

# Snow and Ice in the Hydrologic Cycle

Atmos. Sci. 321

**(first lecture of ESS 431 “Principles of Glaciology”:  
Autumn Quarter MWF 1:30 + field trip)**

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17 May 2010

# Areas covered (in $10^6 \text{ km}^2$ )

**Earth** **512**

**Land** **145**

*"Cryosphere" (all ice on Earth):*

Seasonal snow **45** (30% of land area)  
(North America, Asia)

Mountain glaciers **0.5**

Ice sheets: Antarctica **14** (thickness 2160 m)

Greenland **1.8** (thickness 1500 m)

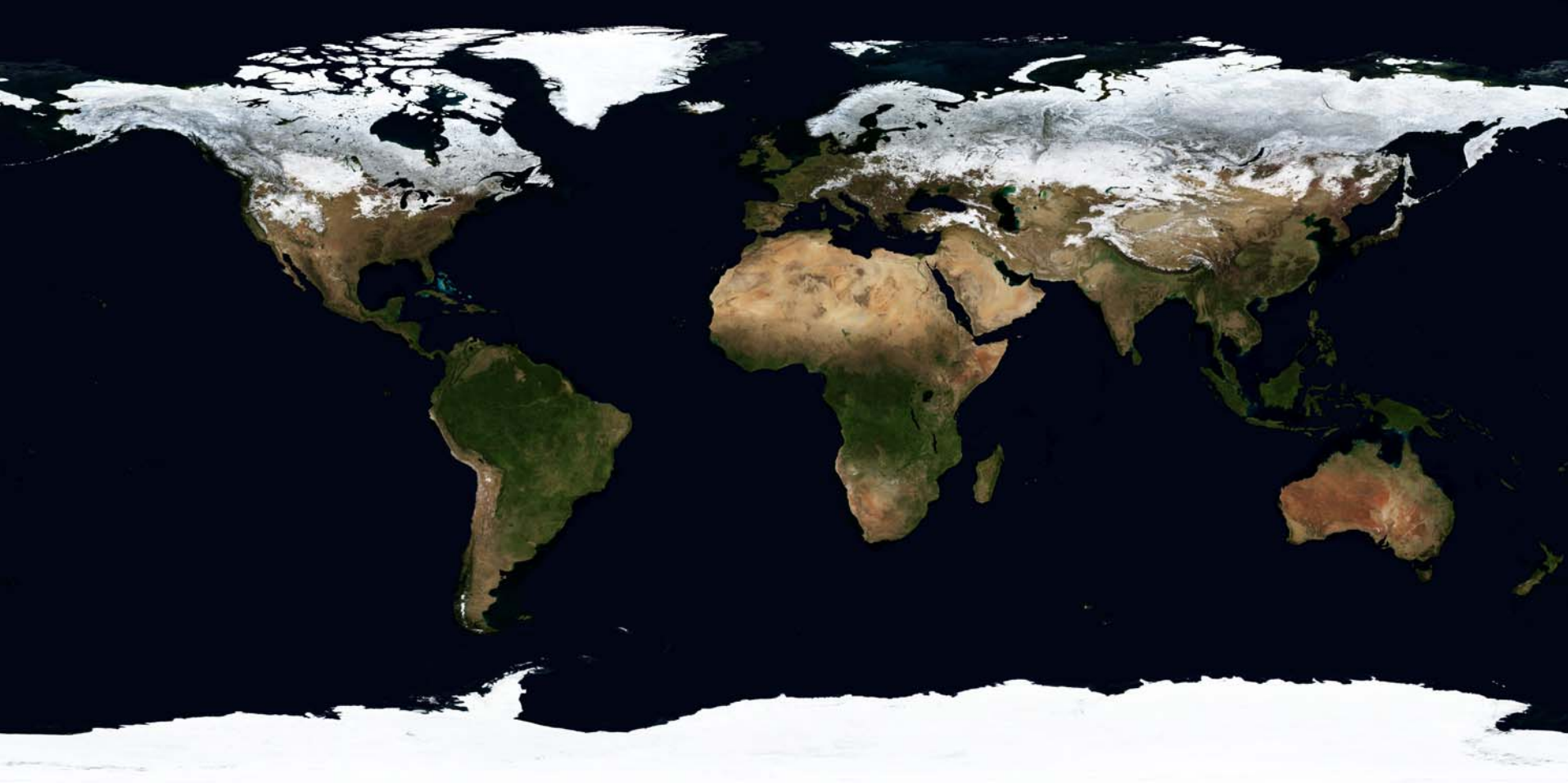
Sea ice max min

Arctic **15** **8.4** (thickness 1-3 m) (*but shrinking!*)

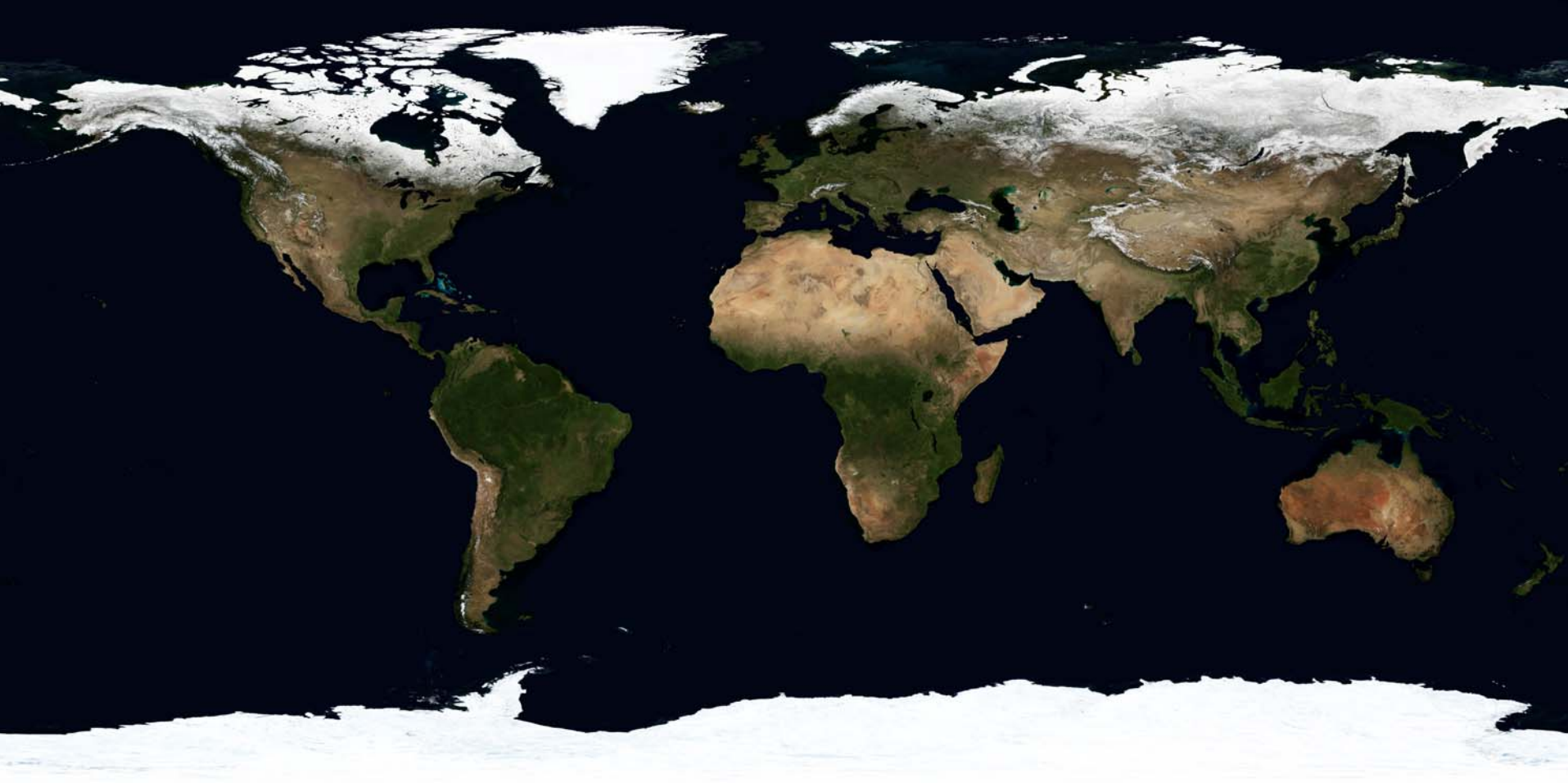
Antarctic **20** **2.5** (thickness 1-2 m)

Permafrost **25** (thickness 0-1400 m)

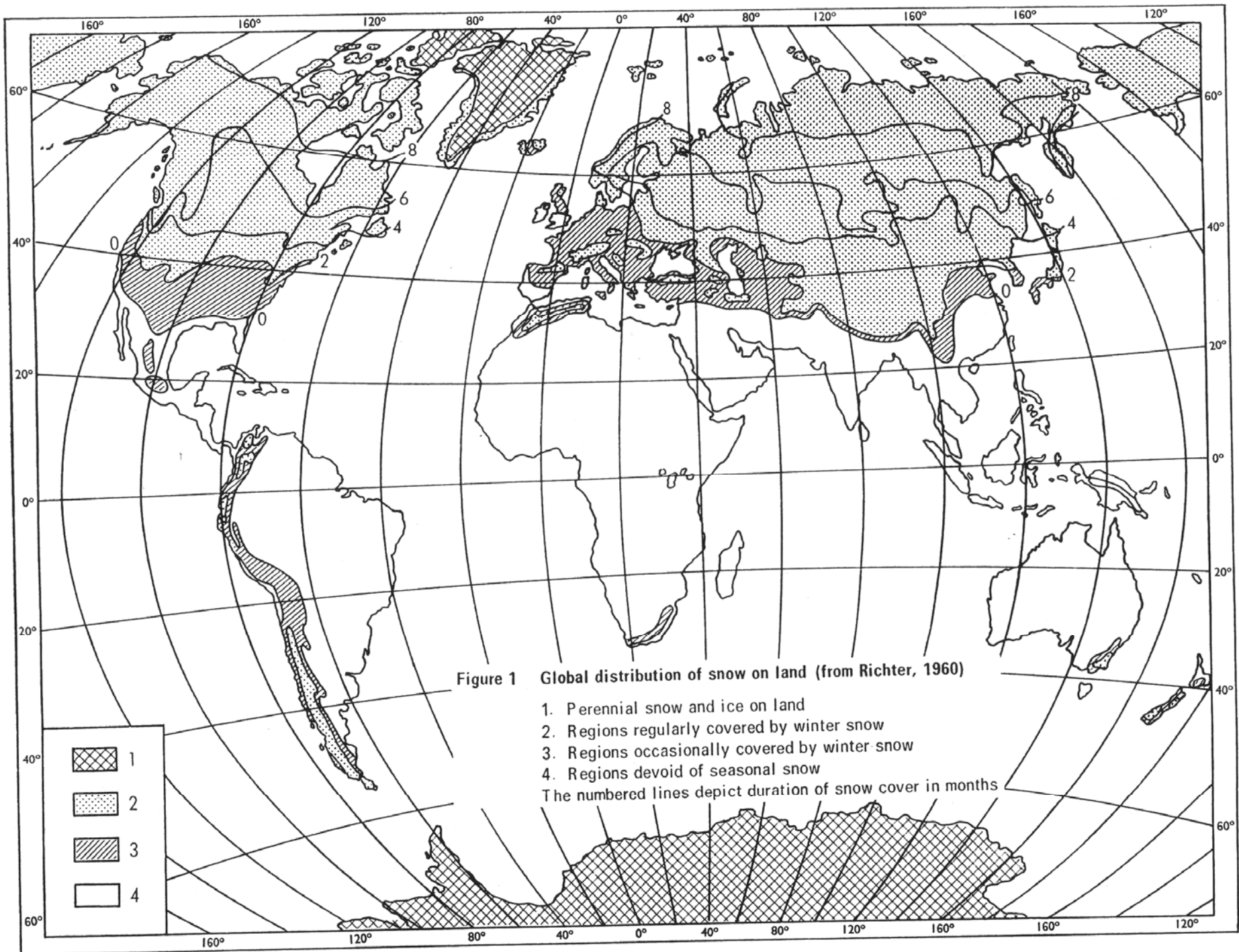
(frozen groundwater) (Canada, Alaska, Siberia)

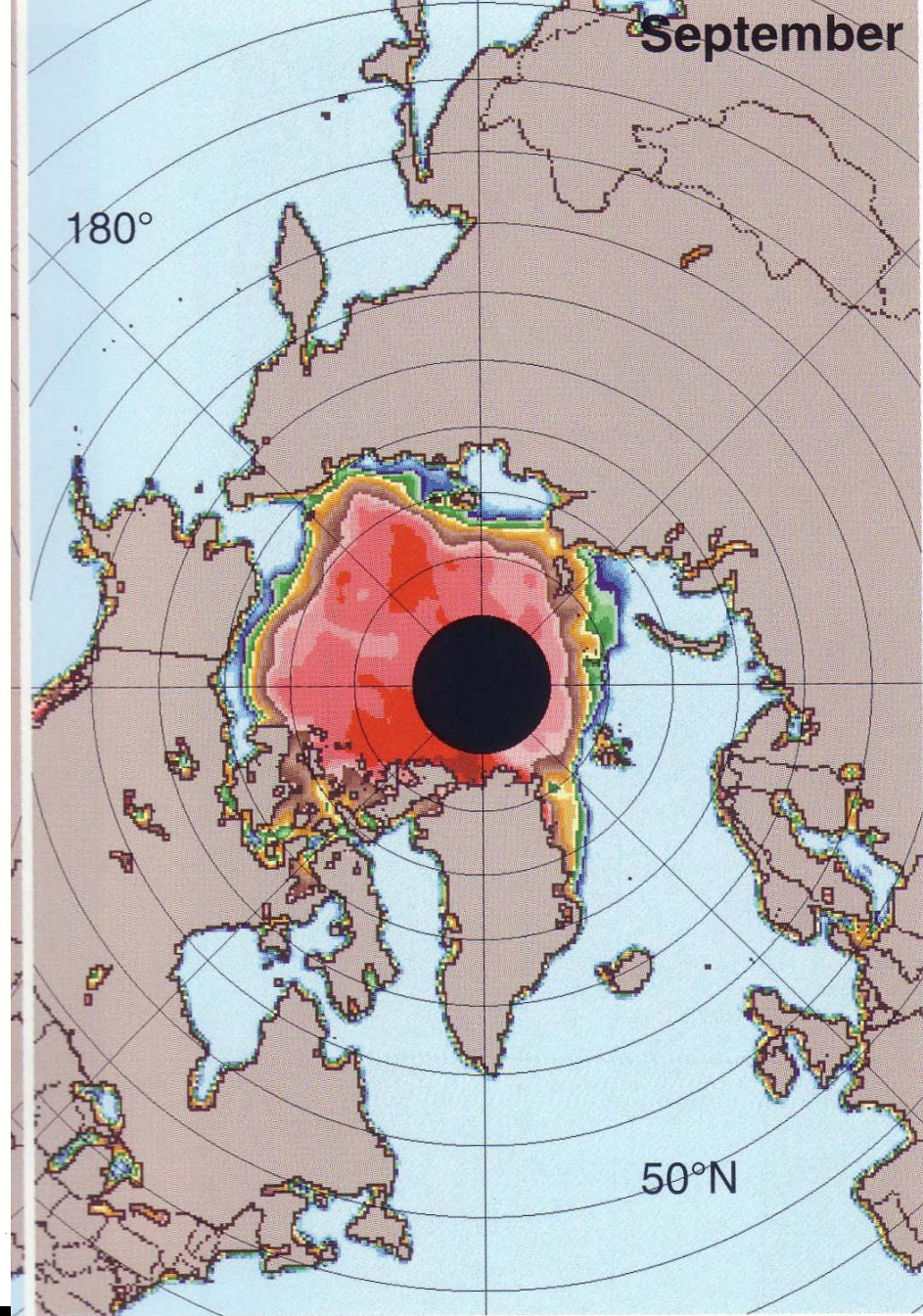
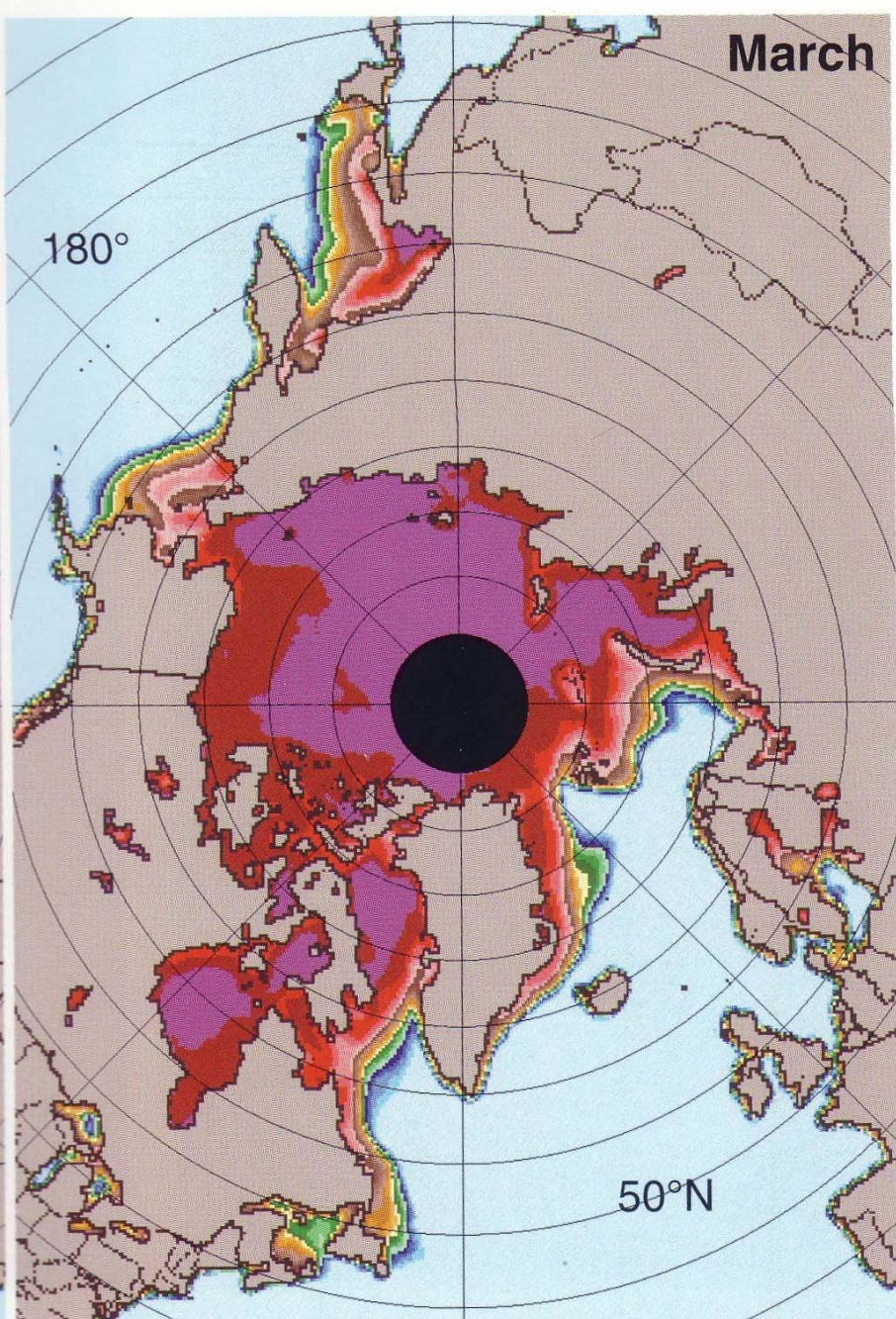


January 2004 snowcover



April 2004 snowcover





Arctic sea ice

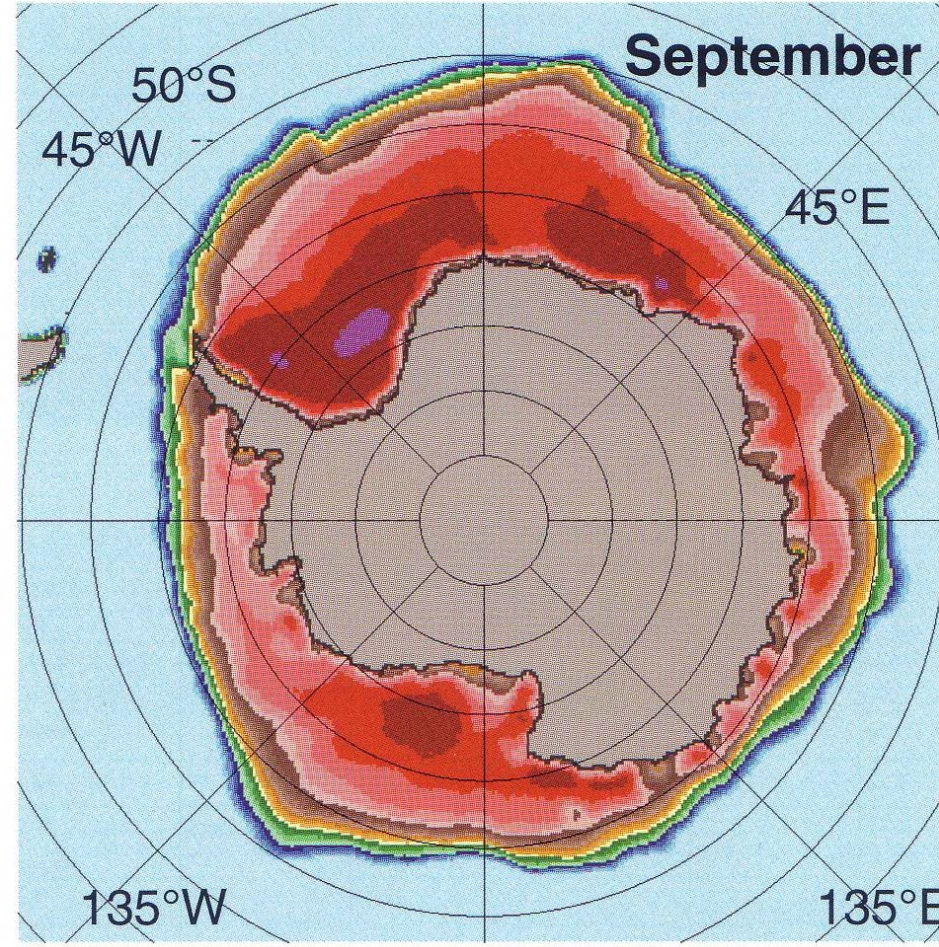
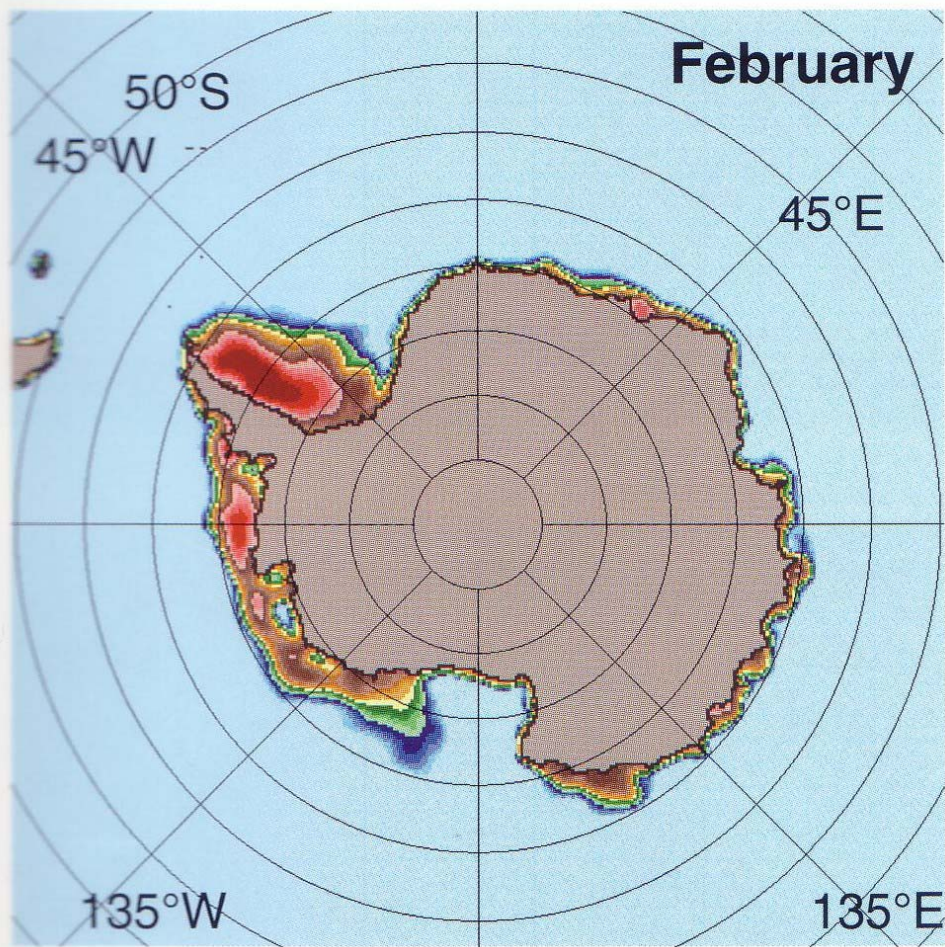


31 March 2007. West coast of Svalbard, 79 degrees N



Puddles on  
snow-free  
Arctic sea ice  
in summer

# Antarctic sea ice







Grease-ice





Pancake-ice



Pancakes



Nilas

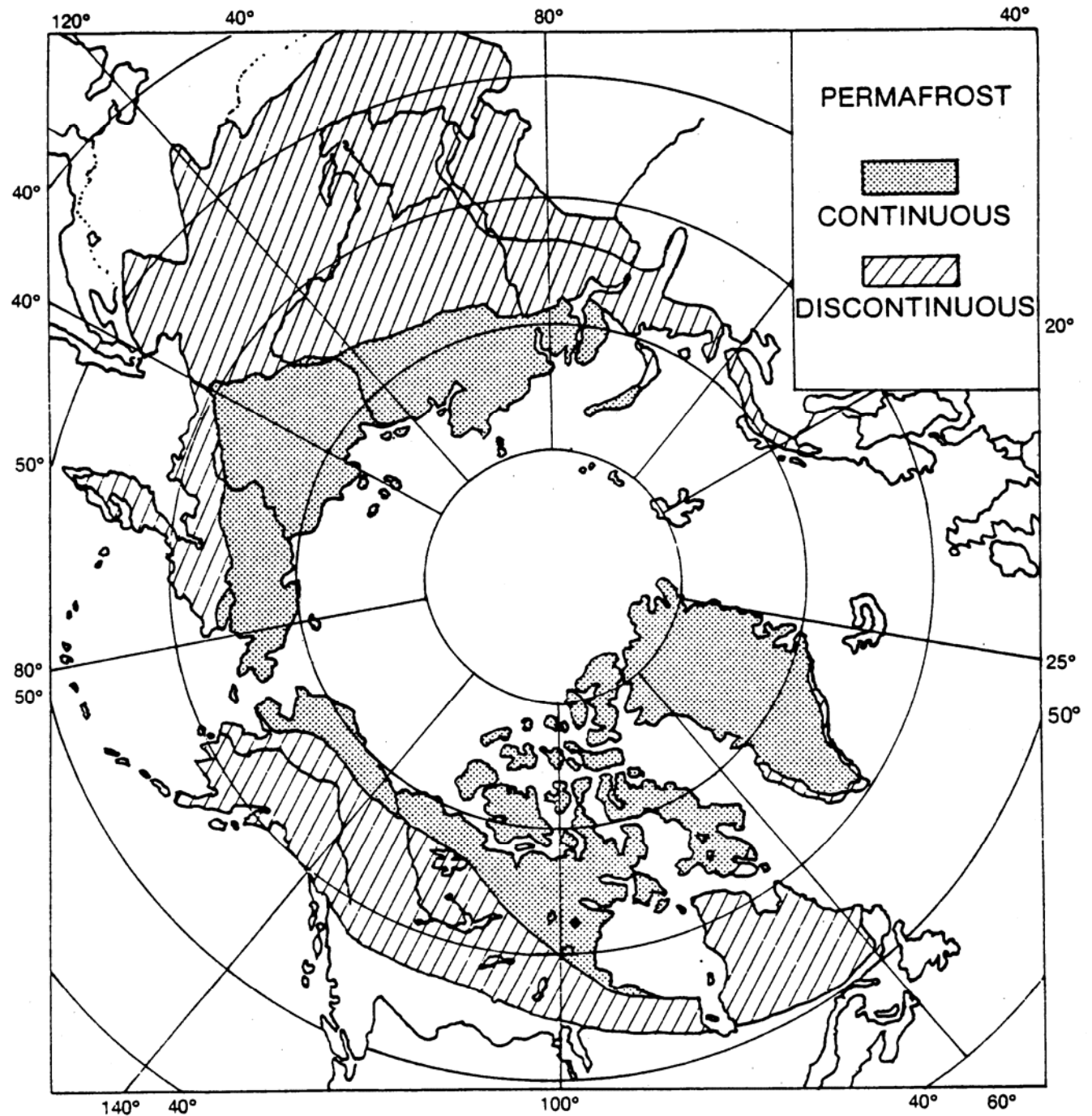
A photograph taken from the deck of a ship, looking out over a vast, flat, snow-covered landscape. The snow is a uniform white, with some darker patches and textures visible. In the distance, a dark, low-lying landmass or island is visible on the horizon. The sky is filled with soft, white clouds. The ship's railing and part of the deck are visible in the foreground on the right side of the frame.

Nilas with  
~2 cm snow



First-year  
ice after a  
full winter  
of growth

# Permafrost



# Cryosphere Components

The components of the cryosphere that interact quickly with climate are the "thin" components: snow and sea-ice. They have small volumes but cover large areas.

***Small volume*** means short residence time, able to melt quickly, respond quickly to climate change.

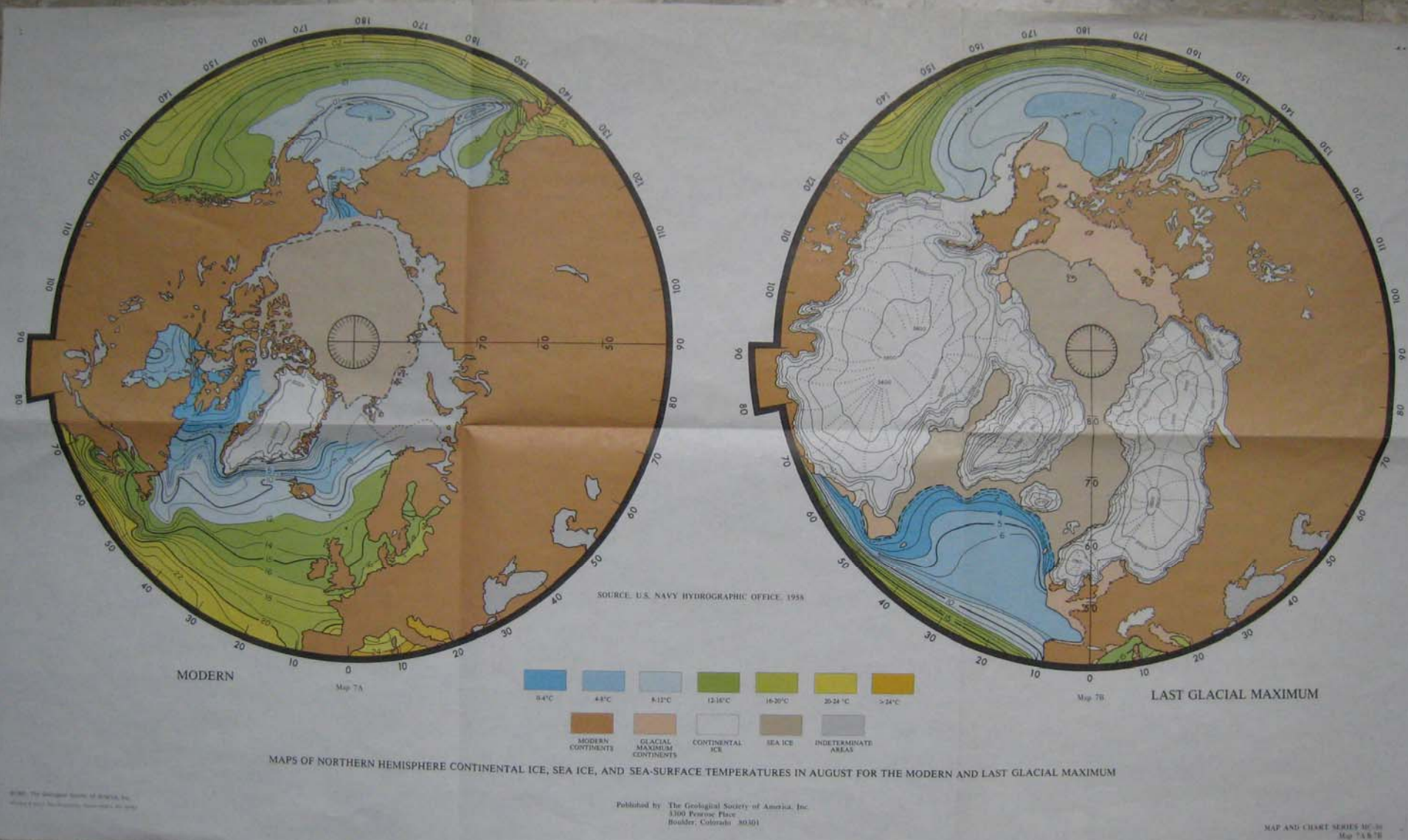
***Large area*** means they can have a big effect on climate.

Snow and sea ice have high *albedo*.

Sea ice insulates the ocean; protects the ocean from rapid loss of heat in the winter.

# Ice Volumes

|                                                                                 | Sea-level equivalent (m) | $10^6 \text{ km}^3$ | percent of total |
|---------------------------------------------------------------------------------|--------------------------|---------------------|------------------|
| <i>Present</i>                                                                  |                          |                     |                  |
| Antarctica                                                                      | ~60                      | 30                  | 88               |
| Greenland                                                                       | 7                        | 2.6                 | 10               |
| Other glaciers                                                                  | 0.3                      | 0.1                 | 1                |
| Permafrost                                                                      | 1                        | 0.4                 |                  |
|                                                                                 |                          |                     |                  |
| <i>Pleistocene 20,000 years ago (in addition to Antarctica &amp; Greenland)</i> |                          |                     |                  |
| North America                                                                   | ~60                      | (total ~120 m)      |                  |
| Scandinavia                                                                     | ~30                      |                     |                  |
| Siberia                                                                         | ~30?                     |                     |                  |



Northern Hemisphere  
of modern Earth

20,000 years ago



# RETREAT OF WISCONSIN AND RECENT ICE IN NORTH AMERICA

Selective ice marginal positions during recession of last ice-sheet complex

## LEGEND

Wisconsin 10000  
Ice margin, retreat of Wisconsin 10000  
Ice margin, retreat of Wisconsin 10000  
Ice margin, retreat of Wisconsin 10000  
Ice margin, retreat of Wisconsin 10000

Scale 1:500,000  
Scale 1:500,000  
Scale 1:500,000  
Scale 1:500,000  
Scale 1:500,000



# Ice Volumes in Distant Past

## *Gondwanan Ice Sheet*

~300 million years ago

~200 m sea-level equivalent

Antarctica, South Africa, India, Australia, South America

## *Snowball Earth*

~700 million years ago

500-1000 m (frozen ocean)

# Ice Through-put for Ice Sheets

|                                                 | <i>Antarctica</i> | <i>Greenland</i> |
|-------------------------------------------------|-------------------|------------------|
| annual snow accumulation<br>(liquid equivalent) | 17 cm             | 40 cm            |
| mass loss                                       |                   |                  |
| by melting                                      | 1%                | 50%              |
| by icebergs                                     | 99%               | 50%              |



Northeast Greenland. View from the helicopter, traveling inland



Northeast Greenland in August. Debris-covered ice, meltwater stream

# **Surface Melt–Induced Acceleration of Greenland Ice-Sheet Flow**

**H. Jay Zwally,<sup>1\*</sup> Waleed Abdalati,<sup>2</sup> Tom Herring,<sup>3</sup>  
Kristine Larson,<sup>4</sup> Jack Saba,<sup>5</sup> Konrad Steffen<sup>6</sup>**

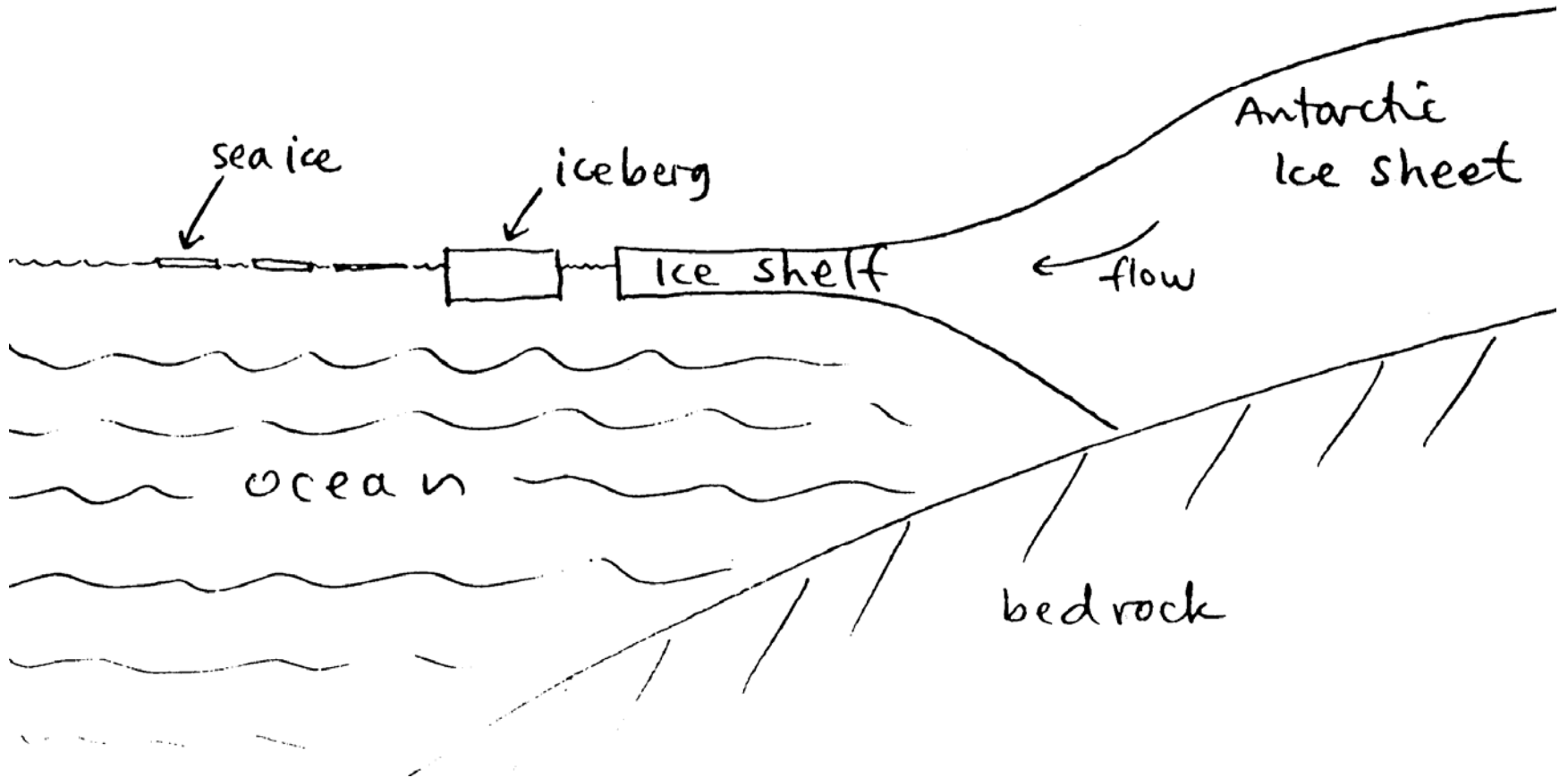
Ice flow at a location in the equilibrium zone of the west-central Greenland Ice Sheet accelerates above the midwinter average rate during periods of summer melting. The near coincidence of the ice acceleration with the duration of surface melting, followed by deceleration after the melting ceases, indicates that glacial sliding is enhanced by rapid migration of surface meltwater to the ice-bedrock interface. Interannual variations in the ice acceleration are correlated with variations in the intensity of the surface melting, with larger increases accompanying higher amounts of summer melting. The indicated coupling between surface melting and ice-sheet flow provides a mechanism for rapid, large-scale, dynamic responses of ice sheets to climate warming.



West Greenland. Ice sheet meets the tundra.



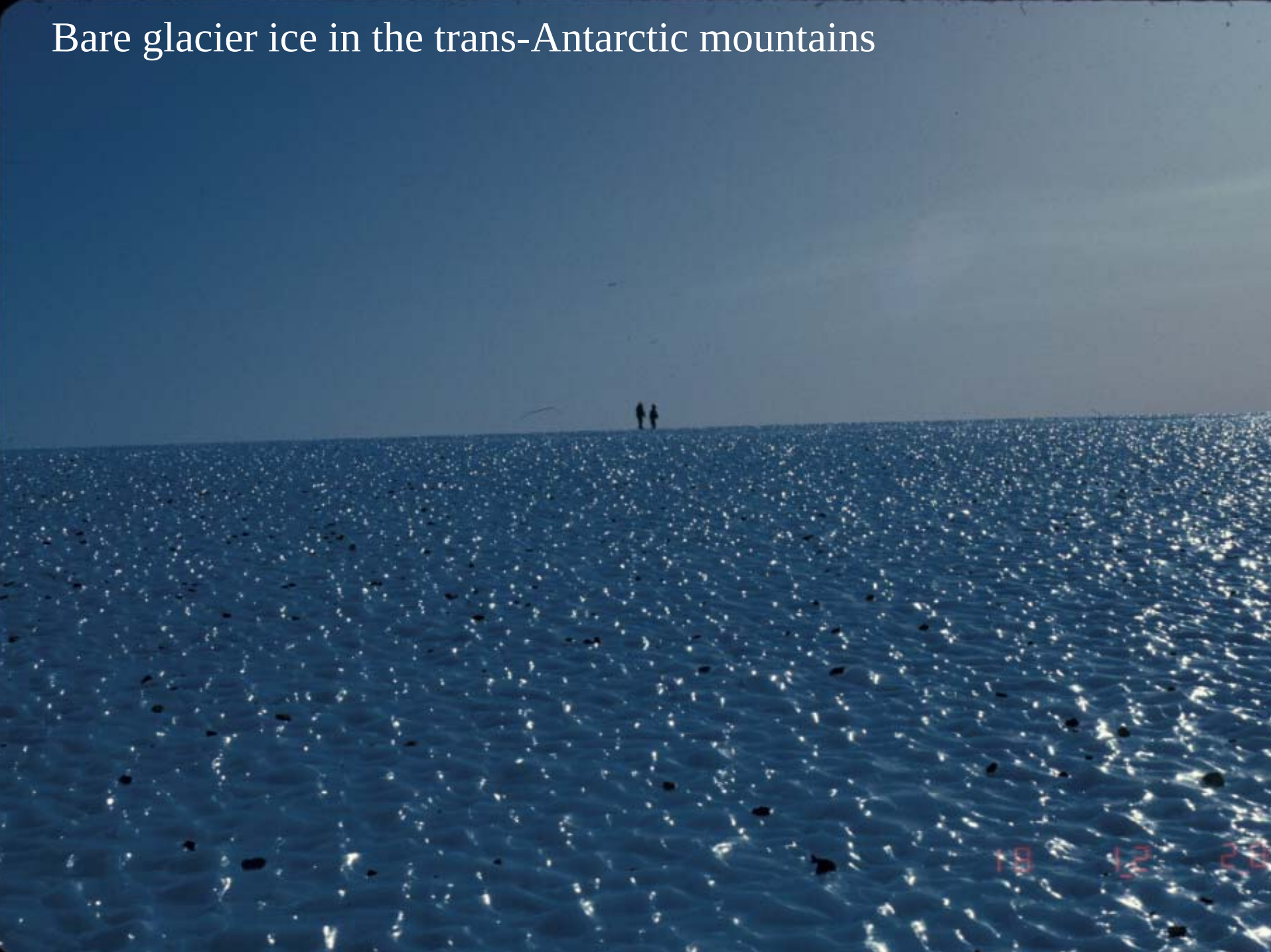
# Terminology





Snow surface of  
East Antarctic Plateau (Dome C)

Bare glacier ice in the trans-Antarctic mountains

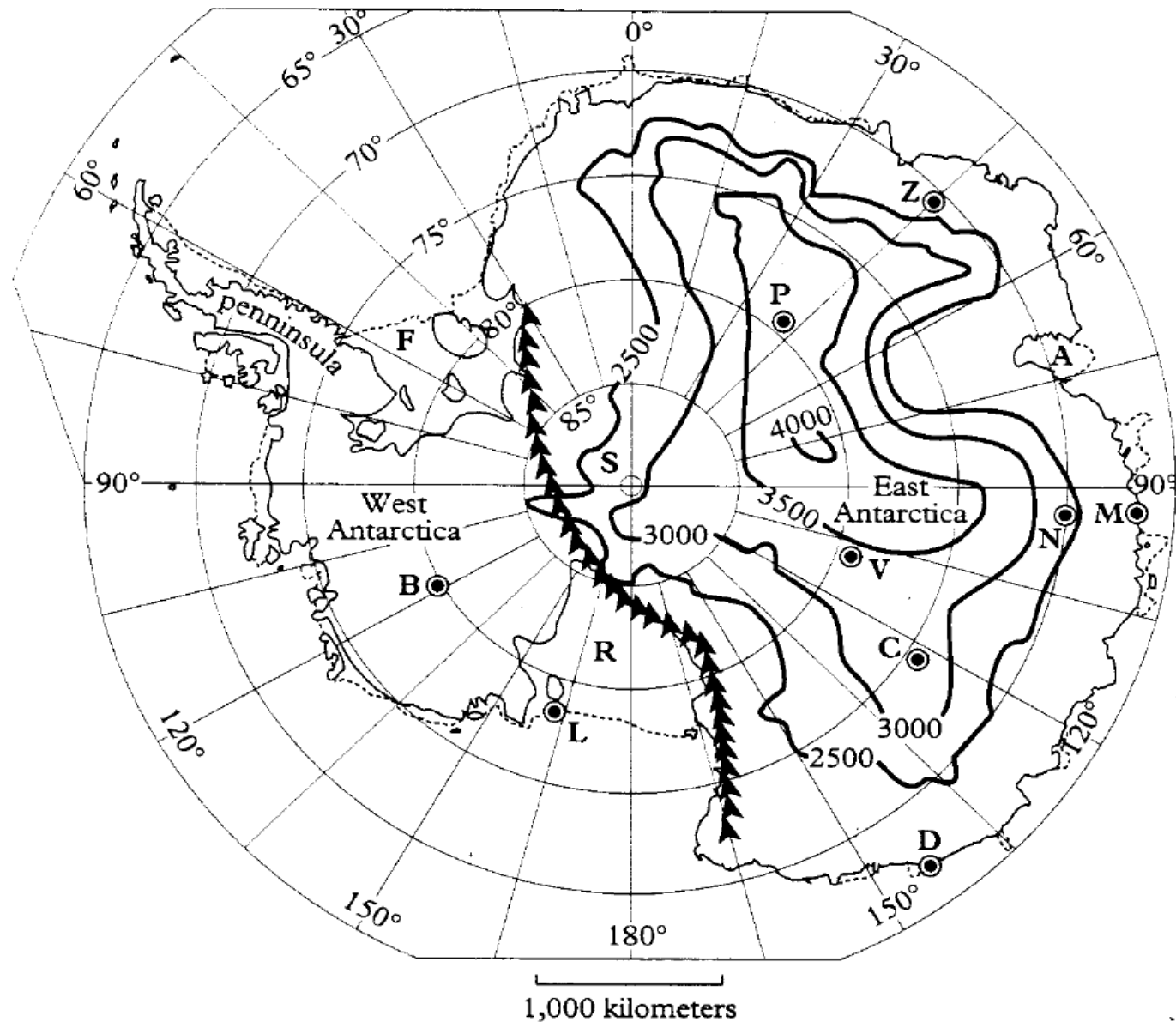




Amery Ice Shelf, East Antarctica







ANTARCTICA. Figure 1. *Map of Antarctica*. Contours of elevation are shown, beginning at 2,500 meters. Locations mentioned in the text are indicated by symbols: Amery Ice Shelf (A), Byrd Station (B), Dome-C (C), Cape Denison (D), Filchner-Ronne Ice Shelf (F), Little America (L), Mirnyy (M), Pionerskaya (N), Plateau Station (P), Ross Ice Shelf (R), South Pole (S), Vostok (V), Mizuho (Z), Trans-Antarctic Mountains (▲).

# Present-Day Antarctica

*Depth of ice:* average 2.2 km, maximum 4.8 km

About 86% of the ice is in East Antarctica

*Mean annual temperature*

from  $-60^{\circ}\text{C}$  on East Antarctic Plateau

(Vostok, Dome C, Plateau Station)

to  $-3^{\circ}\text{C}$  on Antarctic Peninsula

*Snow accumulation*

average  $14\text{-}19\text{ g cm}^{-2}\text{ yr}^{-1}$

on Plateau  $5\text{ g cm}^{-2}\text{ yr}^{-1}$

*Temperature extremes at surface*

World record low temperature:  $-89^{\circ}\text{C}$  (at Vostok)

Record high temperature at South Pole:  $-14^{\circ}\text{C}$

# Snow Accumulation Antarctica

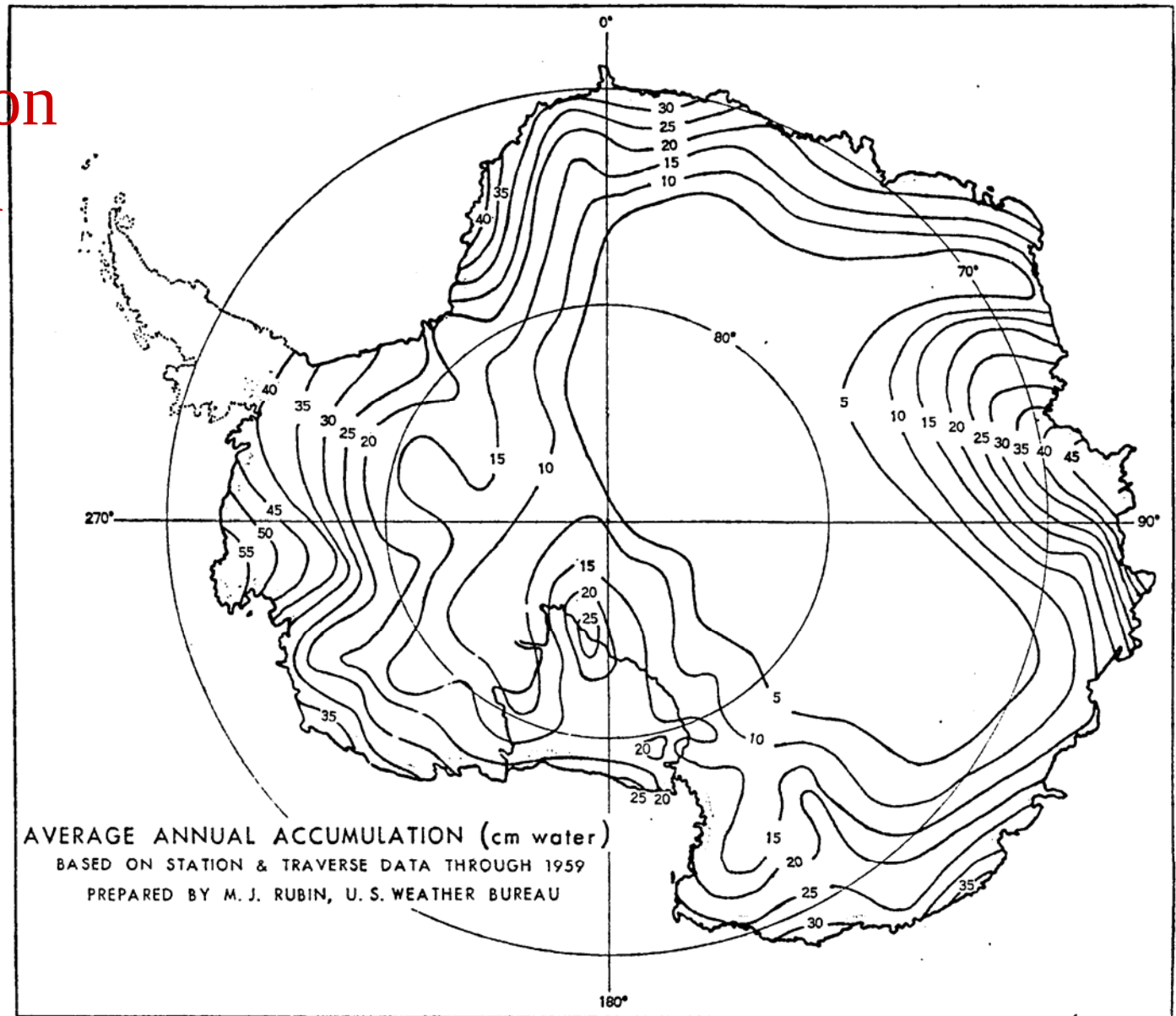


FIG. 2—Annual snow accumulation map of Antarctica

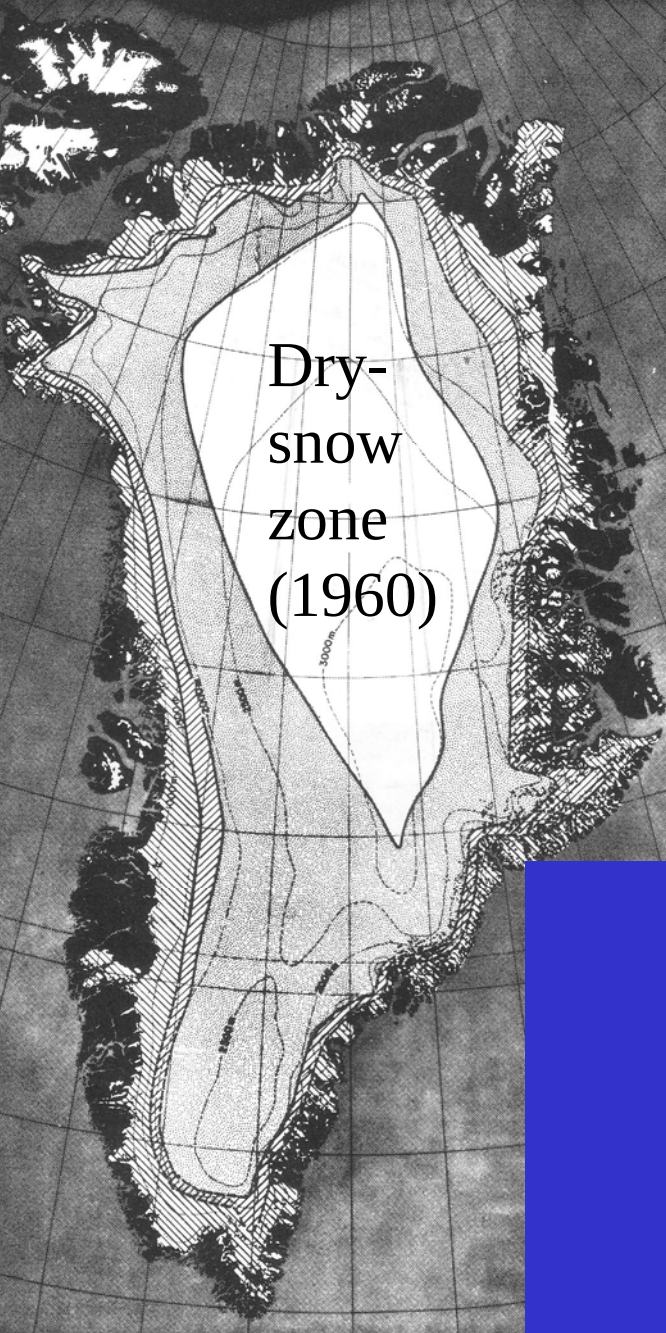
# Present-Day Greenland

*Depth of ice:* average 1.5 km

*Mean annual temperature:*  
from  $-34^{\circ}\text{C}$  (north-central)  
to  $0^{\circ}\text{C}$  (southwest coast)

*Snow accumulation*  
average  $40 \text{ g cm}^{-2}\text{yr}^{-1}$   
North-central  $10 \text{ g cm}^{-2}\text{yr}^{-1}$

*Melting* occurs on  $\sim 70\%$  of the ice-sheet surface area  
Net ablation on  $\sim 15\%$  of ice-sheet surface area



Greenland is 18% dry land, 82% ice-covered.

**Of the ice sheet area (in 1960):**

30% is *dry snow* (no melting)

55% is *wet snow* (some of the winter snow melts in summer, but not all)

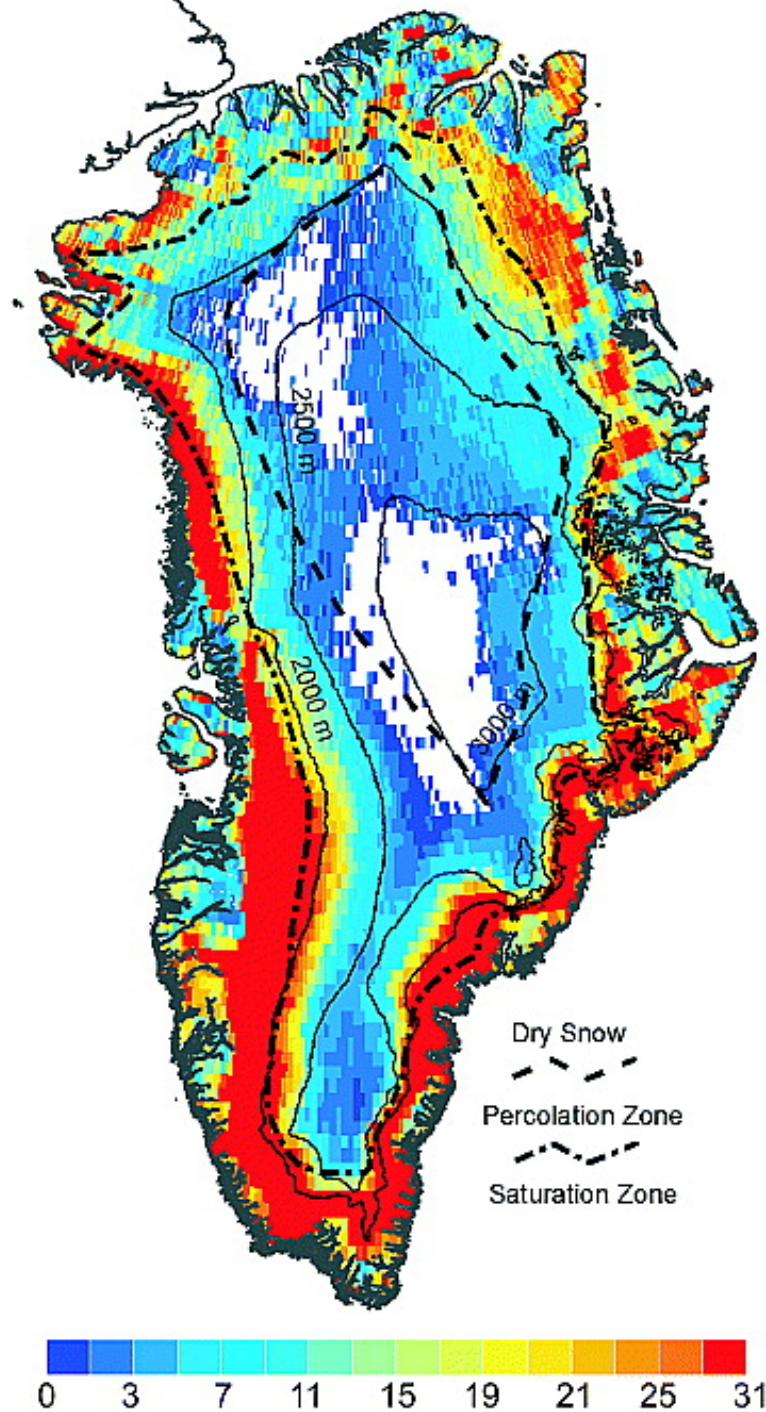
- Percolation zone
- Wet-snow zone
- Slush zone

15% is the Ablation zone (“ablation” meaning “net loss”: all the winter snow melts in summer, and some ice as well).

So some melting occurs on 70% of the ice sheet.

But now the melt area exceeds 70%.

(Carl Benson, 1960).

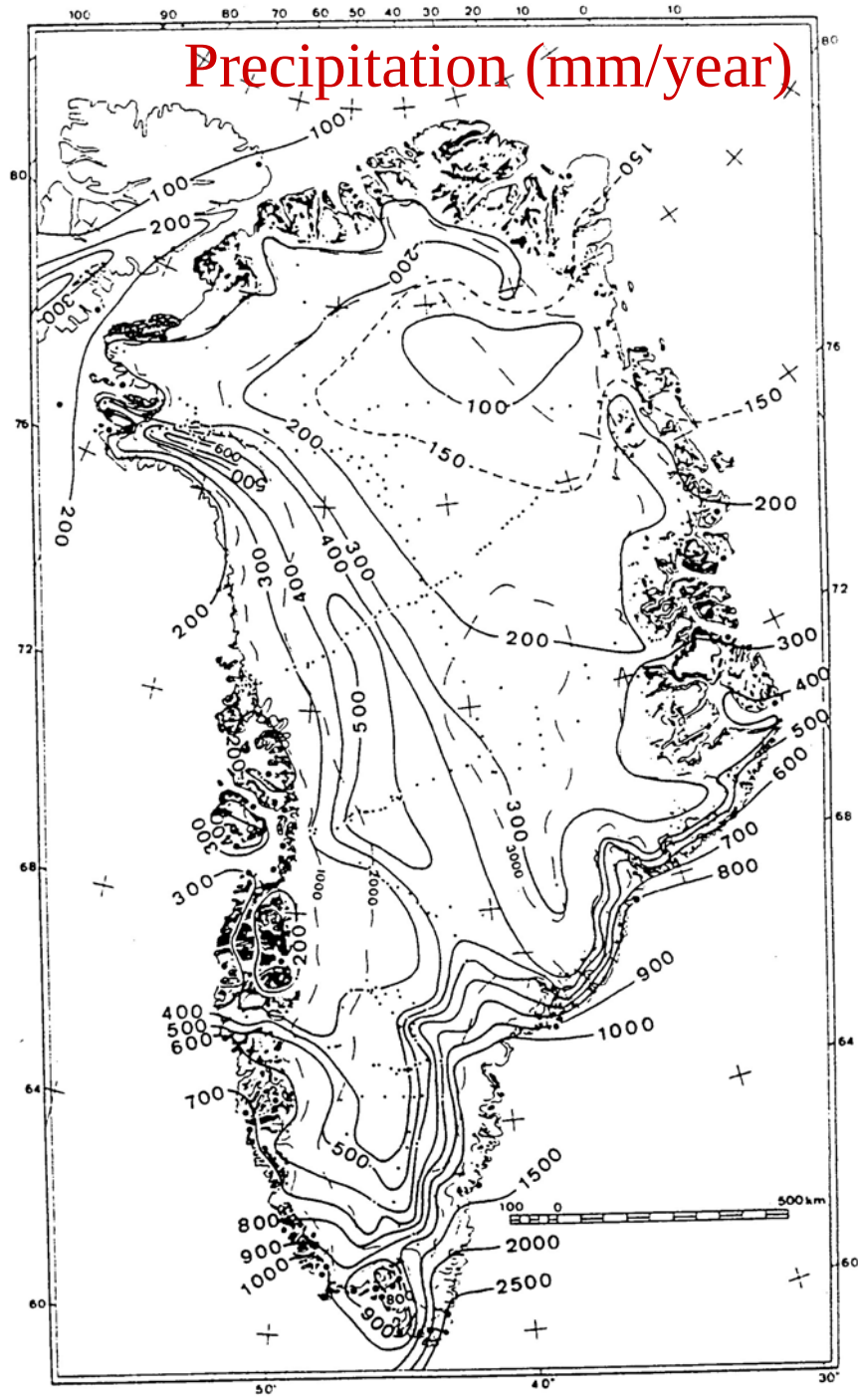


In 2002, only the white area experienced no melting.

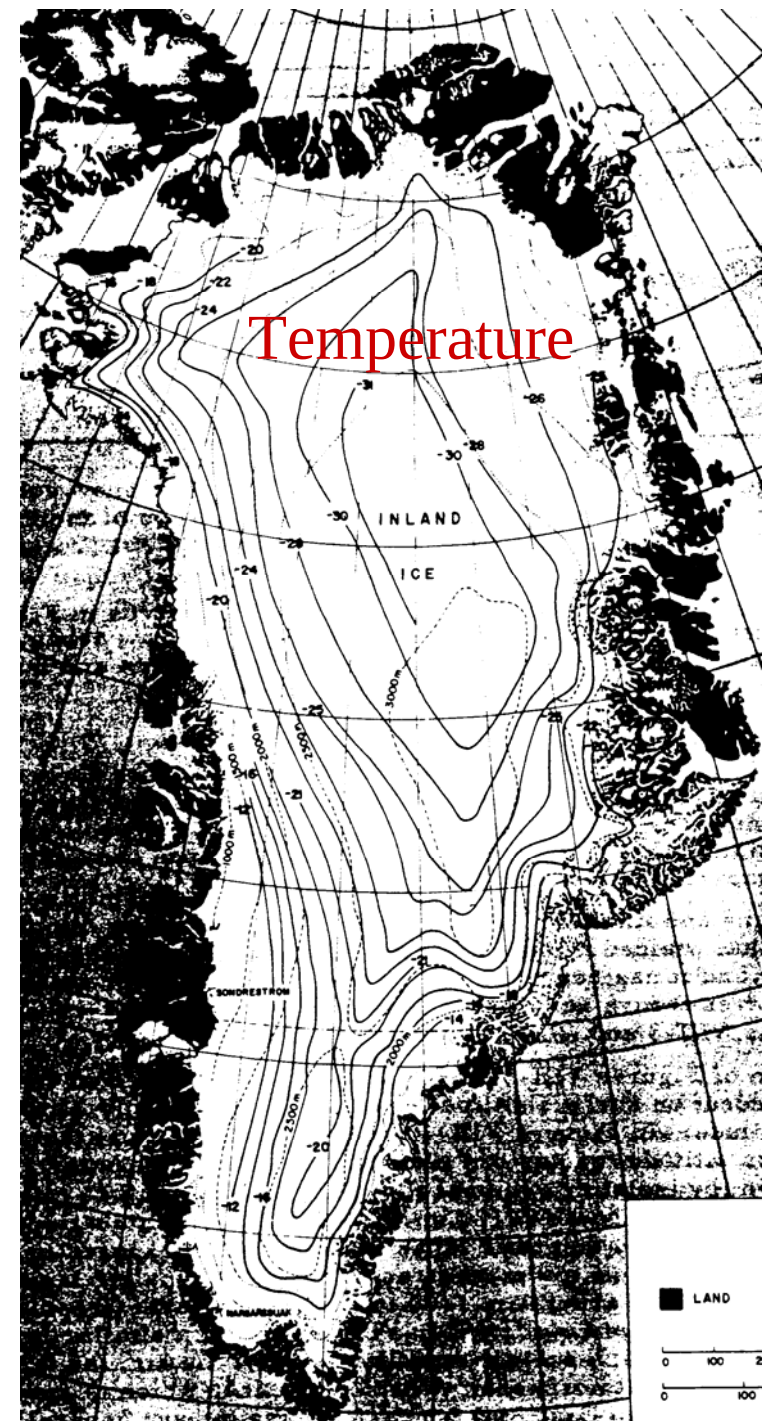
(from Prof. Koni Steffen, Univ. Colorado)

Number of melt days in 2002 (from satellite radar).

# Precipitation (mm/year)



# Temperature



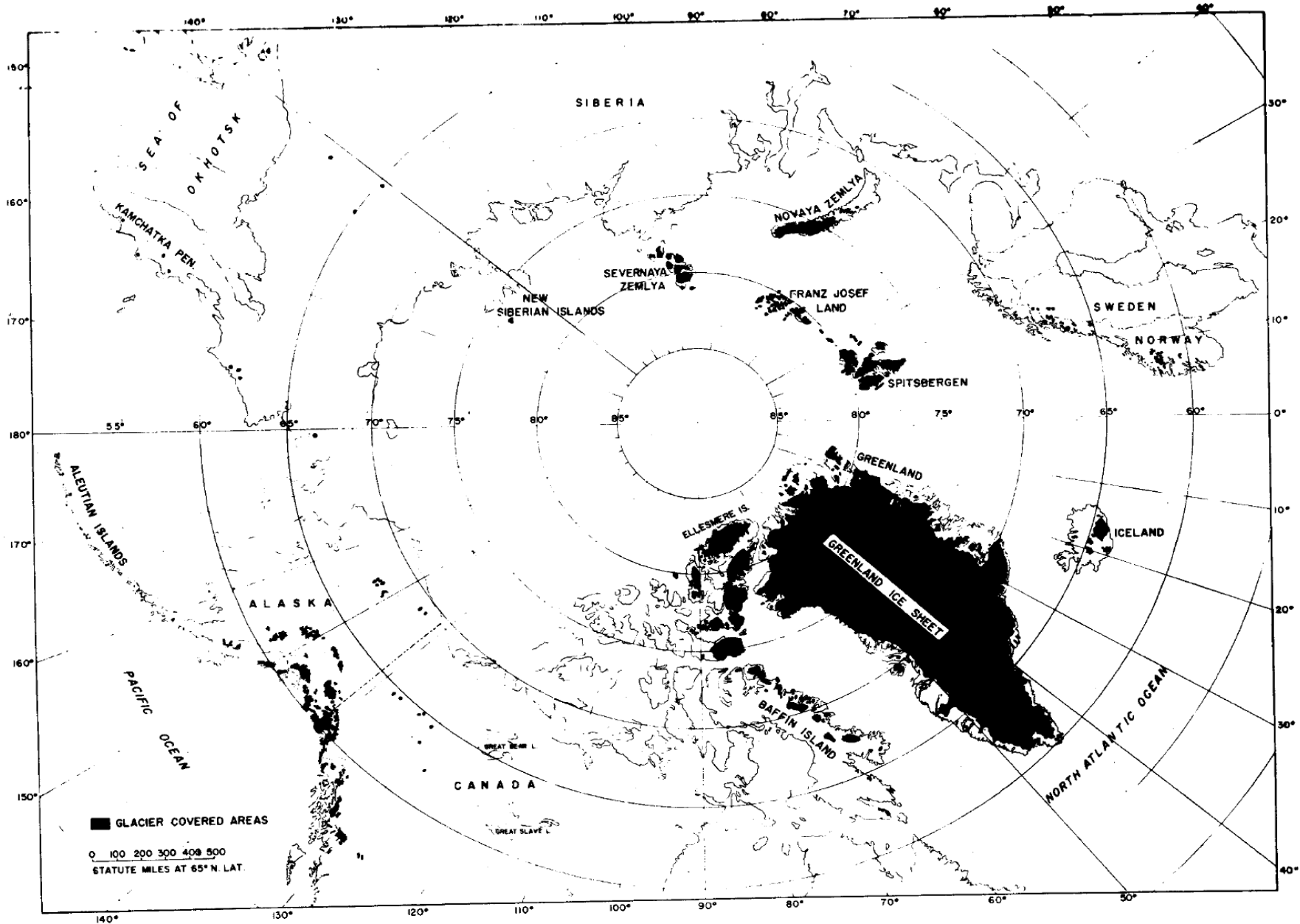


Figure II-14. Distribution of glaciers in the Arctic regions.

# Alaskan Ice

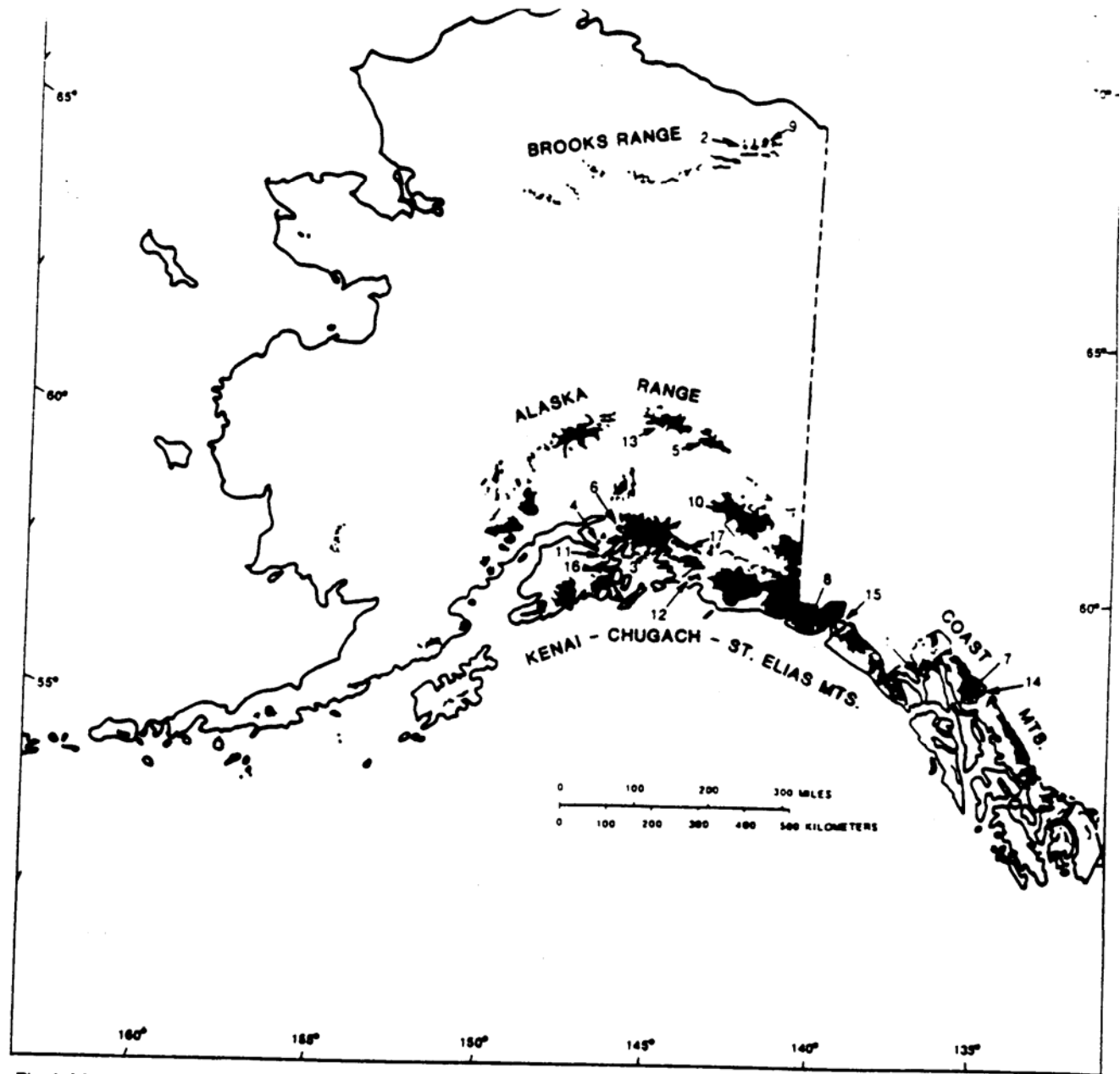
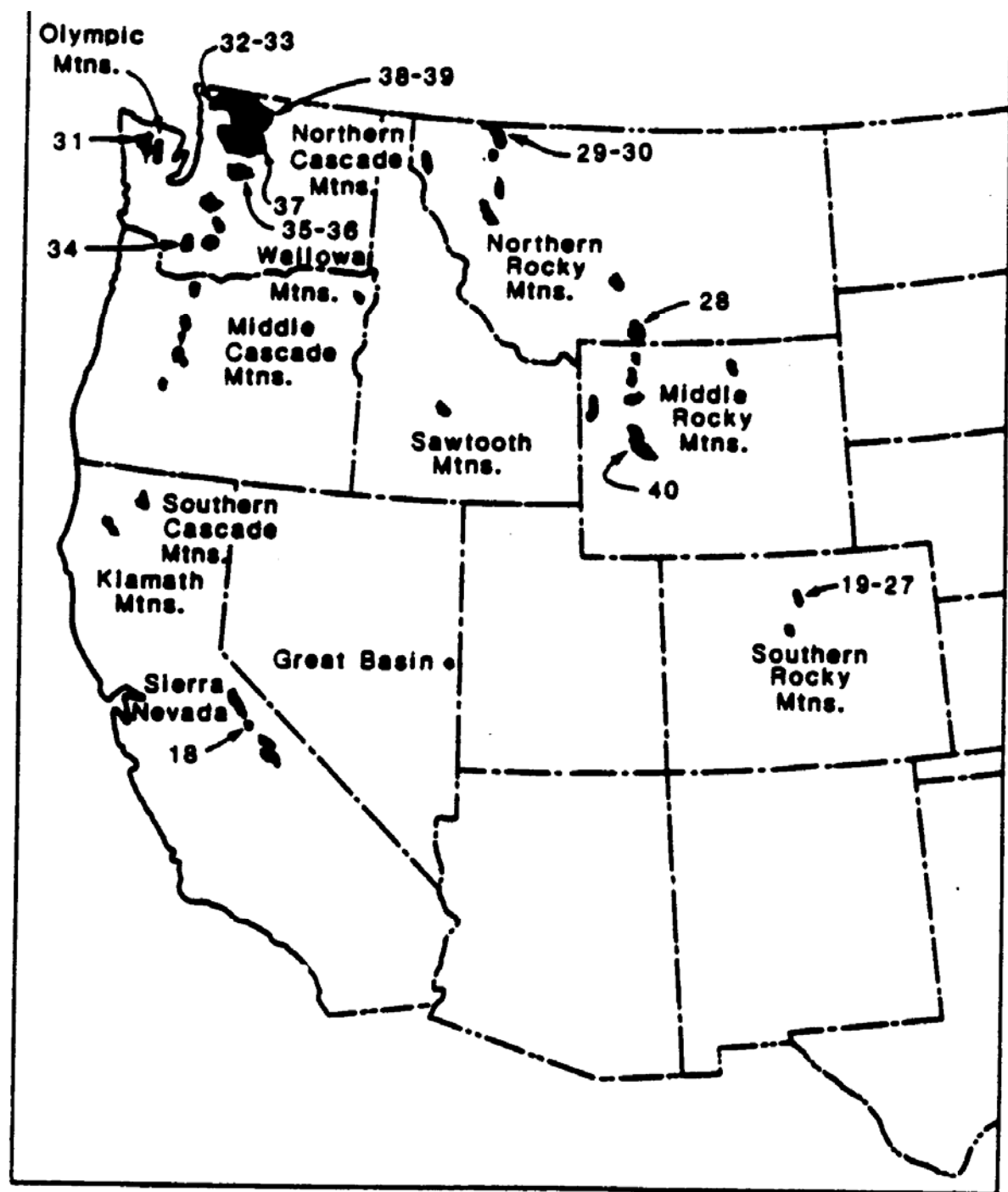


Fig. 1. Map showing locations of research glaciers in Alaska. Shaded areas are glaciers. Numbers refer to glaciers listed in Table 1.

# Ice in Western USA



Wheeler Peak, Nevada. September 2007





Cotopaxi volcano, 1 deg. South, Ecuador



Elevation 4800 m  
on Cotopaxi volcano



At 2000 m on Blue Glacier, 48 N

## ***Glacier contrasts:***

### **1. Latitude versus altitude**

|                     | latitude of terminus | altitude of terminus | annual precipitation |
|---------------------|----------------------|----------------------|----------------------|
| Antarctic ice sheet | 66 S                 | 0 m                  | 17 cm                |
| Blue Glacier        | 48 N                 | 1300 m               | 500 cm               |
| Cotopaxi            | 1 S                  | 4800 m               | 500 cm               |

### **2. Residence times of water in glaciers**

|                  | thickness $H$ | accumulation rate $b$ | residence time $\tau = H/b$ |
|------------------|---------------|-----------------------|-----------------------------|
| Blue Glacier     | 100 m         | 5 m/yr                | 20 yr                       |
| Greenland Summit | 3000 m        | 0.3 m/yr              | 10,000 yr                   |

### **3. Contributions to sea-level rise:**

Glaciers and small ice caps are only 0.5% of the ice, but they are responsible for 70% of the current sea-level rise attributable to ice-loss. [from K. Steffen, Univ. Colorado]

|              | volume                     | snow accumulation | current sea-level rise |
|--------------|----------------------------|-------------------|------------------------|
| Antarctica   | 89%                        | 61%               | 10%                    |
| Greenland    | 10.5%                      | 17%               | 20%                    |
| Glaciers     | 0.5%                       | 22%               | 70%                    |
| Total (100%) | 30 million km <sup>3</sup> | 3100 GT/yr        | 0.8 mm/yr              |

# Arctic-Antarctic differences

## *Ice sheets*

How the ice sheets lose their mass:

Antarctic: 99% icebergs, 1% melting

Greenland: 50% icebergs, 50% melting

So most of Greenland is covered with melting snow in summer.

## *Sea ice*

Arctic Ocean has thicker ice, thinner snow than the Antarctic Ocean

Arctic sea ice melts from the top down, forming puddles

Antarctic sea ice melts from the bottom up, remaining snow-covered

## *Snow*

Antarctic snow is clean; Arctic snow is contaminated.