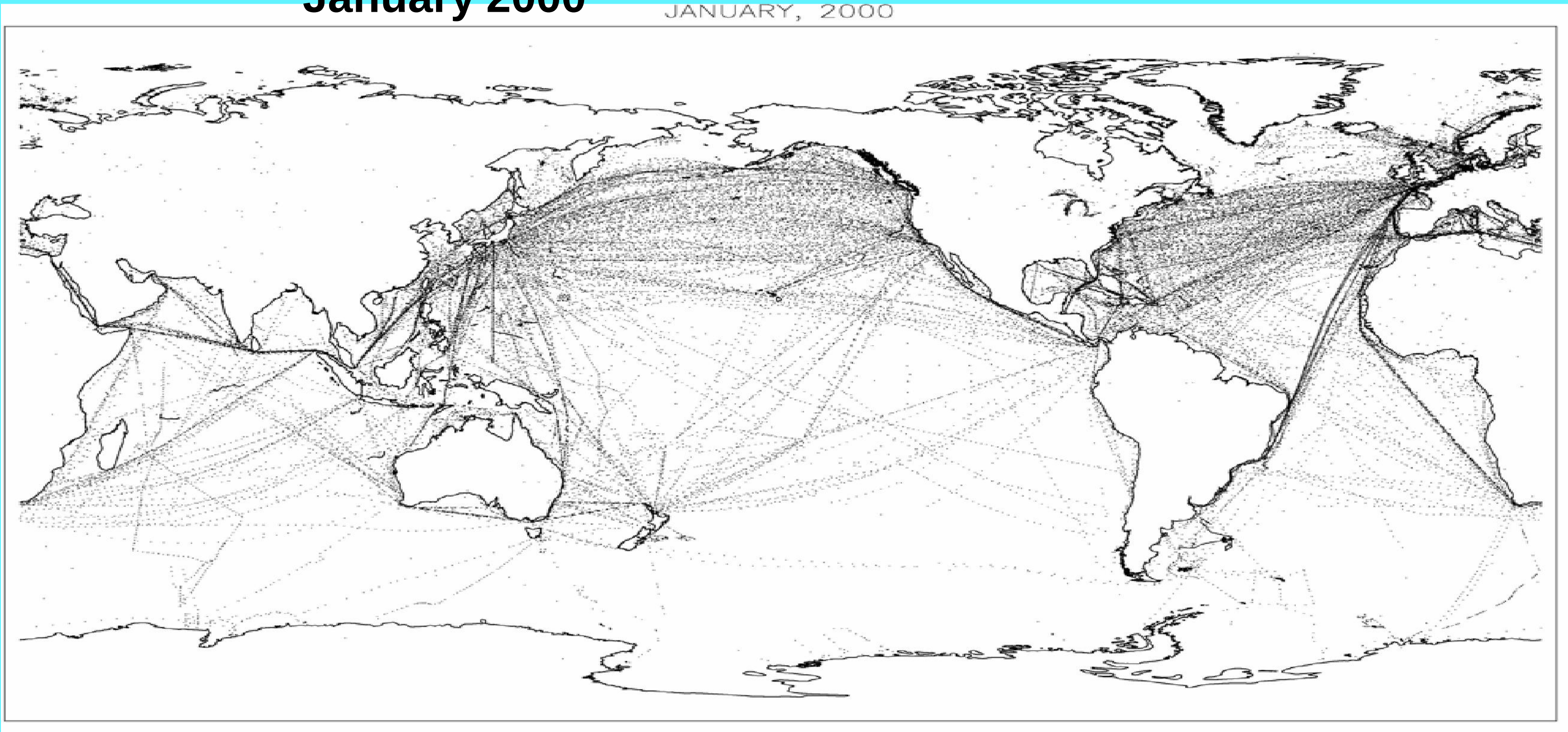
Jet Propulsion Laboratory / California Institute of Technology


The ocean affects climate through its huge capacity of water and heat:
• Has 97% of all Earth’s water,
• The upper 3 m of the ocean has the same amount of heat as the entire atmosphere,
• Absorbed 84% of the heat from global warming.

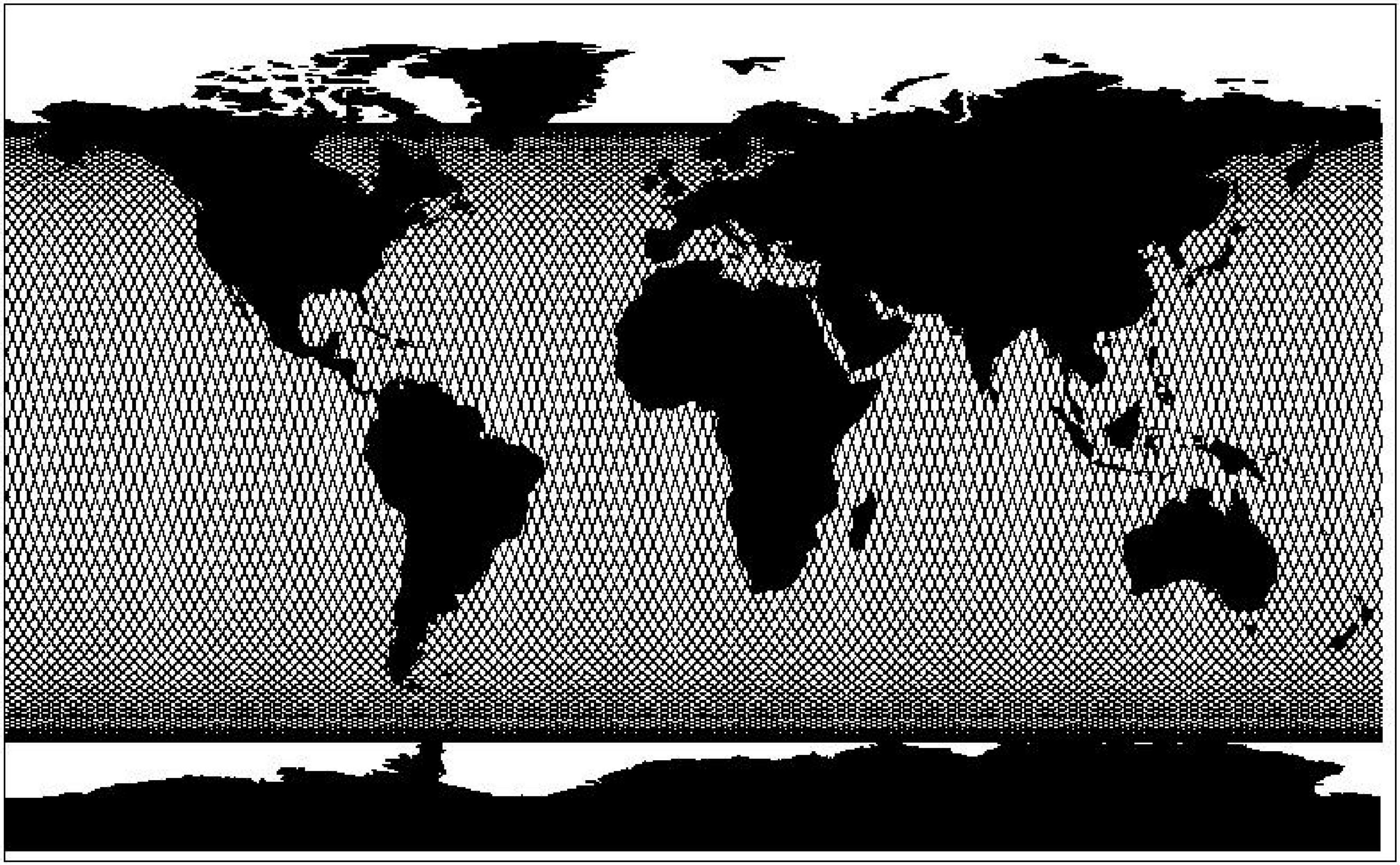

Sun
Incoming heat
Outgoing heat
Top of atmosphere
Net heat input causing global warming
Amount of heat absorbed by different parts of the Earth's climate system over the past 40 years
Oceans (84%)
Atmosphere (4%)
Continents (5%)
Ice (7%)
From Levitus et al., *Geophysical Research Letters* ,2004
From Levitus et al., GRL, 2005

The harsh and vast ocean environment makes ocean observations from ships very scarce.

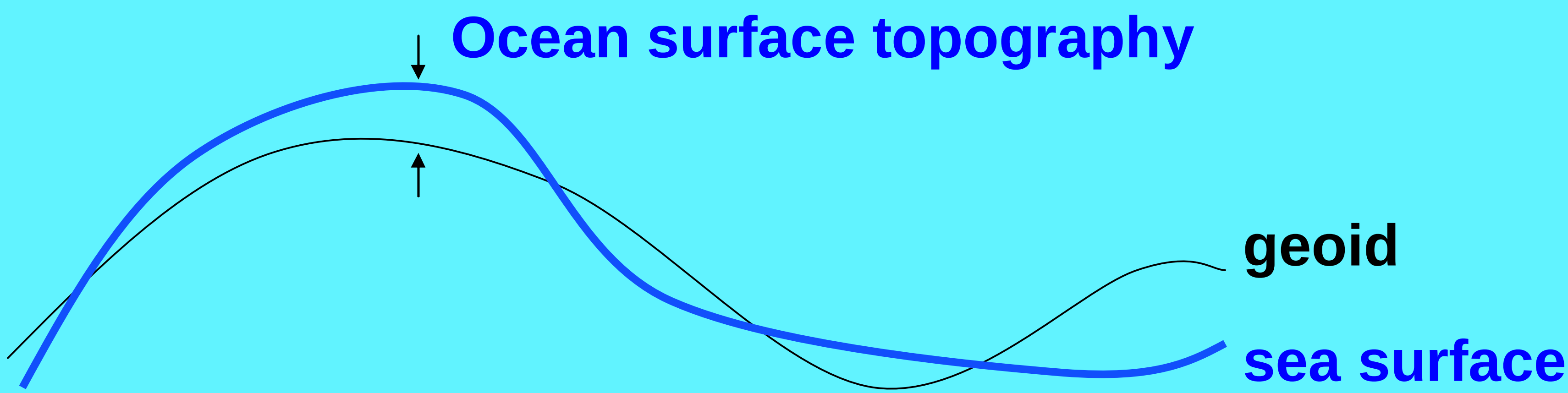
January 2000

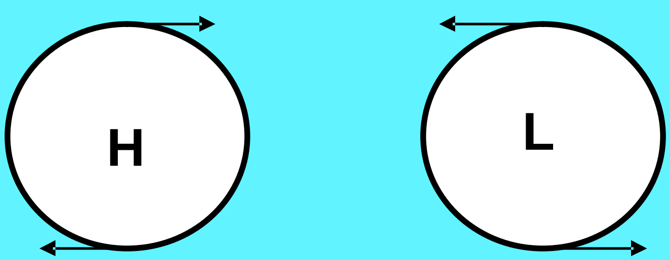


TOPEX/Poseidon ground track coverage every 10 days

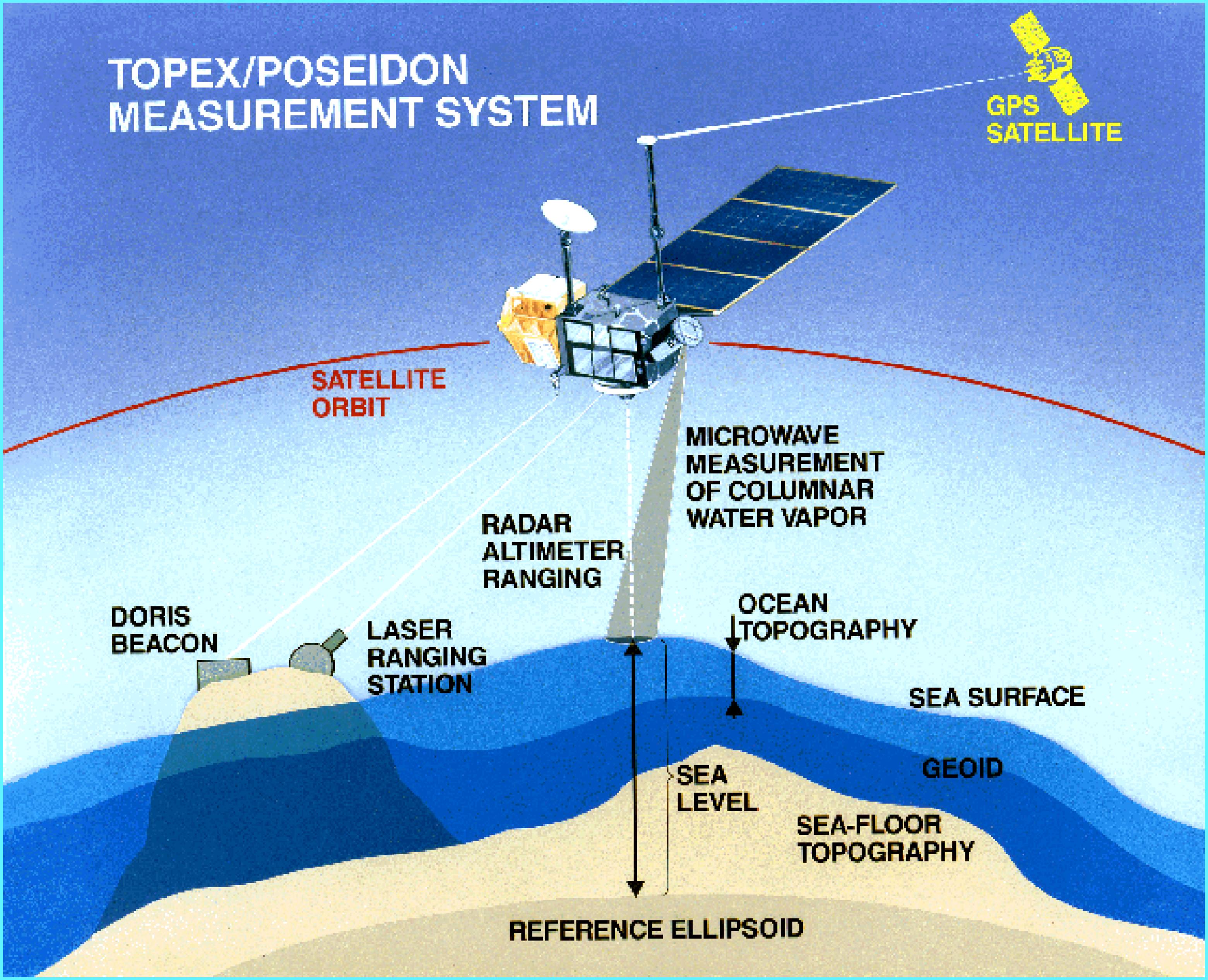


Ocean currents transport heat and regulate climate change. They can be measured from space via ocean surface topography.

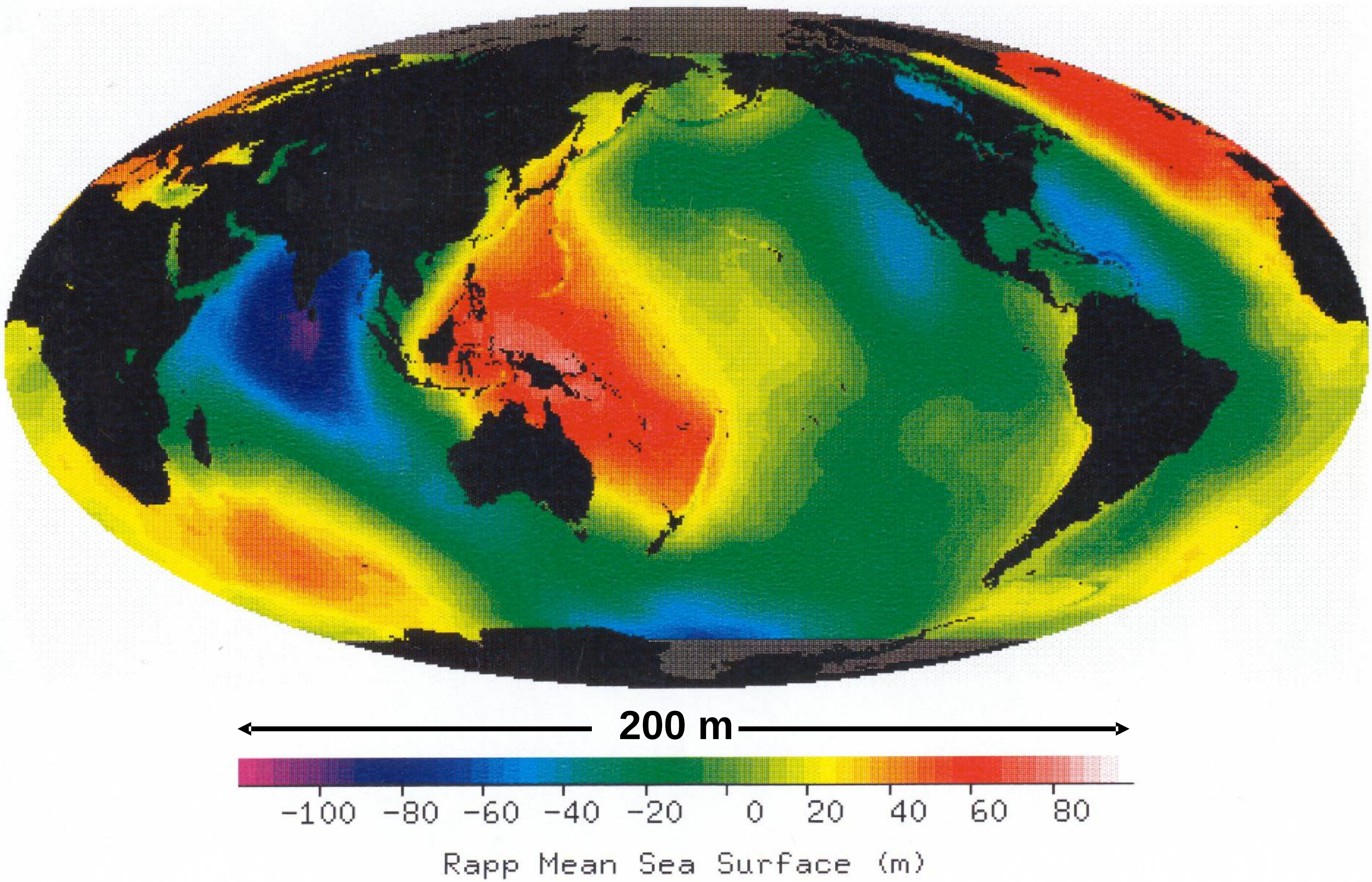


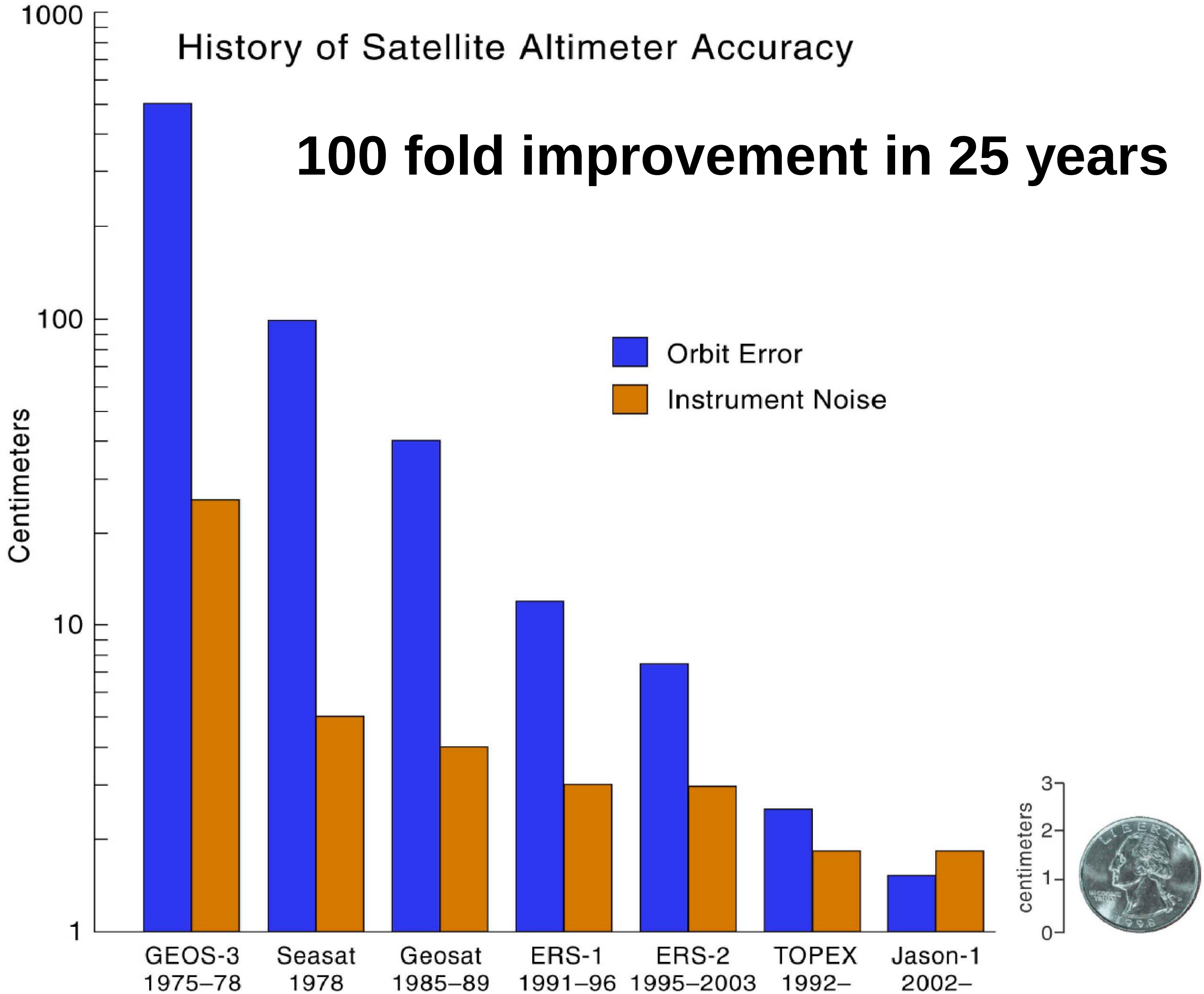


Ocean currents move around the highs and lows of ocean surface topography.


TOPEX/POSEIDON
MEASUREMENT SYSTEM
GPS
SATELLITE
SATELLITE
ORBIT
MICROWAVE
MEASUREMENT
OF COLUMNAR
WATER VAPOR
RADAR
ALTIMETER
RANGING
OCEAN
TOPOGRAPHY
DORIS
BEACON
LASER
RANGING
STATION
SEA SURFACE
GEOID
SEA
LEVEL
SEA-FLOOR
TOPOGRAPHY
REFERENCE ELLIPSOID

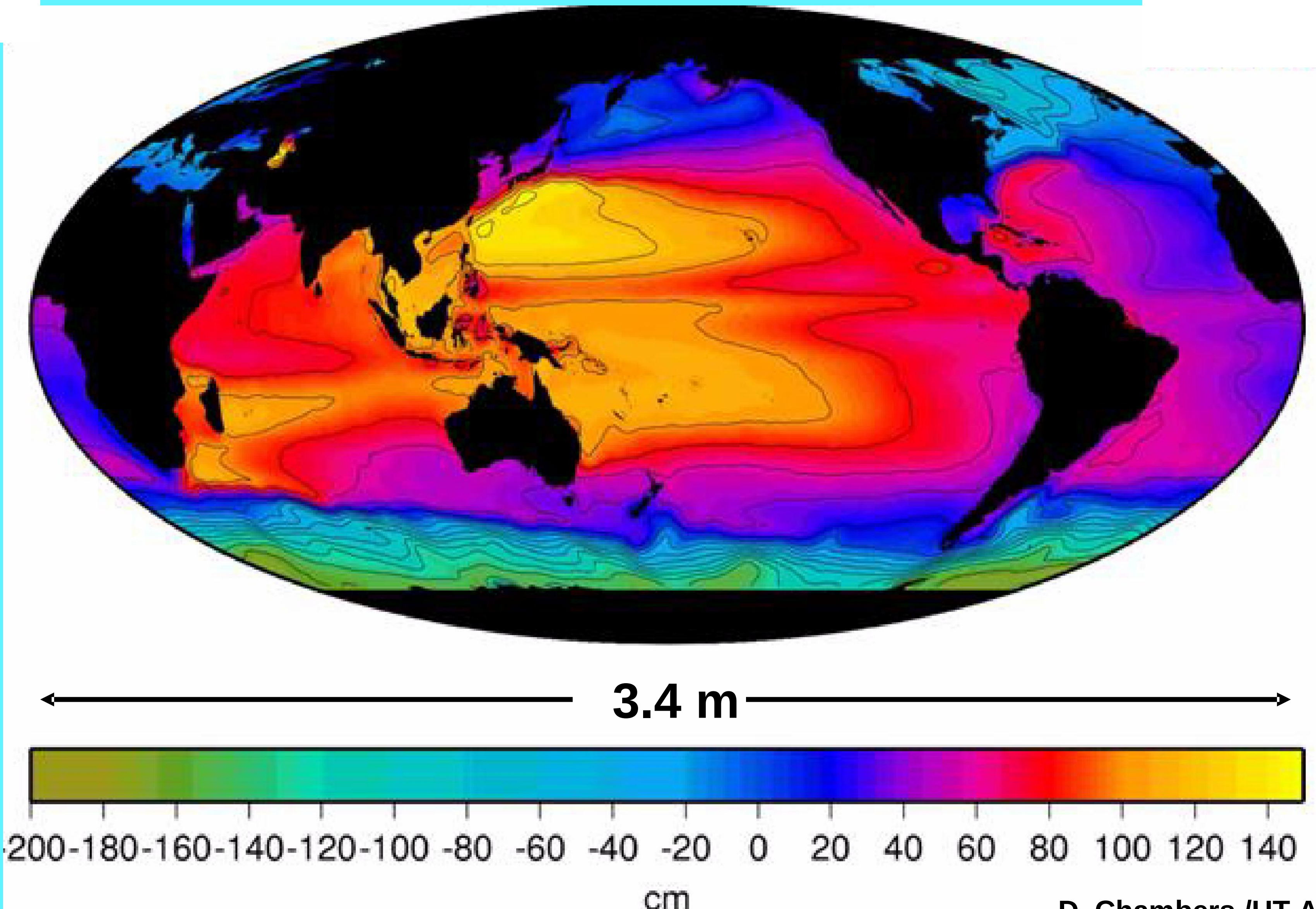
RELIEF OF THE MEAN SEA SURFACE




History of Satellite Altimeter Accuracy
100 fold improvement in 25 years
1000
100
10
1
Centimeters
Orbit Error
Instrument Noise
GEOS-3
1975–78
Seasat
1978
Geosat
1985–89
ERS-1
1991–96
ERS-2
1995–2003
TOPEX
1992–
Jason-1
2002–
centimeters
3
2
1
0

Ocean Surface Topography

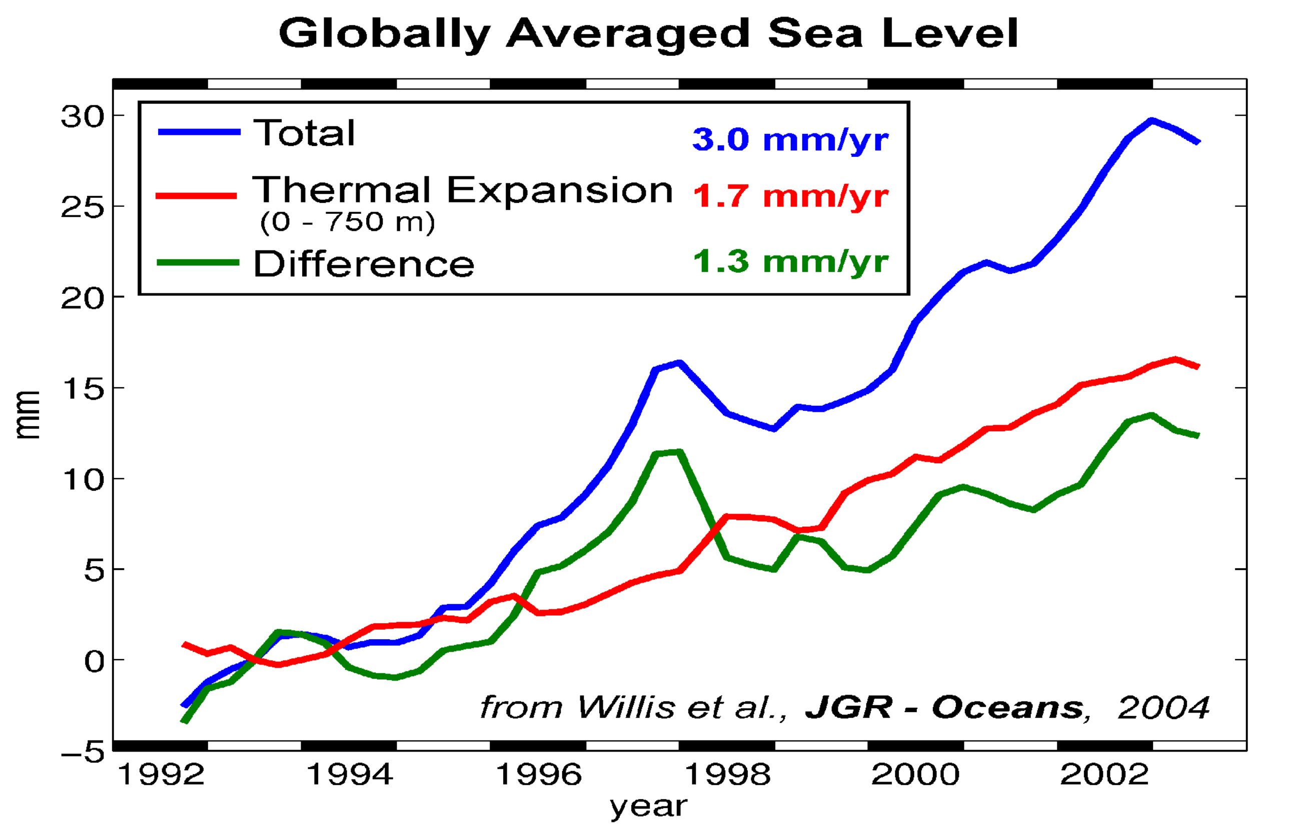
(TOPEX/Poseidon Sea Level – GRACE Geoid)



D. Chambers /UT Austin

Global Mean Sea Level Trends

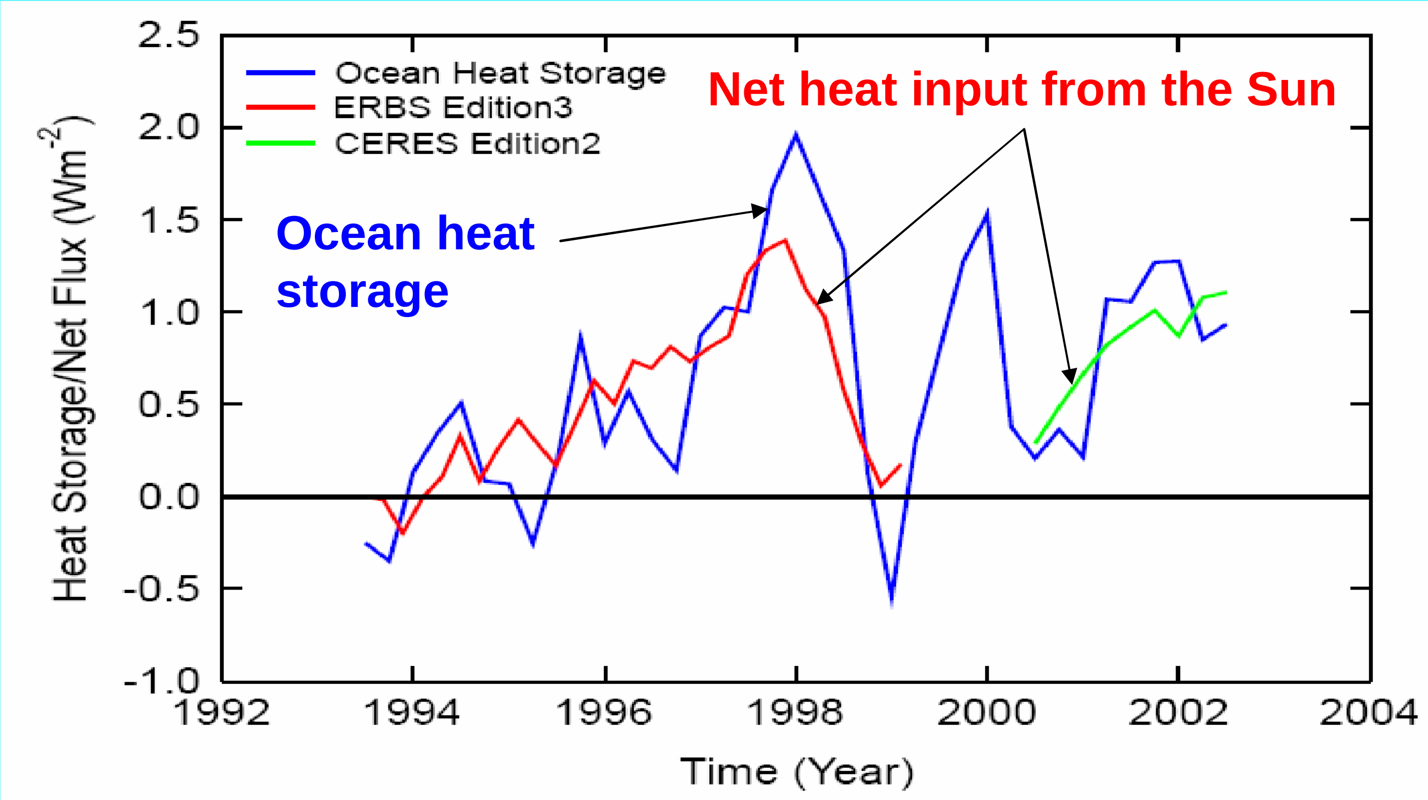
For the first time, global mean sea-level change is estimated directly from global observations. Coupled with ocean temperature observations, the contribution from melting of grounded glacier ice is inferred.



Recent rate of ice discharge from Greenland ~ 0.5mm/year

J. Willis/JPL

The ocean is taking the heat.



Over 10 years, the heat absorbed by the ocean would have been enough to have done one of the following had it not been absorbed by the ocean:

1) ***heat the entire atmosphere by 5 degrees;***
2) ***melt all of the world's sea ice (3 times over);***
3) ***melt enough grounded glacier ice to raise sea level by 24 cm.***

J. Willis/JPL

So? Well… when water is warmed, it expands. The largest part of the answer to the question, "where is the water coming from?" is:

—> THERMAL EXPANSION OF THE OCEAN. <—

That is, heat from climate warming is causing the ocean to expand at constant mass.

During the recent 10-year time period 1993 to 2003, <u>thermal expansion of the ocean</u> is estimated to have accounted for

1.7 ± 0.5 mm/yr ~50%

of observed sea-level rise

(IPCC, Climate Change 2007: The Physical Basis).

What about the other 50% —?

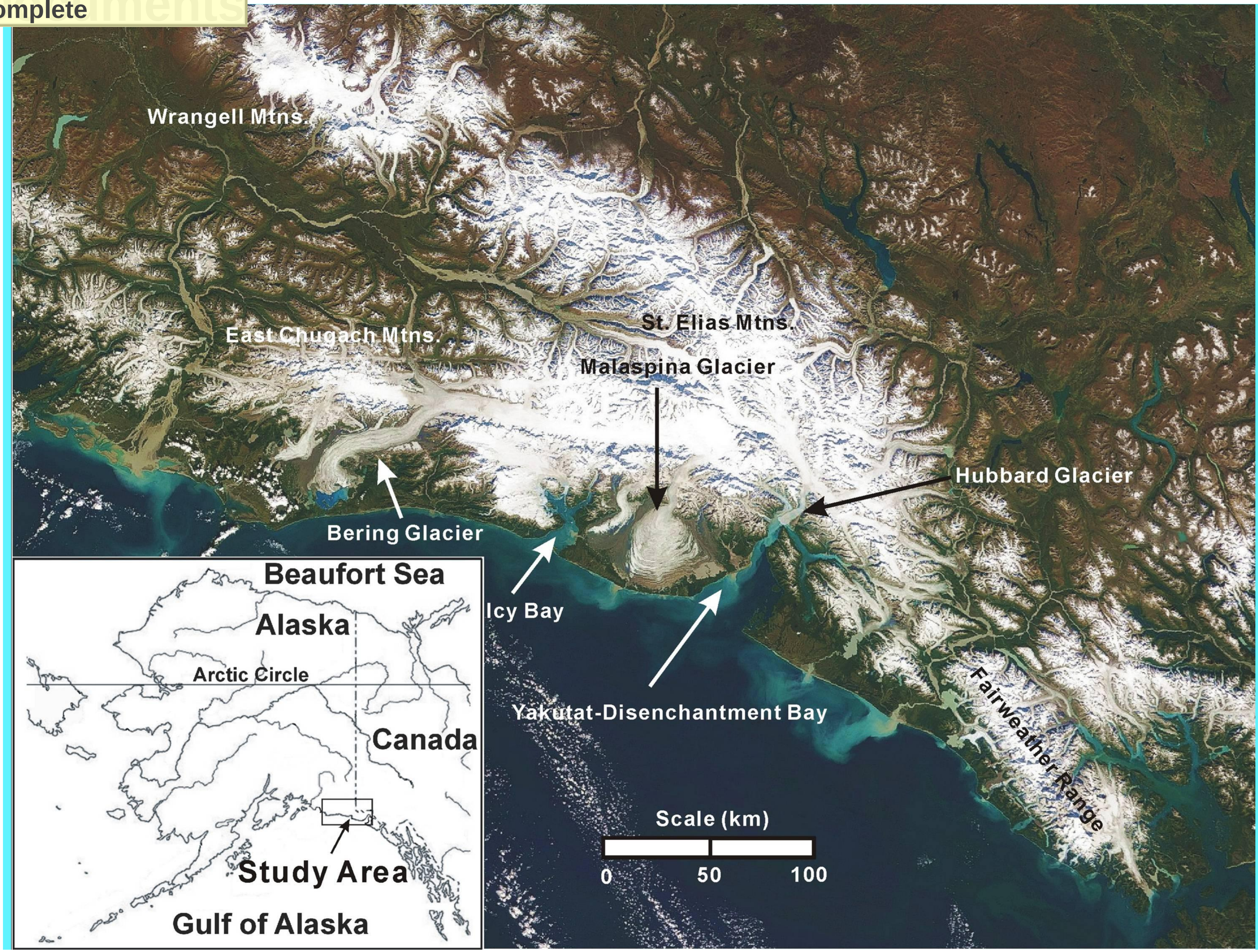
Glaciers and ice caps

worldwide

are thinning and retreating.

How do we know this?

Geodetic glaciology—carried out via small-aircraft laser altimetry and high-resolution airborne and spaceborne SAR-derived digital elevation models (DEMs)—is an effective approach.


Wrangell Mtns.
East Chugach Mtns.
St. Elias Mtns.
Malaspina Glacier
Hubbard Glacier
Bering Glacier
Icy Bay
Yakutat-Disenchantment Bay
Fairweather Range
Scale (km)
0
50
100
Beaufort Sea
Alaska
Arctic Circle
Canada
Study Area
Gulf of Alaska

Glacier elevation & volume changes

from

small-aircraft laser altimetry

relative to USGS DEMs

in Alaska, Yukon,

and northwestern British Columbia

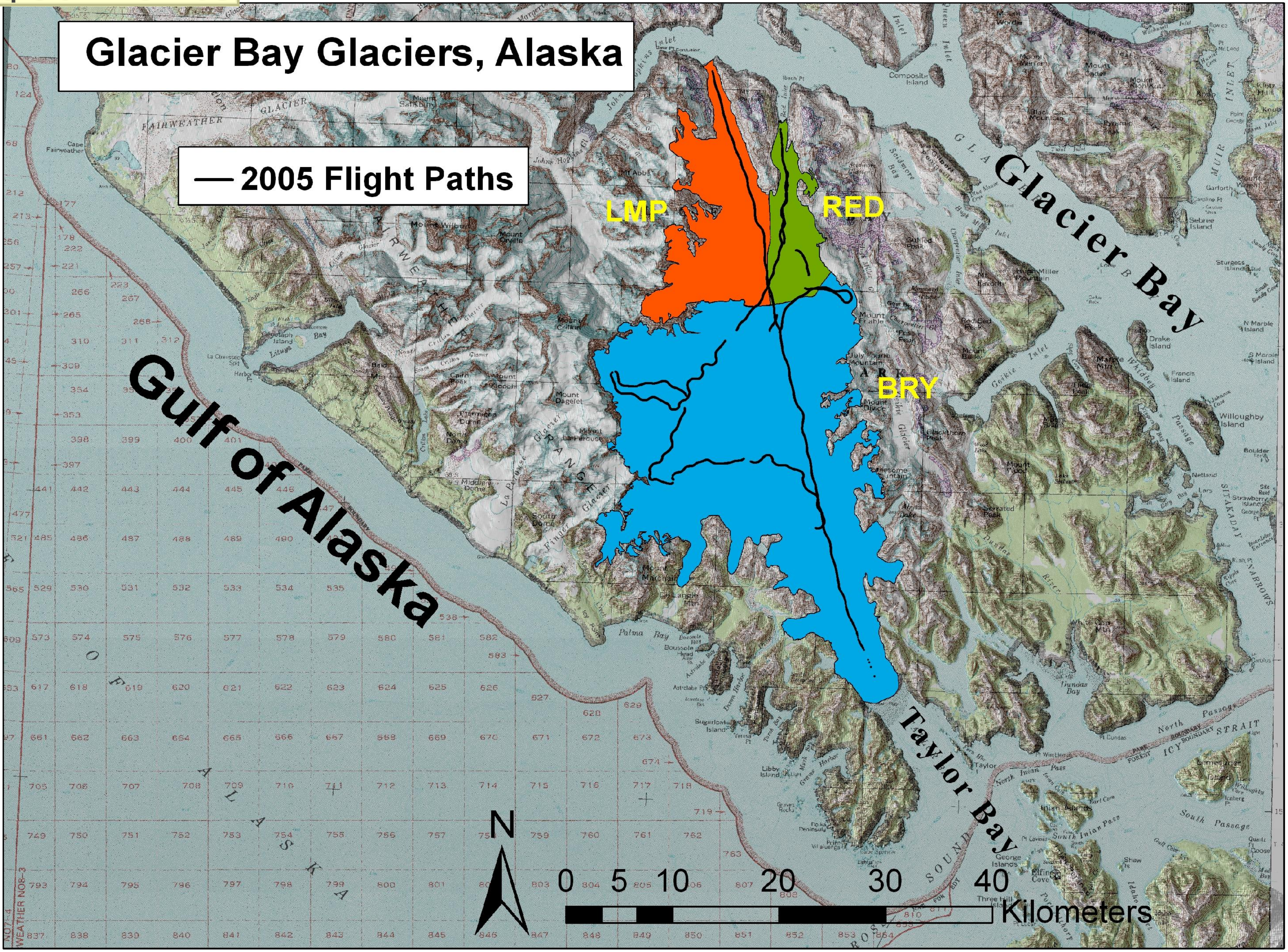
Installing altimeter system in a Cessna 185 in Ultima Thule hanger (Palmer, Alaska): May 2005.

Upper: Chris Larsen (L) and Paul Weber (mechanic and avionics technician)

Lower: Sandra Zirnheld

Altimeter installation in Ultima Thule hanger (Palmer, Alaska). A rebuilt engine & rebuilt alternator had also just been installed by Paul Weber

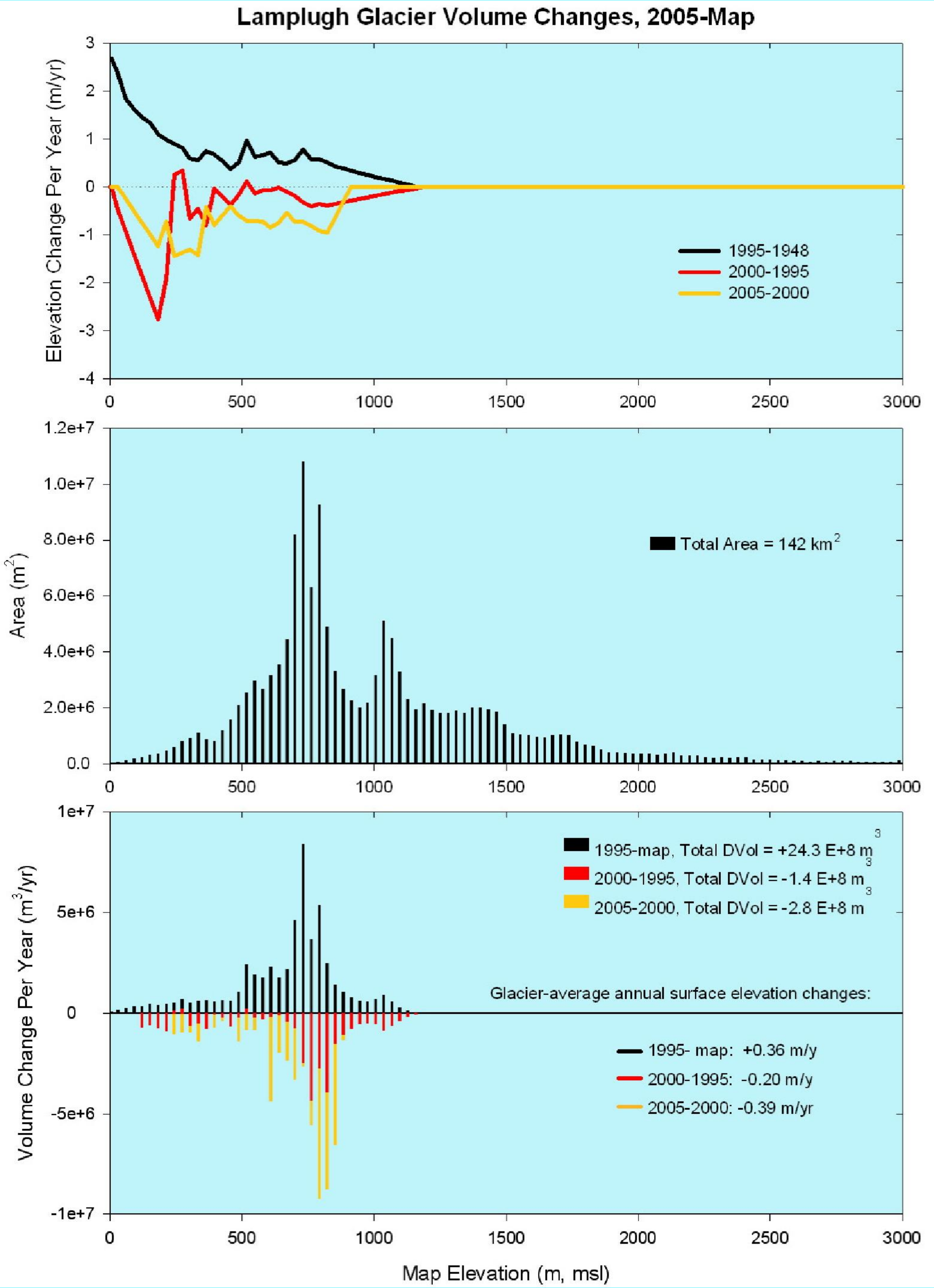
Altimeter testing and calibration at (upper left) Chitina air strip and (other photos) Palmer airport. Lower right: Matt Druckenmiller, Brent Ritchie (right), Paul Claus (fueling airplane).

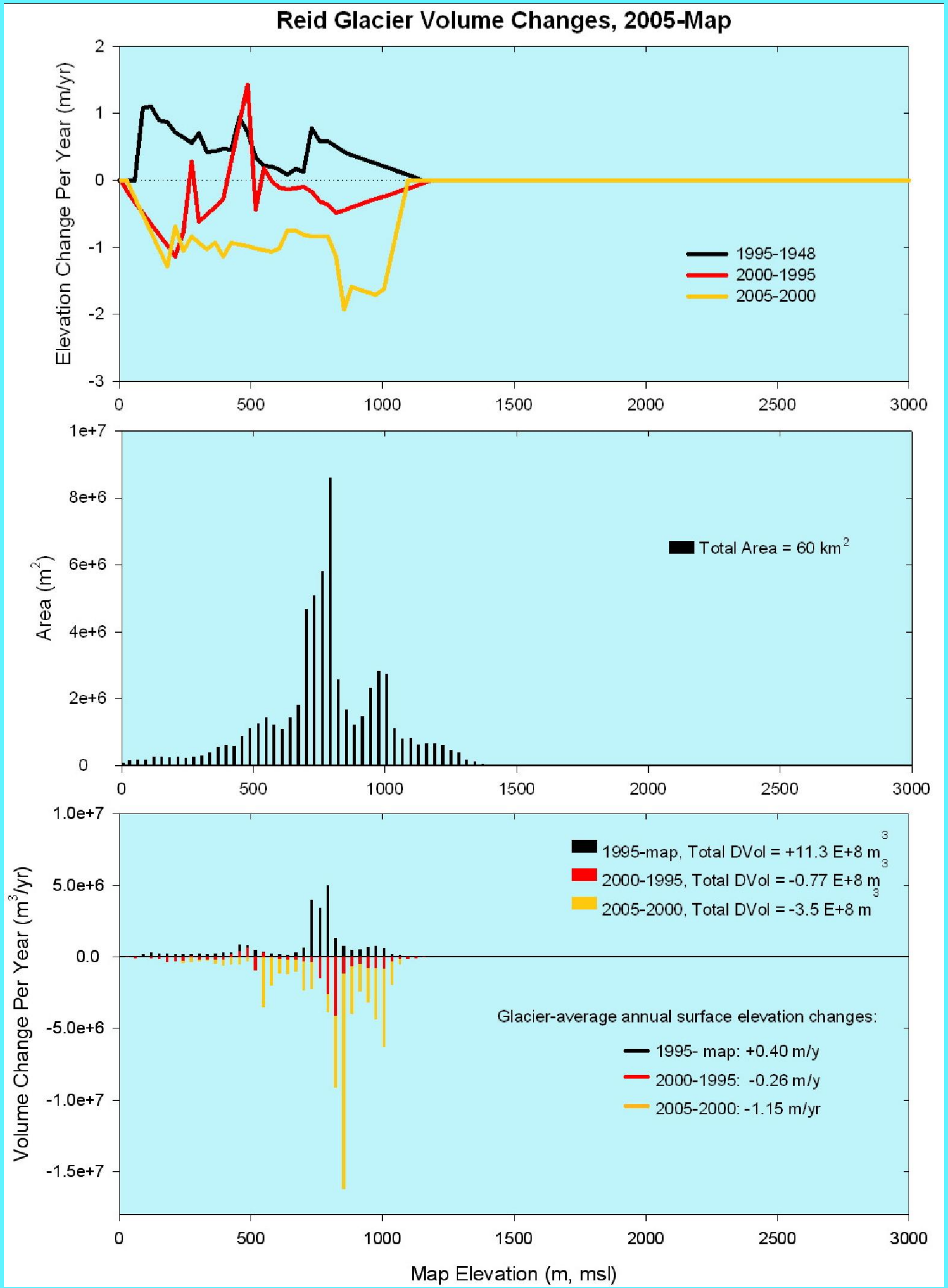

Glacier Bay Glaciers, Alaska
— 2005 Flight Paths
LMP
RED
BRY
Glacier Bay
Gulf of Alaska
Taylor Bay
N
0 5 10 20 30 40
Kilometers

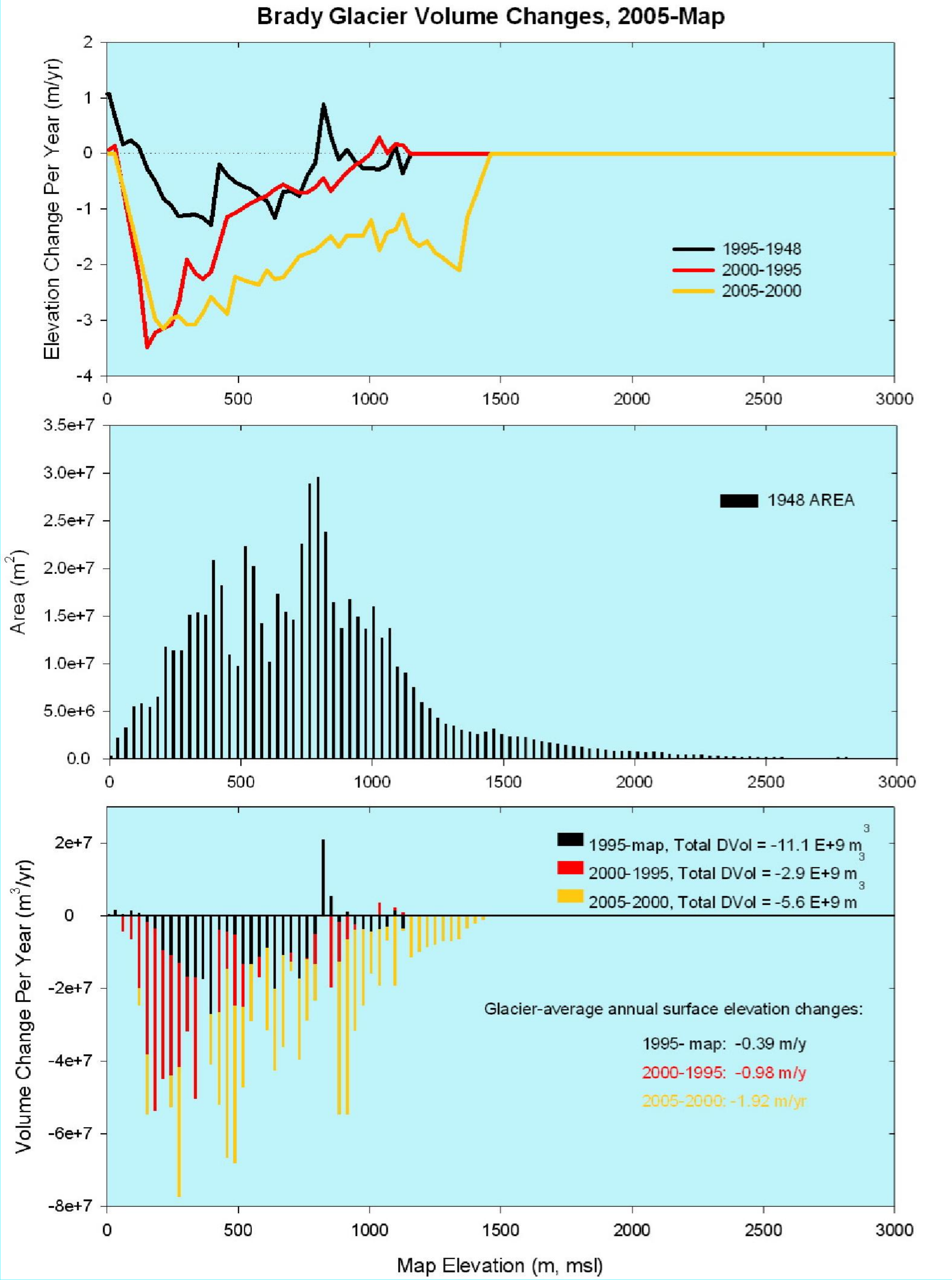

N805

Installing a temporary GPS benchmark at Gustavus Airport, Glacier Bay: Matt Druckenmiller

Lamplugh (lft) & Reid (rt) Glaciers, Fairweather Range. Glacier Bay in distance. View NNE.


Lamplugh Glacier Volume Changes, 2005-Map
Elevation Change Per Year (m/yr)
1995-1948
2000-1995
2005-2000
Area (m2)
Total Area = 142 km2
Volume Change Per Year (m3/yr)
1995-map, Total DVol = +24.3 E+8 m3
2000-1995, Total DVol = -1.4 E+8 m3
2005-2000, Total DVol = -2.8 E+8 m3
Glacier-average annual surface elevation changes:
1995- map: +0.36 m/y
2000-1995: -0.20 m/y
2005-2000: -0.39 m/yr
Map Elevation (m, msl)


Reid Glacier Volume Changes, 2005-Map
Elevation Change Per Year (m/yr)
1995-1948
2000-1995
2005-2000
Area (m²)
Total Area = 60 km²
Volume Change Per Year (m³/yr)
1995-map, Total DVol = +11.3 E+8 m³
2000-1995, Total DVol = -0.77 E+8 m³
2005-2000, Total DVol = -3.5 E+8 m³
Glacier-average annual surface elevation changes:
1995- map: +0.40 m/y
2000-1995: -0.26 m/y
2005-2000: -1.15 m/yr
Map Elevation (m, msl)


Brady Glacier Volume Changes, 2005-Map
Elevation Change Per Year (m/yr)
1995-1948
2000-1995
2005-2000
Area (m²)
1948 AREA
Volume Change Per Year (m³/yr)
1995-map, Total DVol = -11.1 E+9 m³
2000-1995, Total DVol = -2.9 E+9 m³
2005-2000, Total DVol = -5.6 E+9 m³
Glacier-average annual surface elevation changes:
1995- map: -0.39 m/y
2000-1995: -0.98 m/y
2005-2000: -1.92 m/yr
Map Elevation (m, msl)

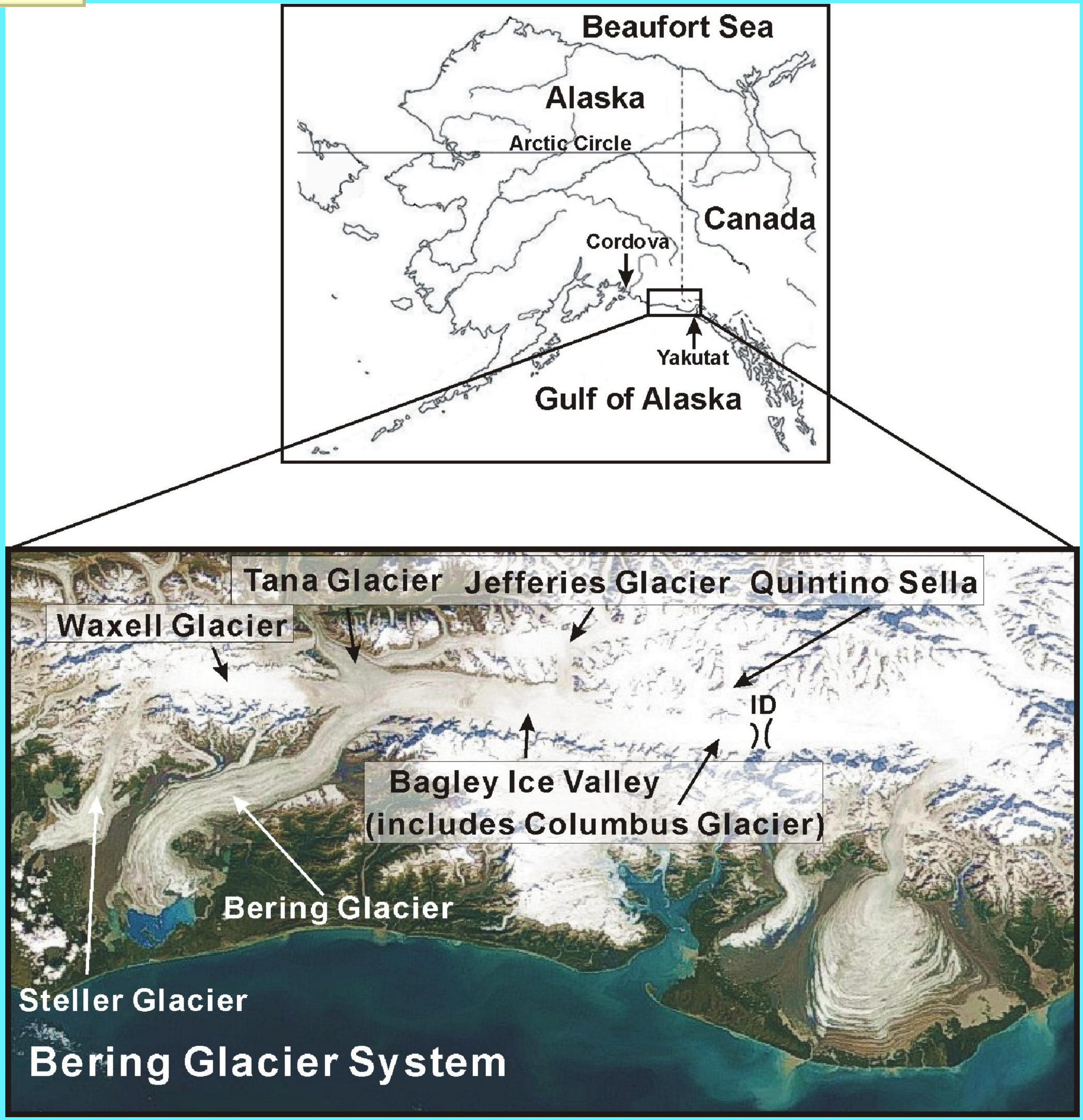
Glacier elevation and volume changes from high-resolution digital elevation models (DEMs):

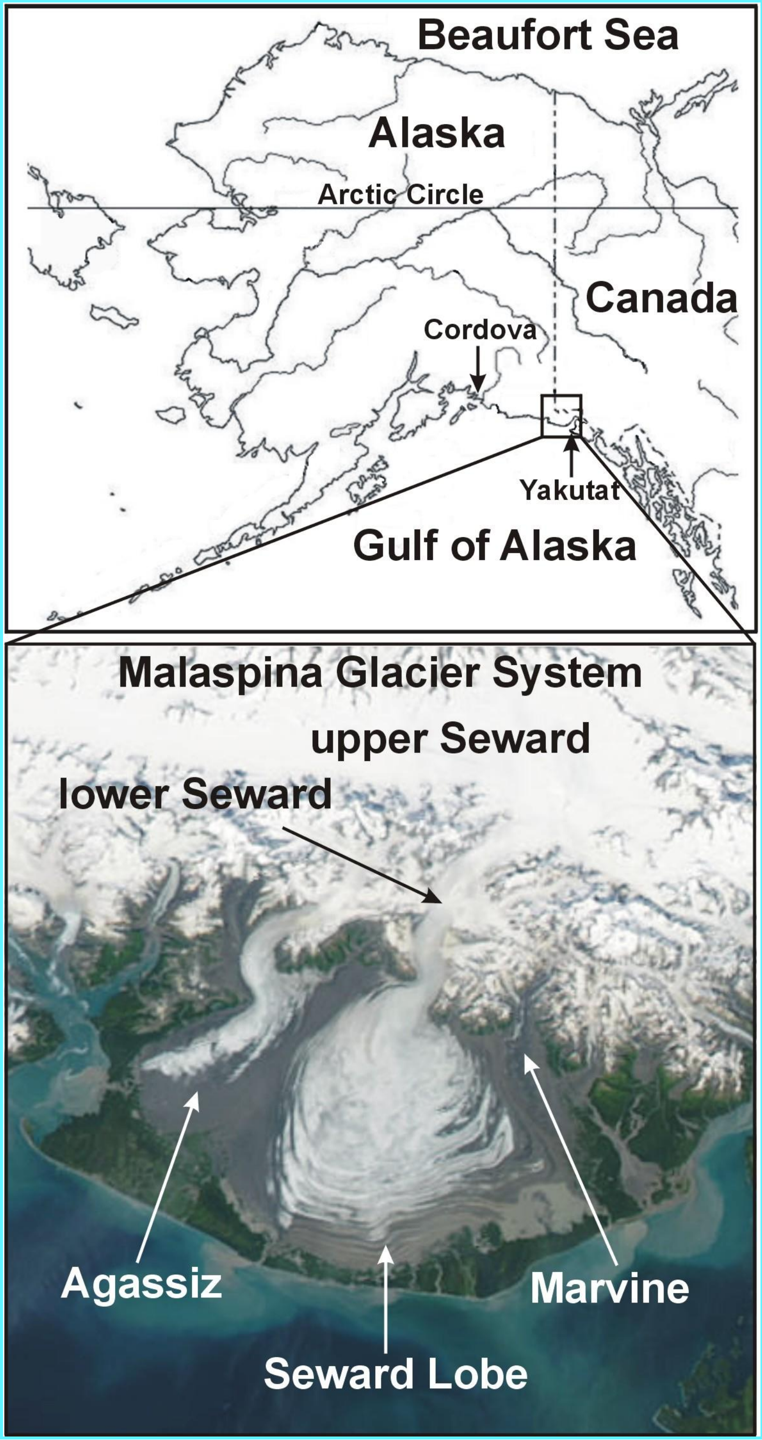
When the climate warms, glaciers melt…

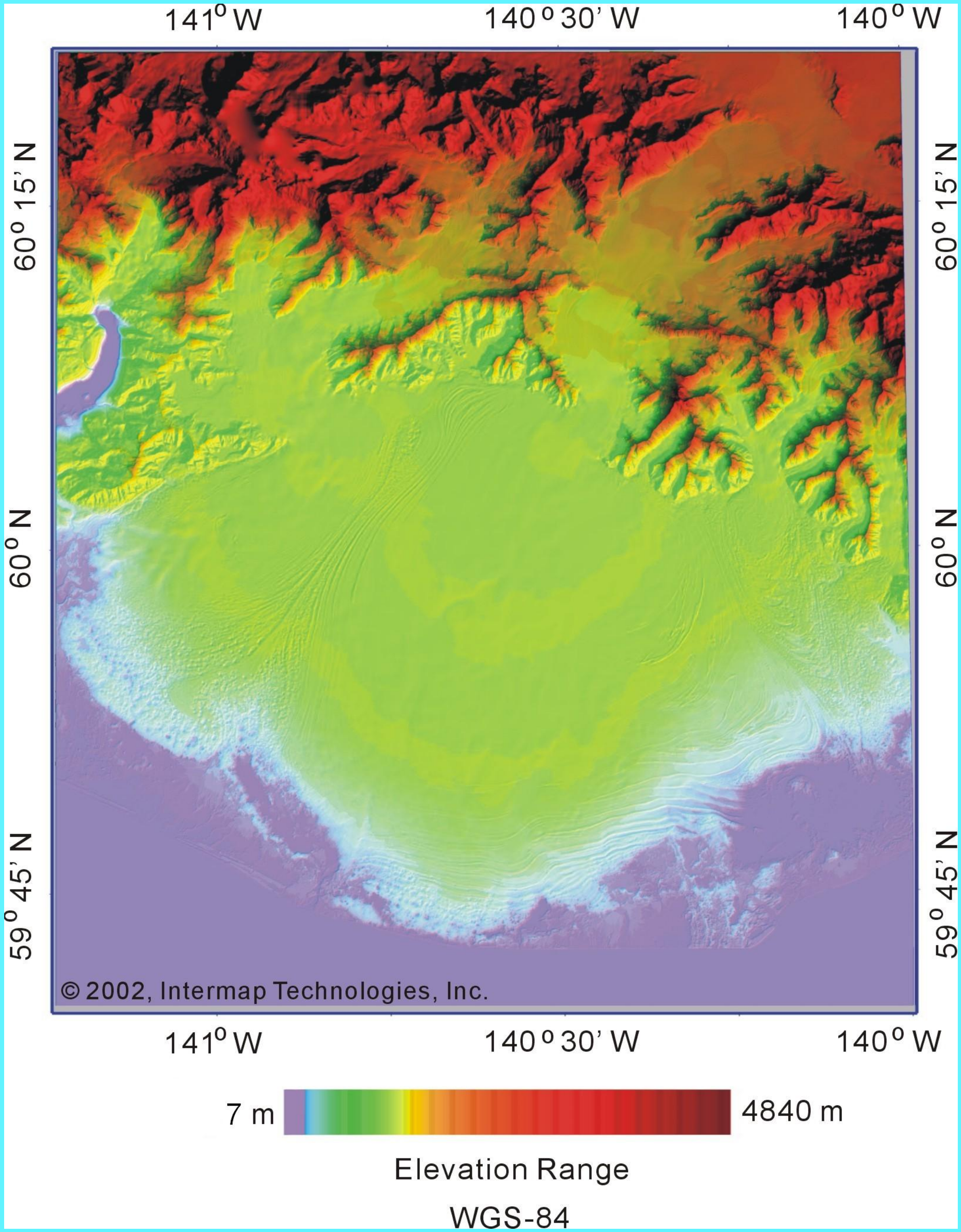
but is there more to it?

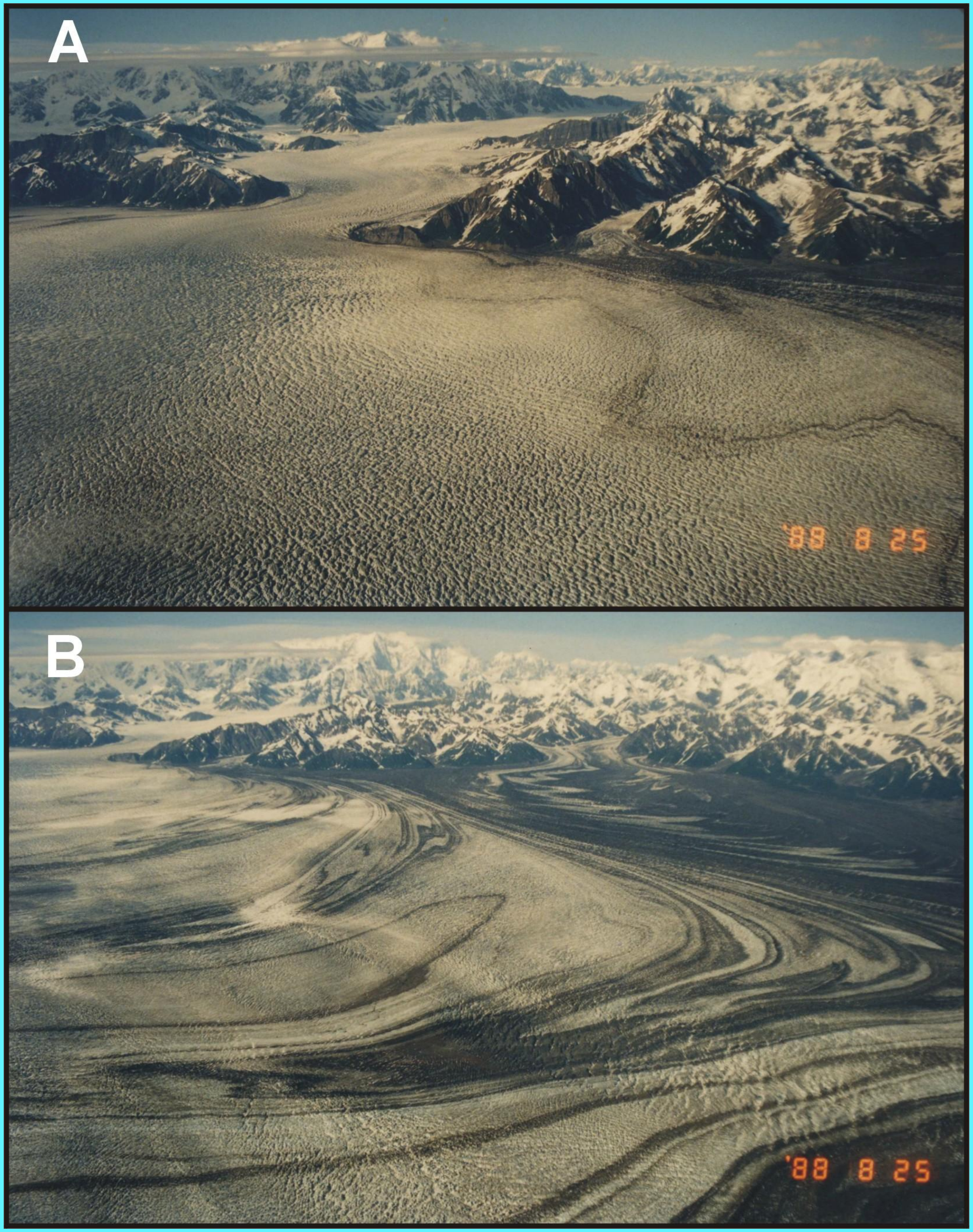
Yes!

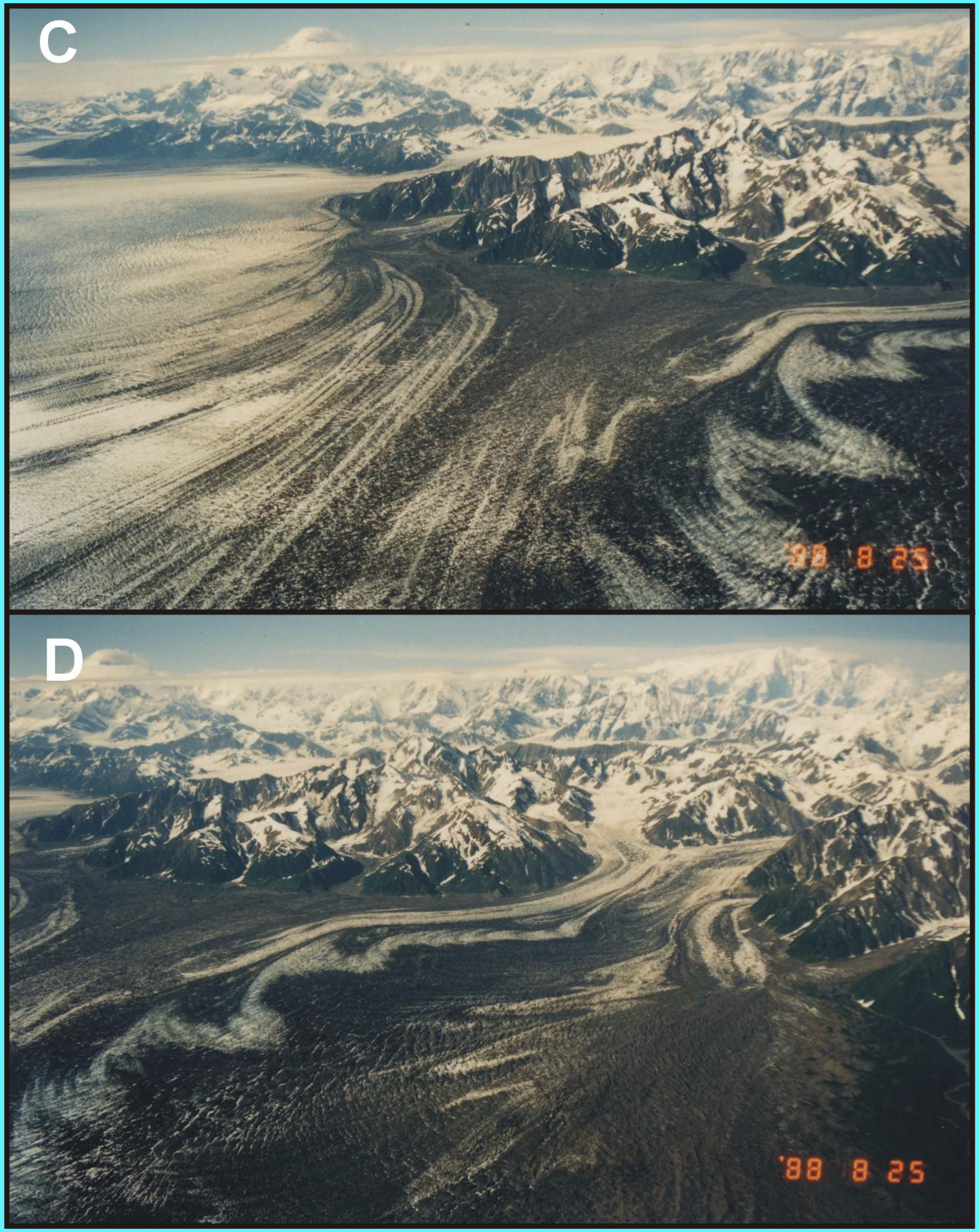
Three near-concurrent surges in the huge Malaspina glacier system illustrate ice dynamics in action.

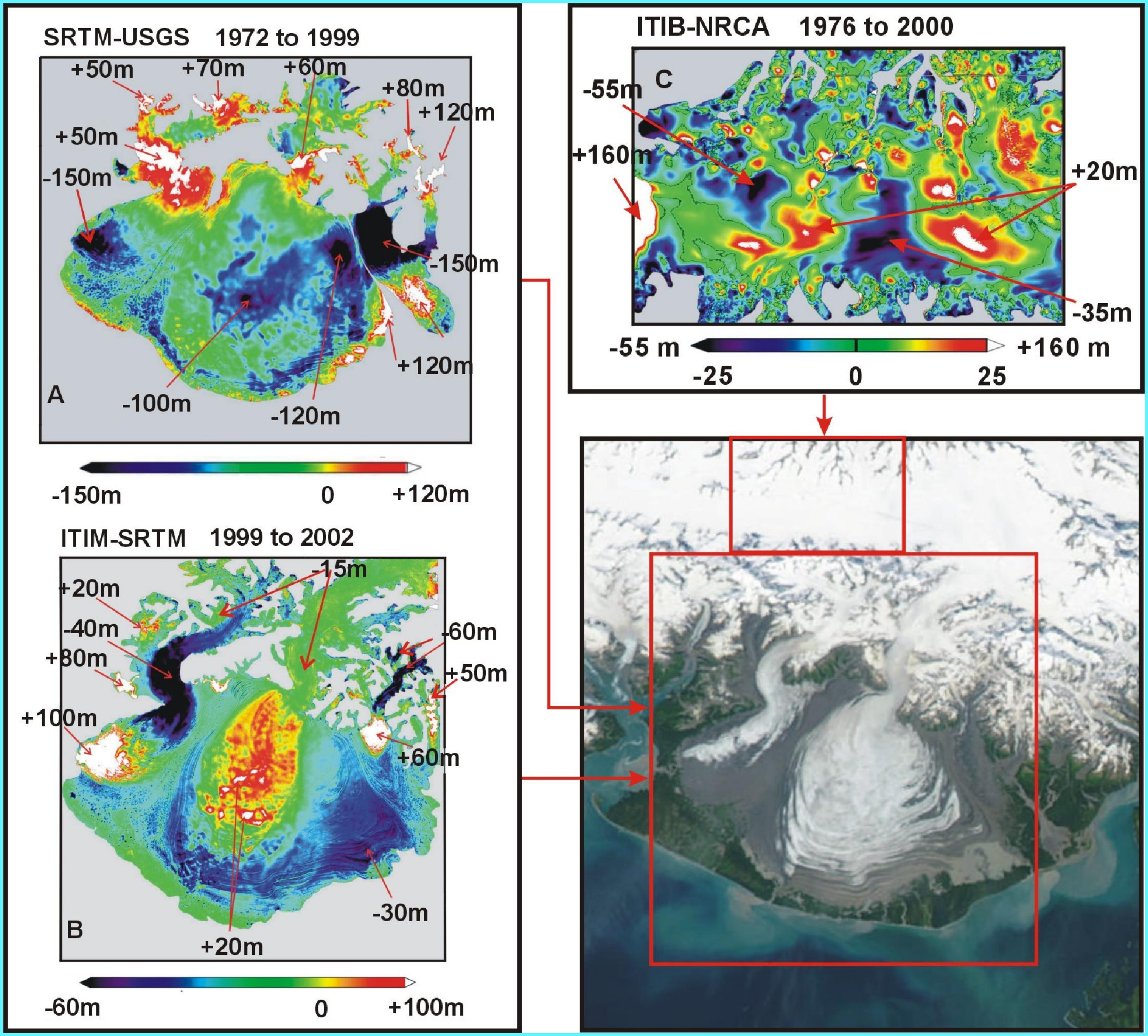

Beaufort Sea
Alaska
Arctic Circle
Canada
Cordova
Yakutat
Gulf of Alaska
Tana Glacier
Jefferies Glacier
Quintino Sella
Waxell Glacier
ID
)(
Bagley Ice Valley
(includes Columbus Glacier)
Bering Glacier
Steller Glacier
Bering Glacier System

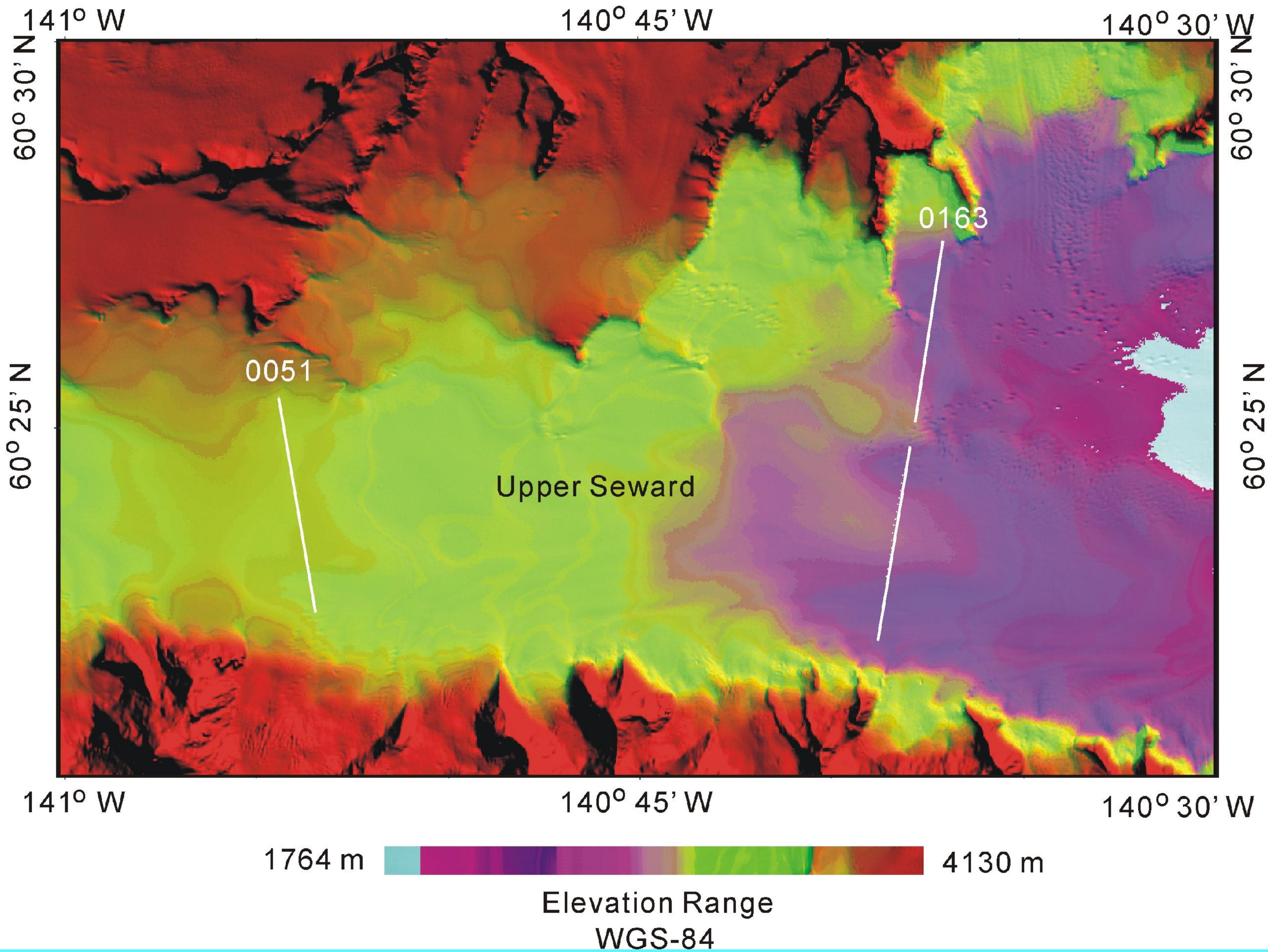

Beaufort Sea
Alaska
Arctic Circle
Canada
Cordova
Yakutat
Gulf of Alaska
Malaspina Glacier System
upper Seward
lower Seward
Agassiz
Marvine
Seward Lobe

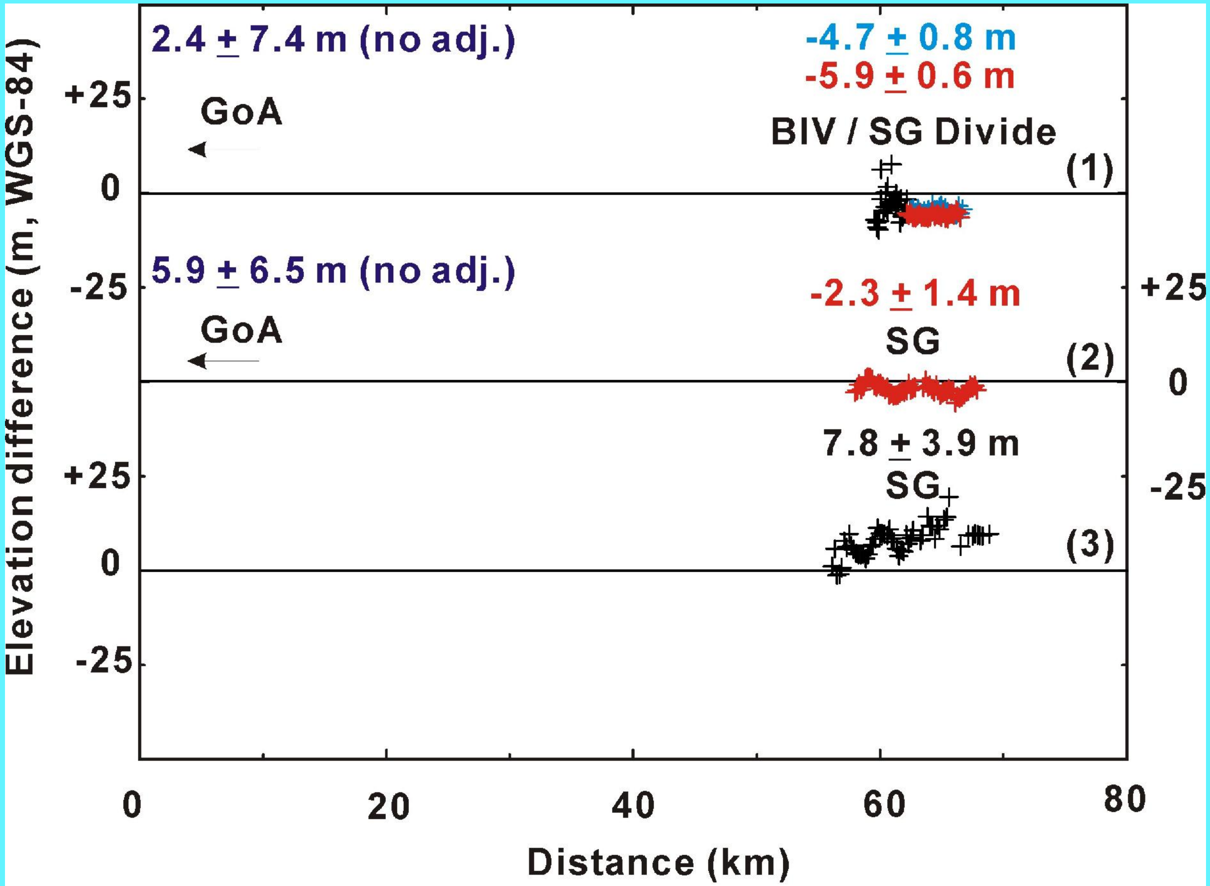

141° W
140° 30' W
140° W
60° 15' N
60° N
59° 45' N
© 2002, Intermap Technologies, Inc.
7 m
4840 m
Elevation Range
WGS-84


A
'88 8 25
B
'88 8 25


C
'88 8 25
D
'88 8 25


SRTM-USGS 1972 to 1999
+50m
+70m
+60m
+80m
+120m
+50m
-150m
-150m
+120m
A
-100m
-120m
-150m
0
+120m
ITIM-SRTM 1999 to 2002
-15m
+20m
-40m
+80m
-60m
+50m
+100m
+60m
B
+20m
-30m
-60m
0
+100m
ITIB-NRCA 1976 to 2000
-55m
C
+160m
+20m
-35m
-55 m
+160 m
-25
0
25

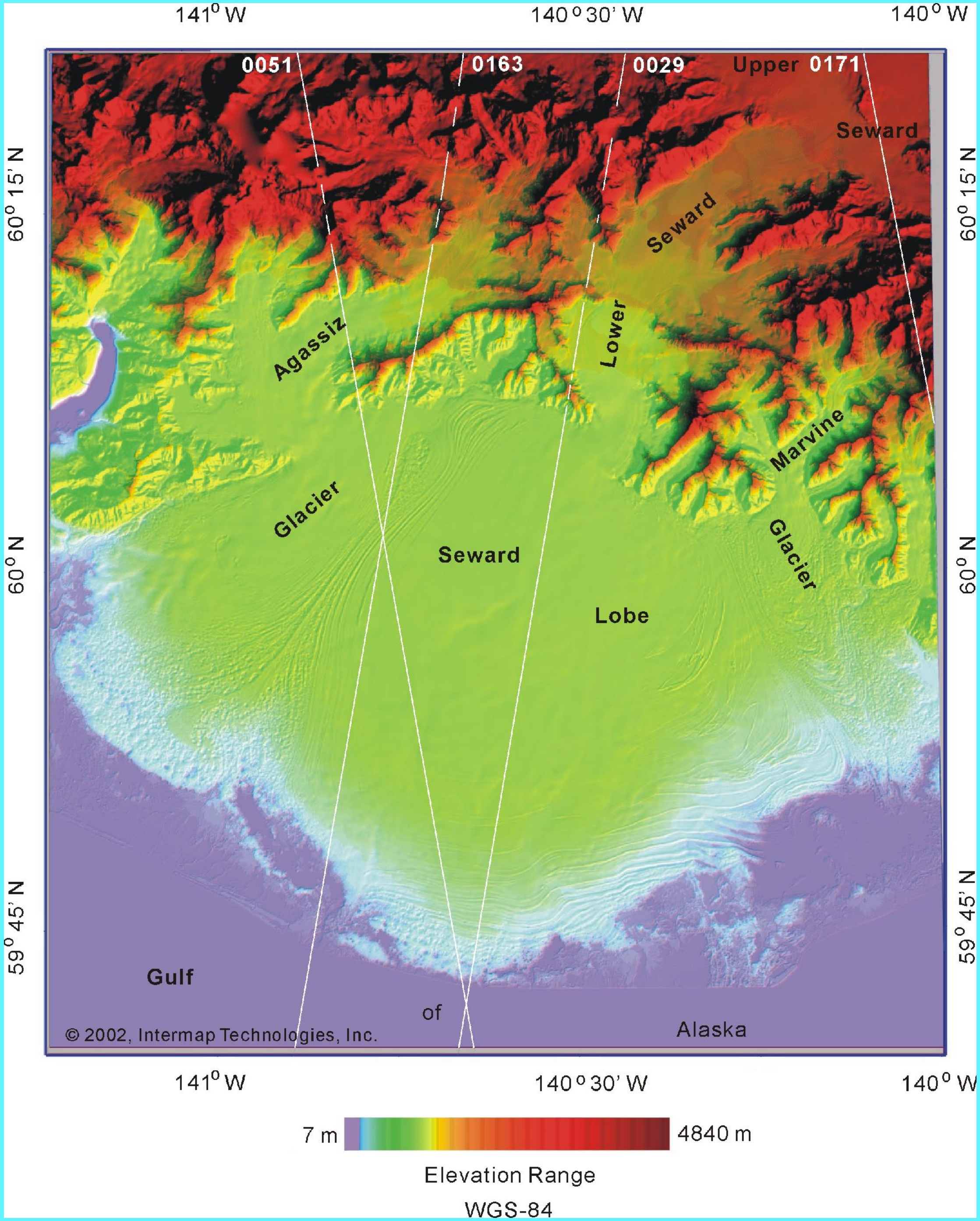

141° W
140° 45' W
140° 30' W
60° 30' N
60° 25' N
0163
0051
Upper Seward
141° W
140° 45' W
140° 30' W
1764 m
4130 m
Elevation Range
WGS-84

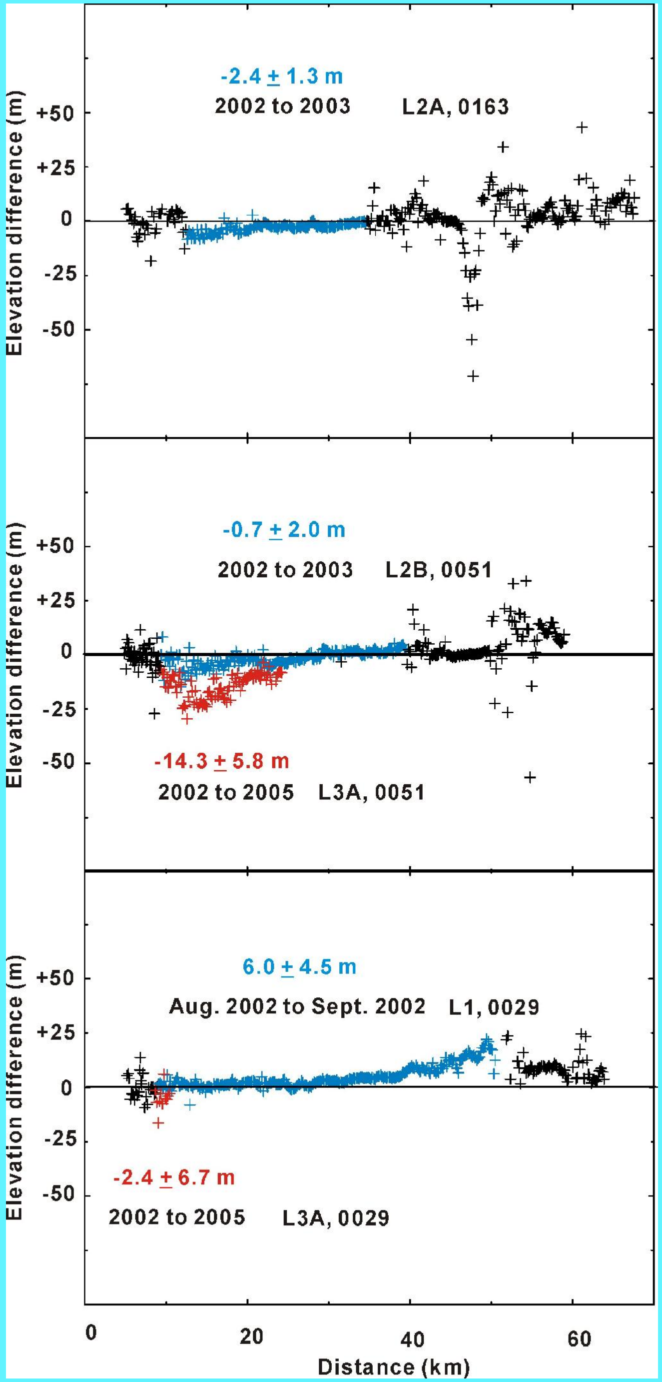


(1) L2B, 0051
2000 to 2003
L3A, 0051
2002 to 2005
@ 2060 m elevation

(2) L2A, 0163
2000 to 2003
@ 1890 m elevation

(3) L3A, 0171
2002 to 2004
@ 1650 m elevation


141° W
140° 30' W
140° W
0051
0163
0029
Upper
0171
Seward
Seward
Agassiz
Lower
Marvine
Glacier
Seward
Glacier
Lobe
60° 15' N
60° N
59° 45' N
Gulf
of
Alaska
© 2002, Intermap Technologies, Inc.
7 m
4840 m
Elevation Range
WGS-84


-2.4 ± 1.3 m
2002 to 2003
L2A, 0163
-0.7 ± 2.0 m
2002 to 2003
L2B, 0051
-14.3 ± 5.8 m
2002 to 2005
L3A, 0051
6.0 ± 4.5 m
Aug. 2002 to Sept. 2002
L1, 0029
-2.4 ± 6.7 m
2002 to 2005
L3A, 0029
Elevation difference (m)
+50
+25
0
-25
-50
0
20
40
60
Distance (km)

Volume loss & surface lowering on the <u>Malaspina glacier system, Alaska-Yukon</u>

1972/73 to 1999 (USGS DEM to SRTMx DLR DEM*):

-138 ± 15 km^3 (w.e.)

=> -1.4 ± 0.1 m/yr (w.e.) area-average surface lowering.

1999 to 2002 (SRTMx DLR DEM* to Intermap InSARx DEM):

$-12.8 + 1.1$ km^3 (w.e.)

⇒ -1.8 ± 0.2 m/yr (w.e.) area-average surface lowering.

****Adjusted for late-Sept. '99 to mid-Feb. '02 snow accamulation using the PTAA mass balance model (Tangborn, 1999).***

—from R.R. Muskett, 2007. Ph.D. dissertation, U. Alaska Fairbanks.

Regional estimates of mass loss from the glaciers of Alaska, Yukon, & NW British Columbia

Mid-1950's to mid-1990's*:

-52 + 15 km^3/yr (w.e.)

=> 0.14 ± 0.04 mm/yr (w.e.) sea level equiv.

~6 to 10% of observed sea-level rise.

Mid-1990's to 2000/'01*:

-96 ± 35 km^3/yr (w.e.)

=> 0.27 ± 0.1 mm/yr sea lev. equiv.

~5 to 12% of (now faster) observed sea-level rise.

****USGS DEMs to small-aircraft laser altimetry***

—from A.A. Arendt et al, Science, 2002.

A regional measurement of volume loss & surface lowering on glaciers throughout SE Alaska & NW British Columbia (only):

DEM to DEM method, USGS & Canadian DEMs based on airphotos acquired 1948 to 1987; SRTMc DEMs derived from spaceborne InSAR data acquired mid-February 2000.

Volume loss rate = 16.7 ± 4.4 km^3/yr of ice

=> area-average surface lowering at 1.15 m/yr.

This is more than 2x the loss-rate estimated for these glaciers by Arendt et al. (2002).

Reason: the earlier study did not adequately sample the many tidewater & lake calving glaciers that were losing mass rapidly due to DYNAMIC THINNING.

—from C.F. Larsen et al., J. Geophys. Res, 2007—

The second-largest part of the answer to the question, "where is the water coming from?" is:

—> GLACIERS & ICE CAPS. <—

Thinning and retreating glaciers and ice caps worldwide, including the detached ice caps around the Greenland and Antarctic ice sheets, are making the second-largest contribution to rising sea level:

-402 $\pm$ 95 km^3/yr water equivalent (w.e.) in 2006

=> 1.1 $\pm$ 0.3 mm/yr ~ 32% of observed sea-level rise.

—from M.F. Meier et al., Science, 2007

Accelerating mass loss from the *Greenland Ice Sheet*

1994 to 1999: 51 ± ? km^3/yr (ice loss), from airborne laser altimetry[1]

1996: 91 ± 31 km^3/yr ("), from InSAR surface velocities[3]

2002 to 2004: 82 ± 28 km^3/yr ("), from GRACE gravity data[2]

2000: 138 ± 31 km^3/yr ("), from InSAR surface velocities[3]

2005: 224 ± 41 km^3/yr ("), from InSAR surface velocities[3]

2003 to 2005: 111 ± 18 km^3/yr ("), from GRACE gravity data[4]

Note accelerating ice loss. From GRACE (only), ~96 km3/yr (average) ~8% of observed sea-level rise during 2000 - 2007.

[1]W. Krabill et al., Science, 2000
[2]I. Velicogna and J. Wahr, Geophys. Res. Lttrs., 2005
[3]E. Rignot and P. Kannagaratnam, Science, 2006
[4]S. Luthcke et al., Science, 2006

Contribution from Antarctica

The net mass balance of the entire Antarctic Ice Sheet is not yet well known, because of the vastness of the ice sheet and the short time period since the launch of the gravity recovery and climate experiment (GRACE) satellite system.

During April 2002 to August 2005, the Antarctic ice sheet contributed 152 +/- 80 km³/yr (w.e.) to rising sea level

=> 0.4 +/- 0.2 mm/yr ~12% of observed sea-level rise.

Most of this, 148 ± 21 km³/yr (w.e.), came from the West Antarctic ice sheet.

—from I. Velicogna and J. Wahr, Science, 2006—

Since publication of the first IPCC report in1990, it is now possible to answer convincingly —for the first time— the question, "where is the water coming from?" that is driving sea-level rise.

Thermal expansion of the ocean:	***~50%***
Melting glaciers and ice caps:	***~32%***
Dynamic thinning & melting of the Greenland ice sheet:	***~8%***
Dynamic thinning of the West Antarctic ice sheet:	***~12%***
Total:	***~102%***

[The excess 2% easily falls within the uncertainty range.]

How much is sea level likely to rise during the coming century, by 2100?

S. Rahmstorf (Science, 2007) asserts it is too complicated to model all the processes contributing to rising sea level, and instead establishes an empirical relation between global mean temperature increase above pre-industrial levels and the mean rate of sea-level rise (3.4 mm/yr per ^{o}C).

For the range of IPCC (2001) temperature-increase scenarios (1.4 to 5.8 ^{o}C by 2100), Rahmstorf projects a

<u>0.5 to 1.4 m sea-level rise above the 1990 level by 2100</u>.

<u>The IPCC (2007) projected rise is 0.18 to 0.59 m by 2100</u>.

Why the difference?

A probable reason, from the point of view of glaciers, is

—> ICE DYNAMICS. <—

Tidewater glaciers, which calve icebergs into fjords, after thinning to a critical point due to negative mass balance, can begin retreating catastrophically with greatly increased calving and accelerated flow. This results in dramatic and sustained ice loss.

Periodic surging, characteristic of many large Alaska glaciers, transports ice rapidly from higher to lower elevations where it melts more rapidly.

These processes are difficult to quantify, and are not included in glacier mass balance models.

Why the difference? (cont'd)

From the point of view of ice sheets, a probable reason is also

-—> ICE DYNAMICS. <—

Most discharge from ice sheets is via fast-flowing ice streams— which discharge into floating ice shelves, in Antarctica, and floating outlet glaciers in fjords, in Greenland.

When ice shelves and outlet glaciers thin and break up due to sub-glacial circulation of warming ocean water, their buttressing effect on their "feeder" ice streams is lost. The ice streams can accelerate dramatically, physically drawing down their upstream catchment areas. This dynamic thinning is in progress in Greenland and on the Antarctic Peninsula.

These processes are also difficult to simulate, and are not adequately included in ice sheet models.