Radiative Properties of Snow, Clouds, and Sea Ice from Surface Measurements in the Arctic and Antarctic

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University of Washington, Seattle

Outline

Antarctic Ice Sheet

- snow
- clouds over snow
- temperatures

Antarctic sea ice

- snow on sea ice
- clouds over sea ice

Arctic

- Greenland Ice Sheet
- Sea ice
- dirty snow

Announcements

- Cloud climatology from surface observations
- Optical constants of ice

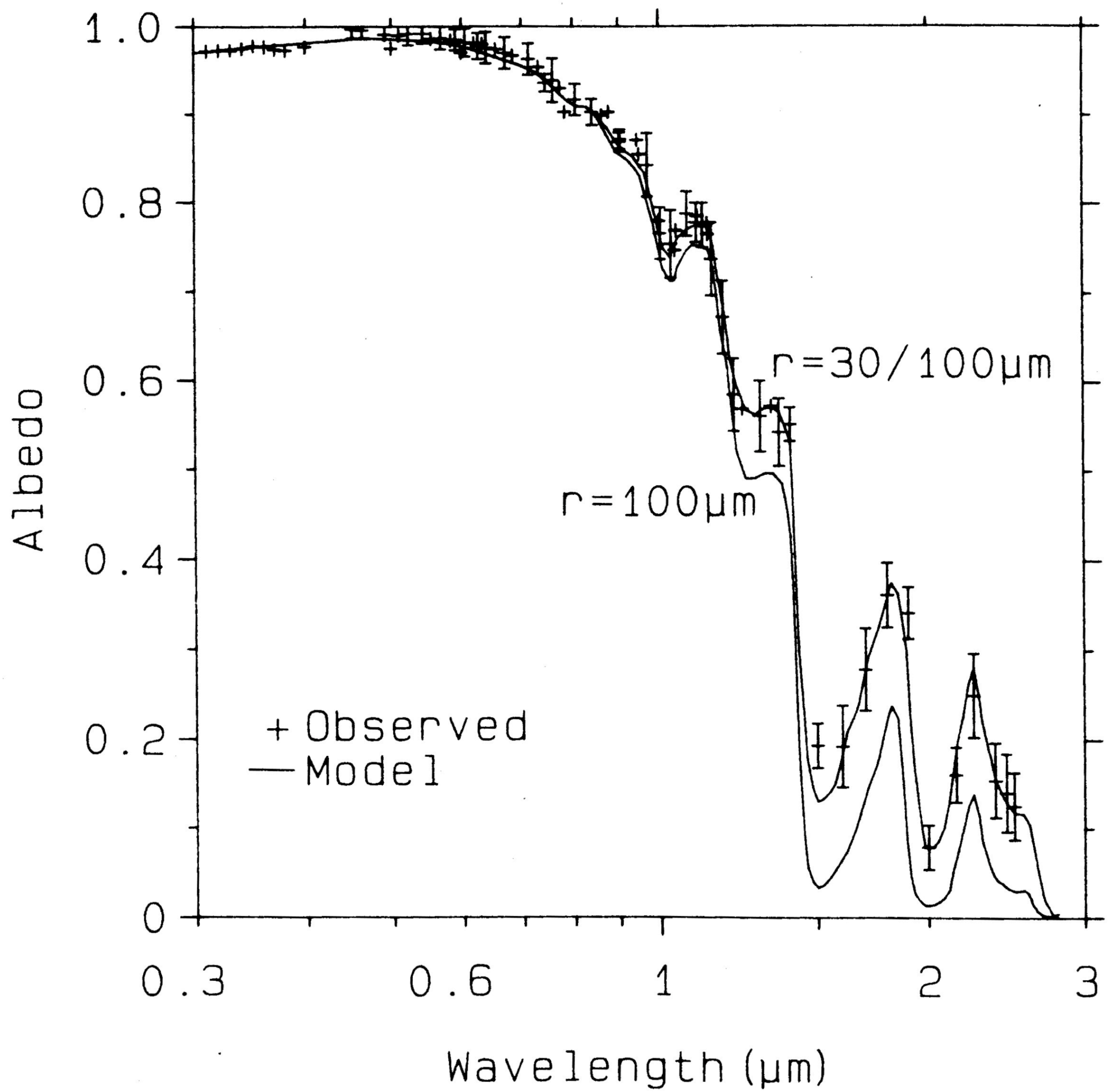
ANTARCTICA. Table 2. *Surface energy budget at Pionerskaya (70° south latitude, 95° east longitude, 2,700 meters)**

	June	December
Downward shortwave (solar) radiation	0	372
Upward shortwave radiation	0	−312
Downward longwave (infrared) radiation	106	173
Upward longwave radiation	−134	−209
Net radiation	−28	+24
Sensible heat	23	−16
Latent heat	1	−2
Sum	−4	+6

*Energy fluxes are in watts per square meter; a positive number means that the flux is in the downward direction (from the atmosphere to the surface).

Data from Rusin, 1961.

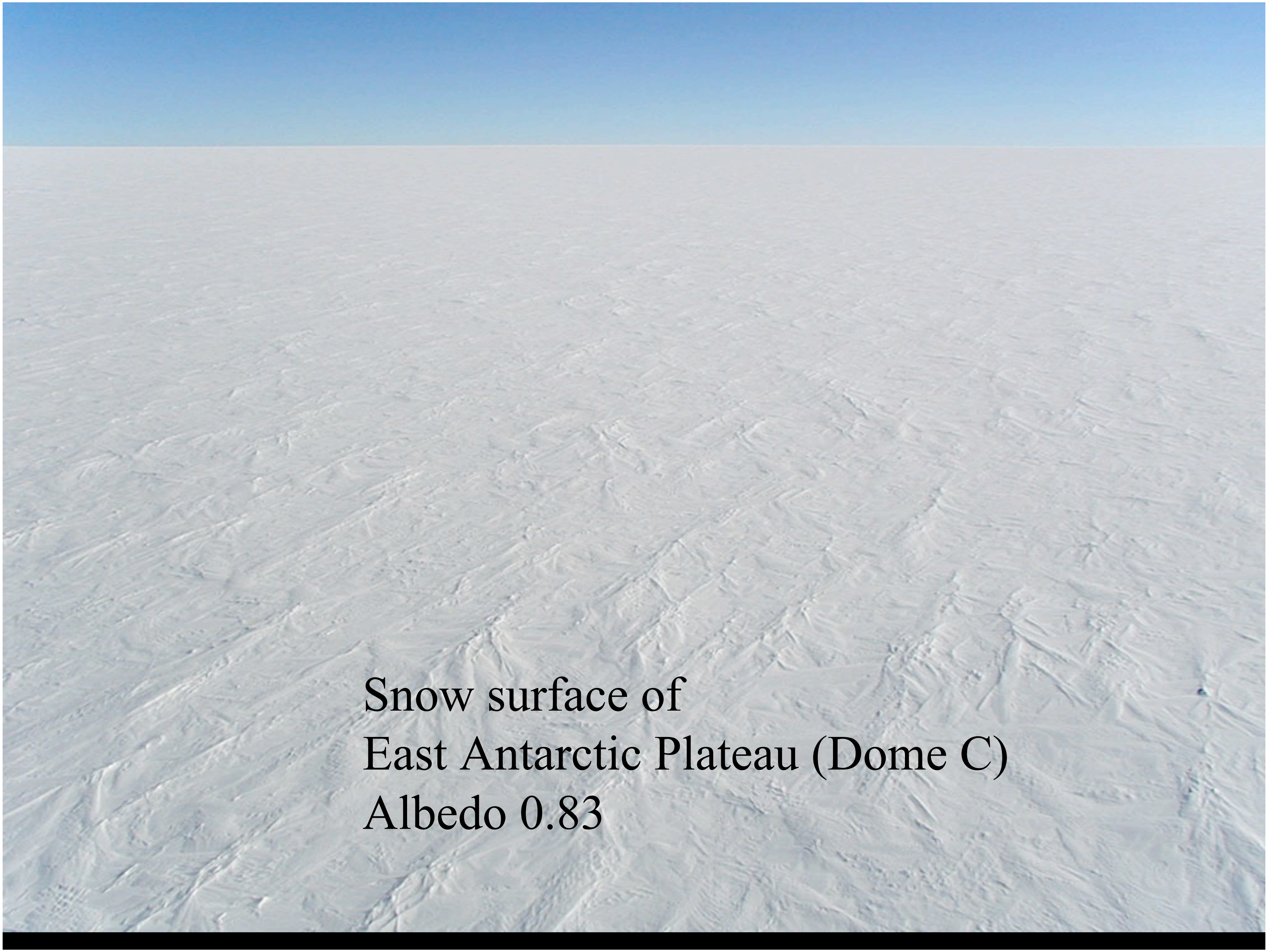
(Sensible heat flux can be much larger in the sea-ice zone.)

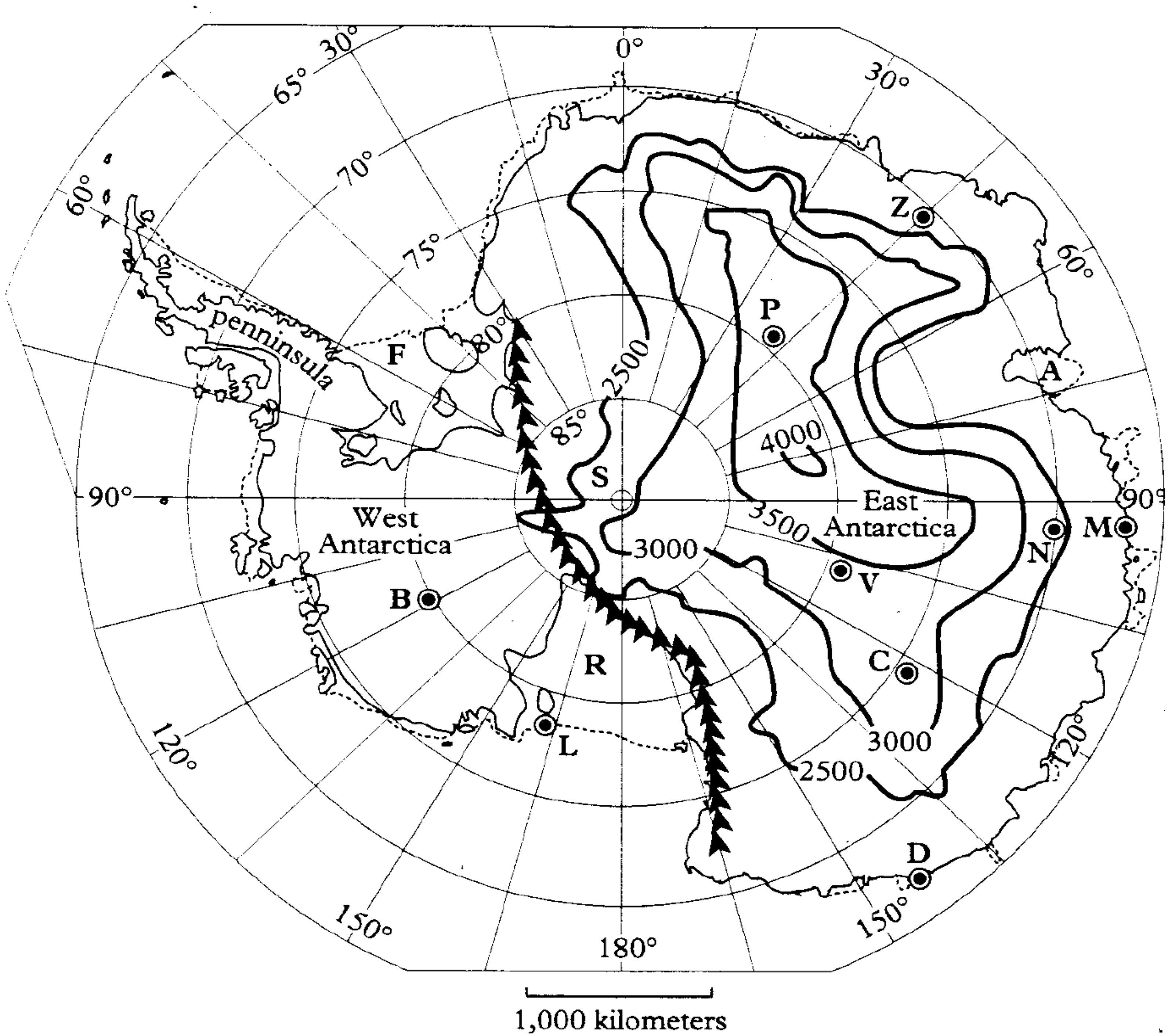


Spectral albedo of Antarctic snow (South Pole)

Grenfell, Warren, Mullen

JGR 1994


Snow surface of
East Antarctic Plateau (Dome C)
Albedo 0.83



0°
30°
30°
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60°
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70°
75°
80°
85°
90°
90°
120°
120°
150°
150°
180°
penninsula
F
S
P
Z
A
M
N
V
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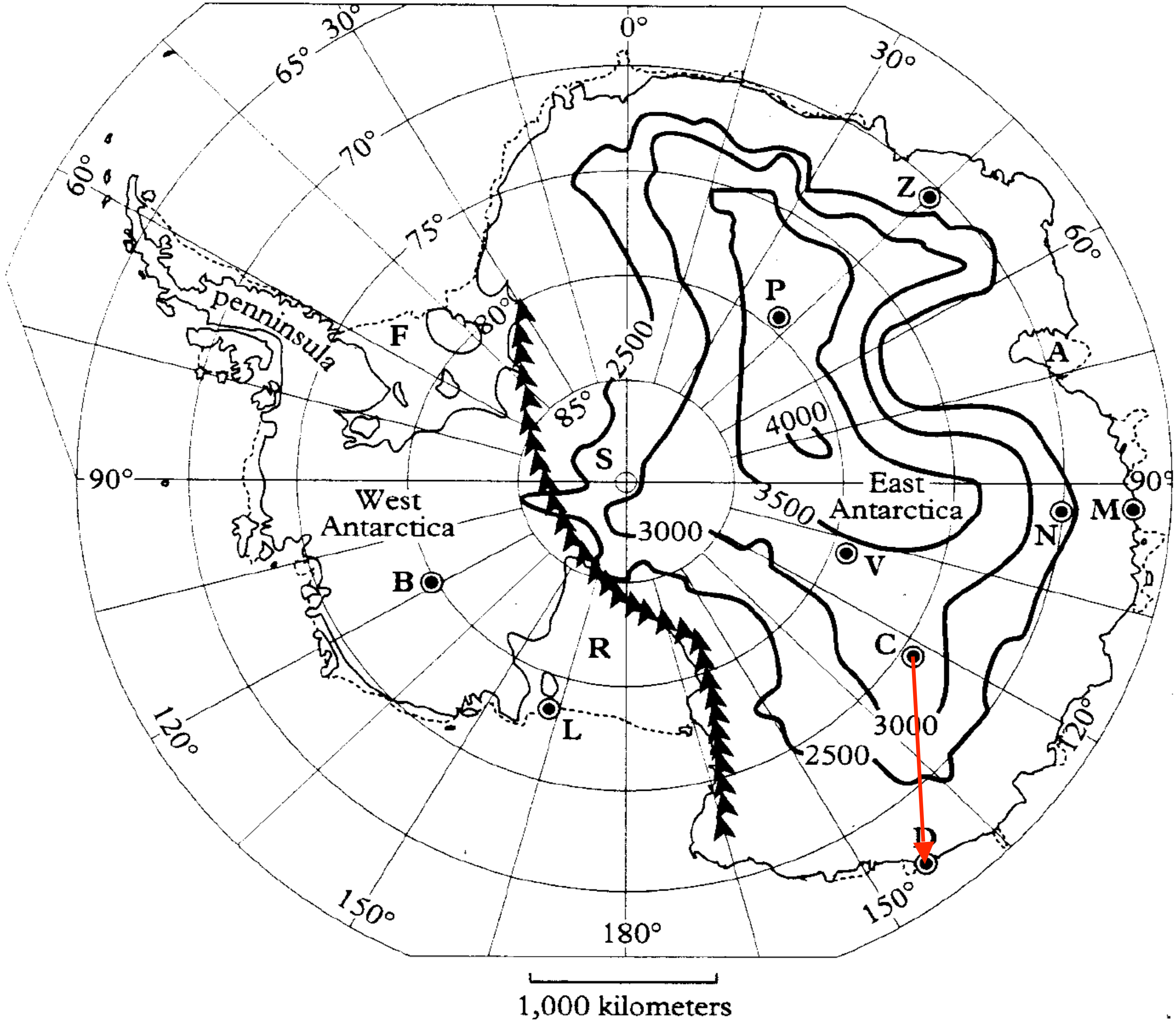
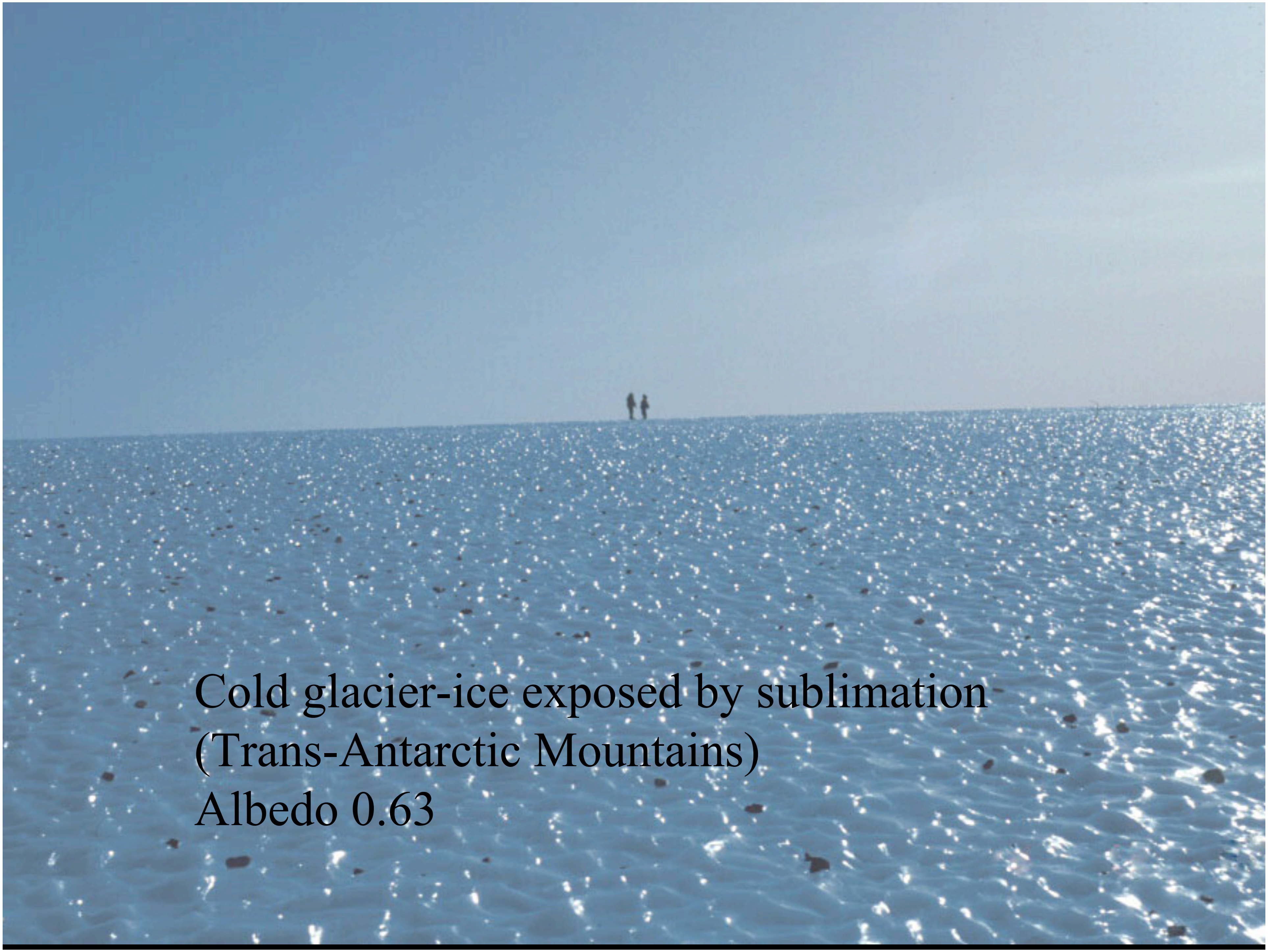
D
B
R
L
West Antarctica
East Antarctica
2500
2500
3000
3000
3000
3500
4000
1,000 kilometers


0°
30°
30°
65°
70°
75°
80°
85°
60°
60°
90°
90°
120°
120°
150°
150°
180°
penninsula
F
S
P
Z
A
M
N
V
C
D
B
L
R
2500
3000
3500
4000
3000
2500
West Antarctica
East Antarctica
1,000 kilometers

Tractor train from Dome C to Dumont d’Urville (photo by Yann Arthus-Bertrand


Cold glacier-ice exposed by sublimation
(Trans-Antarctic Mountains)
Albedo 0.63

Snow albedo depends on (in the Antarctic):

- Grain size (age)
- Variation of grain size with depth
- Solar zenith angle

In addition, ***non-Antarctic snow albedo*** depends on

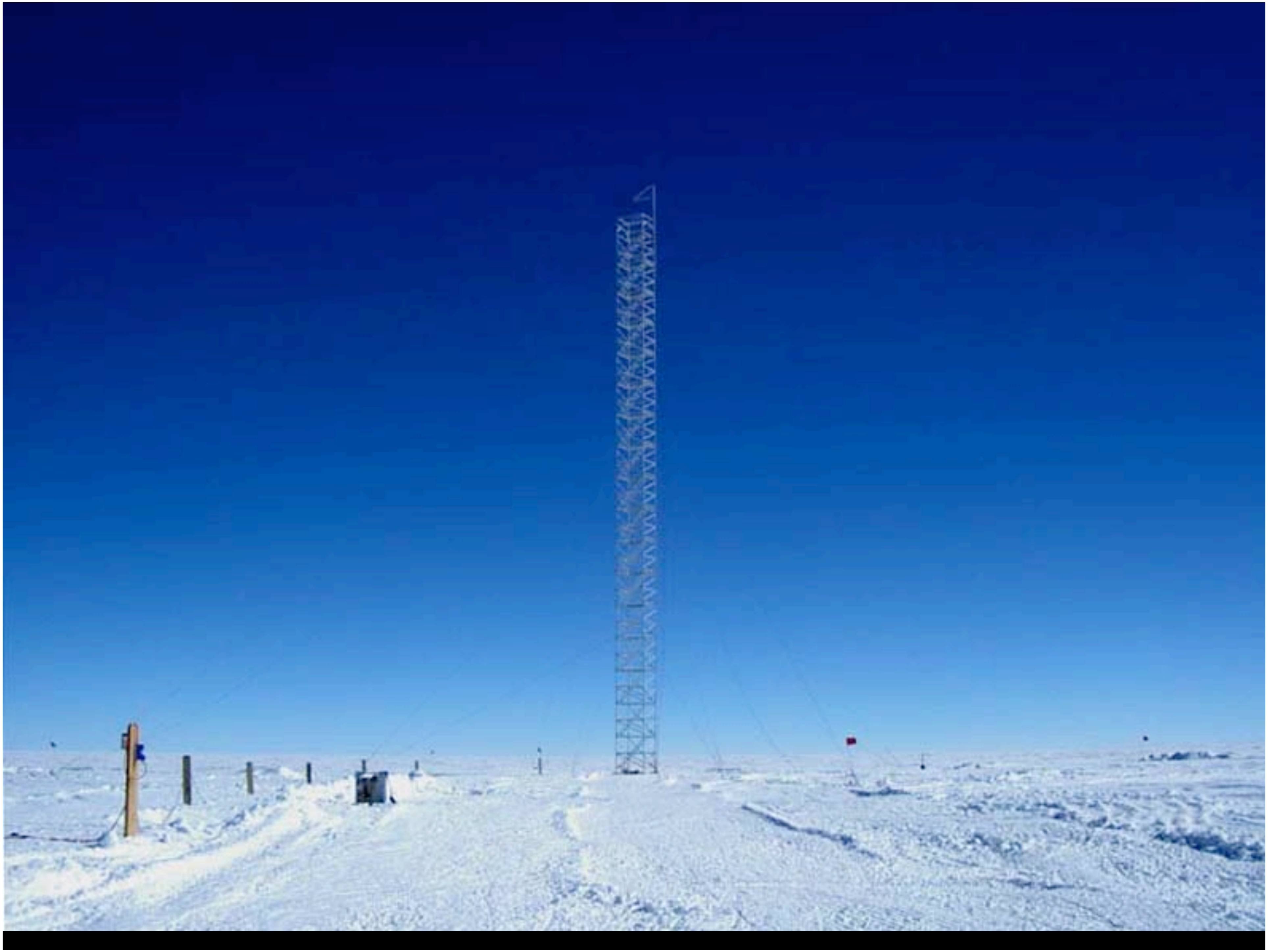
- Snow depth (& vegetation)
- Impurities: dust, black carbon (soot)

In addition, ***Bidirectional reflectance*** depends on:

Grain shape (frost)

Surface roughness

Fig. 73. SASTRUGI.

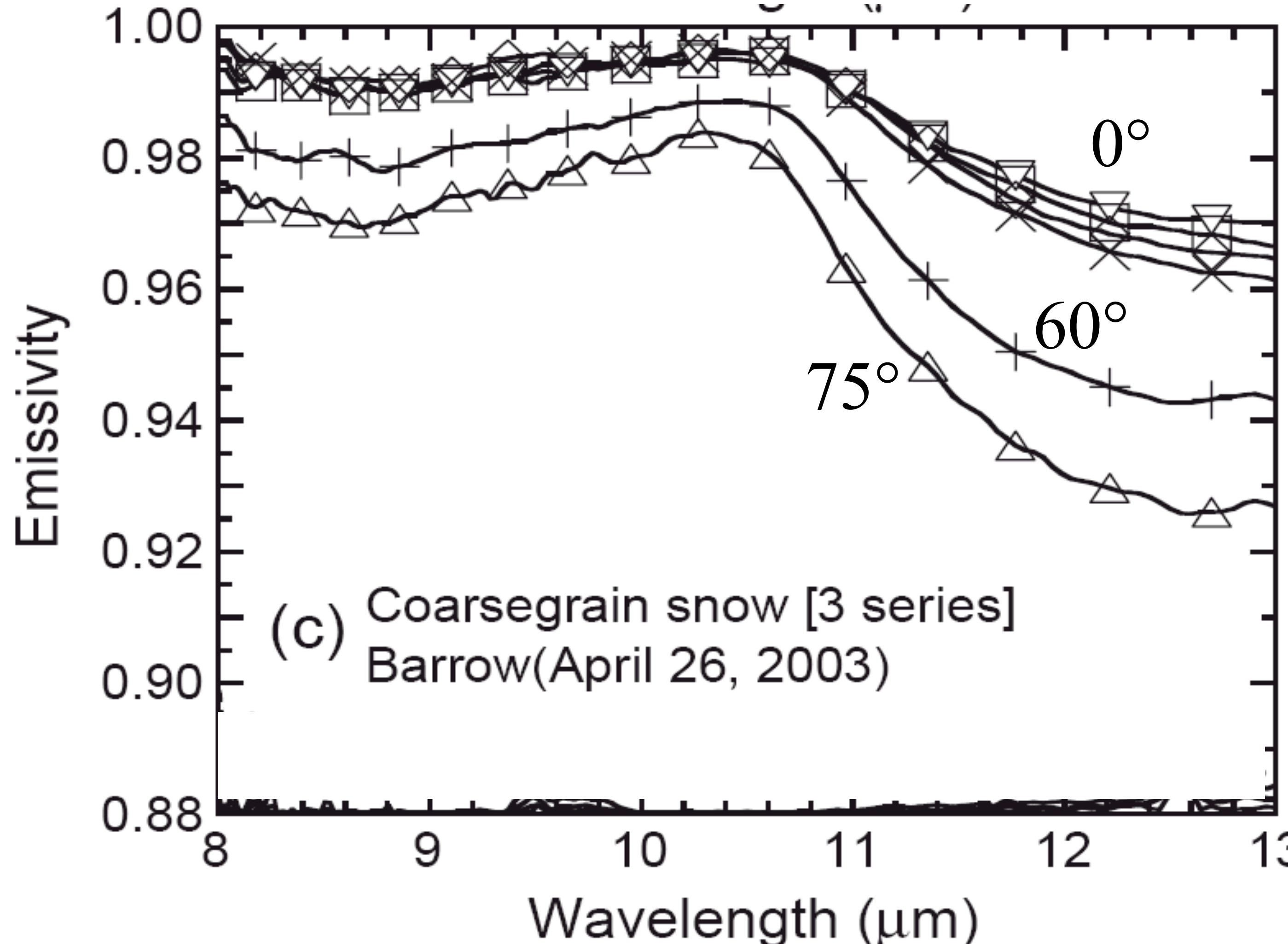


Spectral bidirectional reflectance of Antarctic snow: Measurements and parameterization JGR 2006

Stephen R. Hudson,[1] Stephen G. Warren,[1] Richard E. Brandt,[1] Thomas C. Grenfell, and Delphine Six[2]

Spectral emissivity of snow in thermal infrared

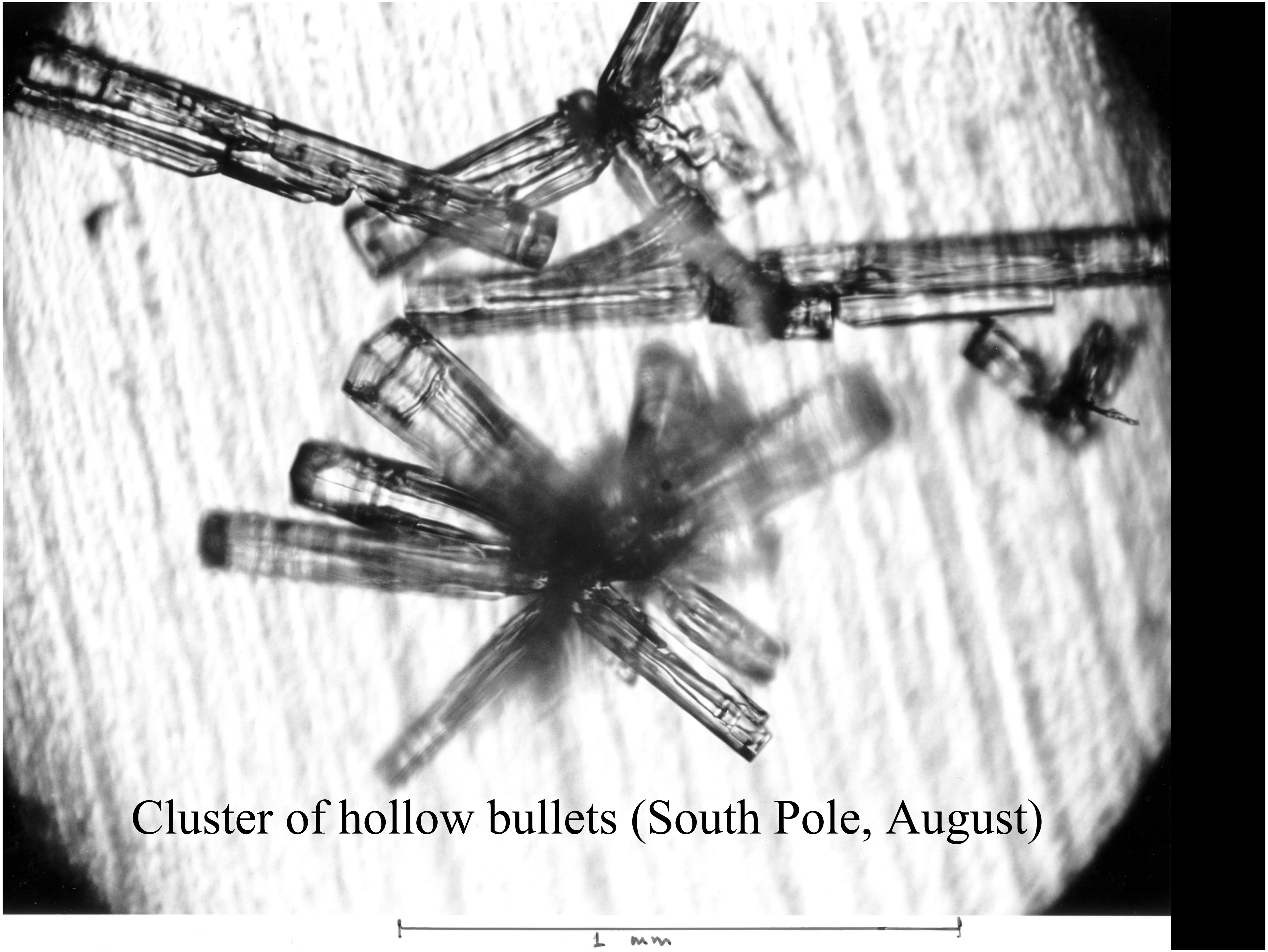
Hori et al.
Rem. Sens. Environ.
2006



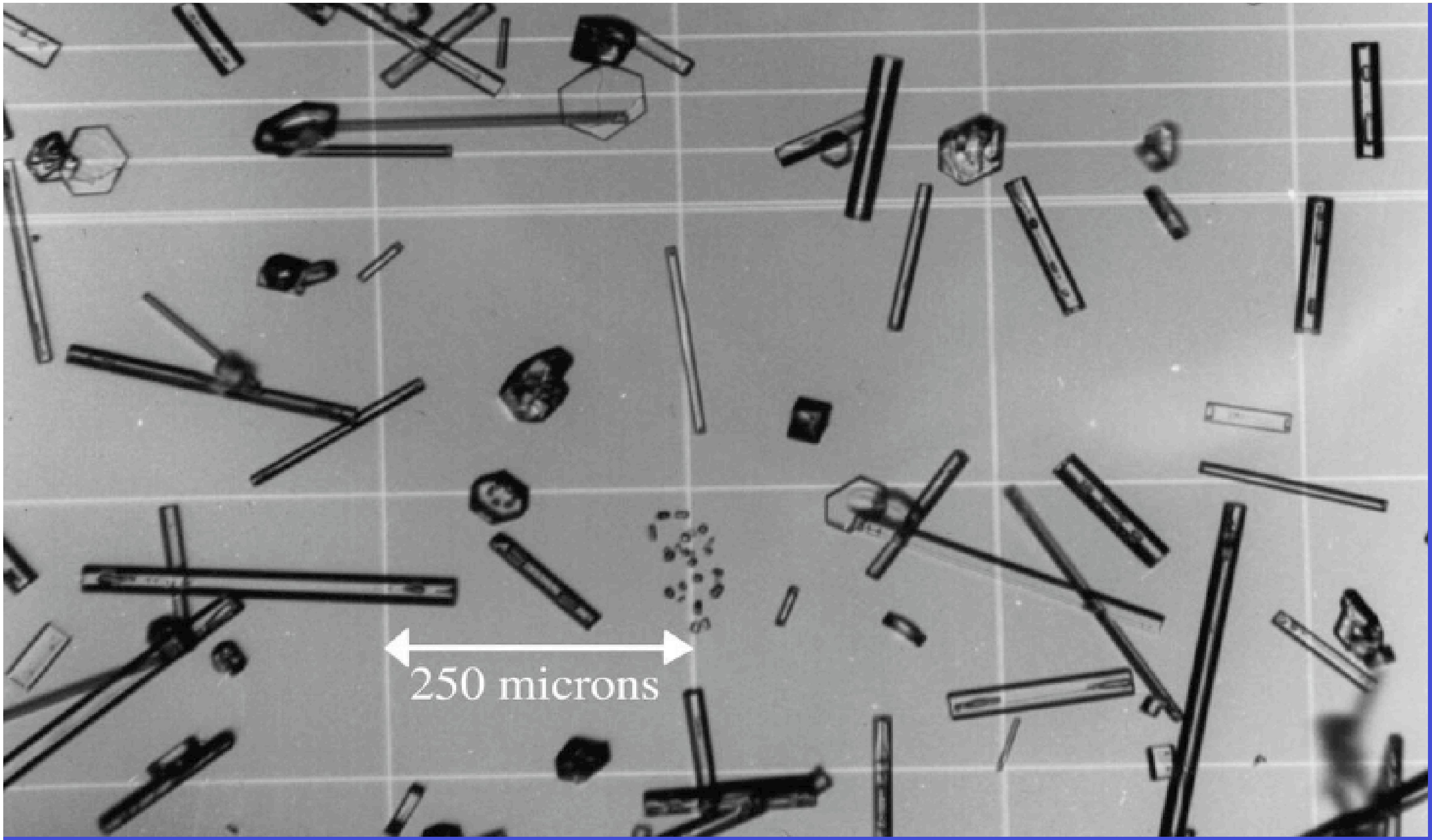
Viewing zenith angles 0°, 15°, 30°, 45°, 60°, 75°

In-situ measured spectral directional emissivity of snow and ice in the 8–14 μm atmospheric window

Masahiro Hori [a,*], Teruo Aoki [b], Tomonori Tanikawa [c], Hiroki Motoyoshi [d], Akihiro Hachikubo [e], Konosuke Sugiura [f], Teppei J. Yasunari [g], Hans Eide [h], Rune Storvold [i], Yukinori Nakajima [j], Fumihiro Takahashi [k]



Cluster of hollow bullets (South Pole, August)

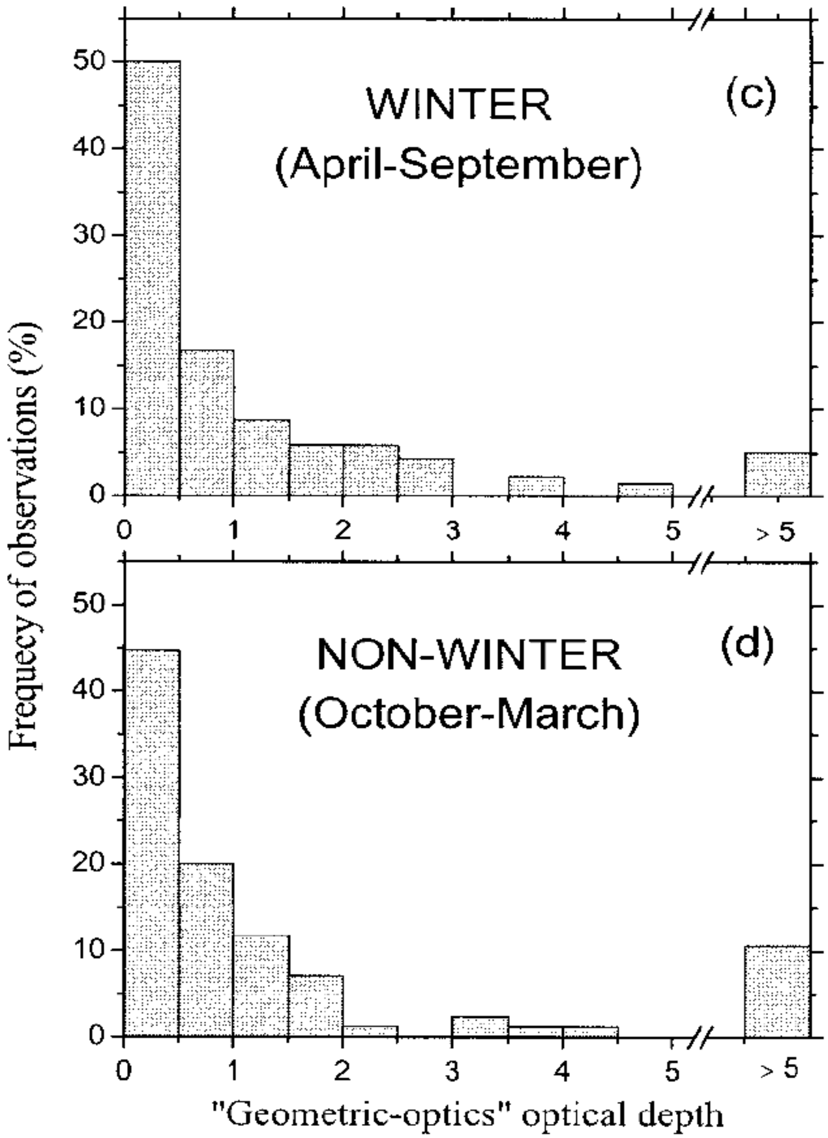


“Diamond dust” forms in near-surface temperature inversion under clear sky.

(Photo from Walden, Warren, Tuttle, JAM 2003)

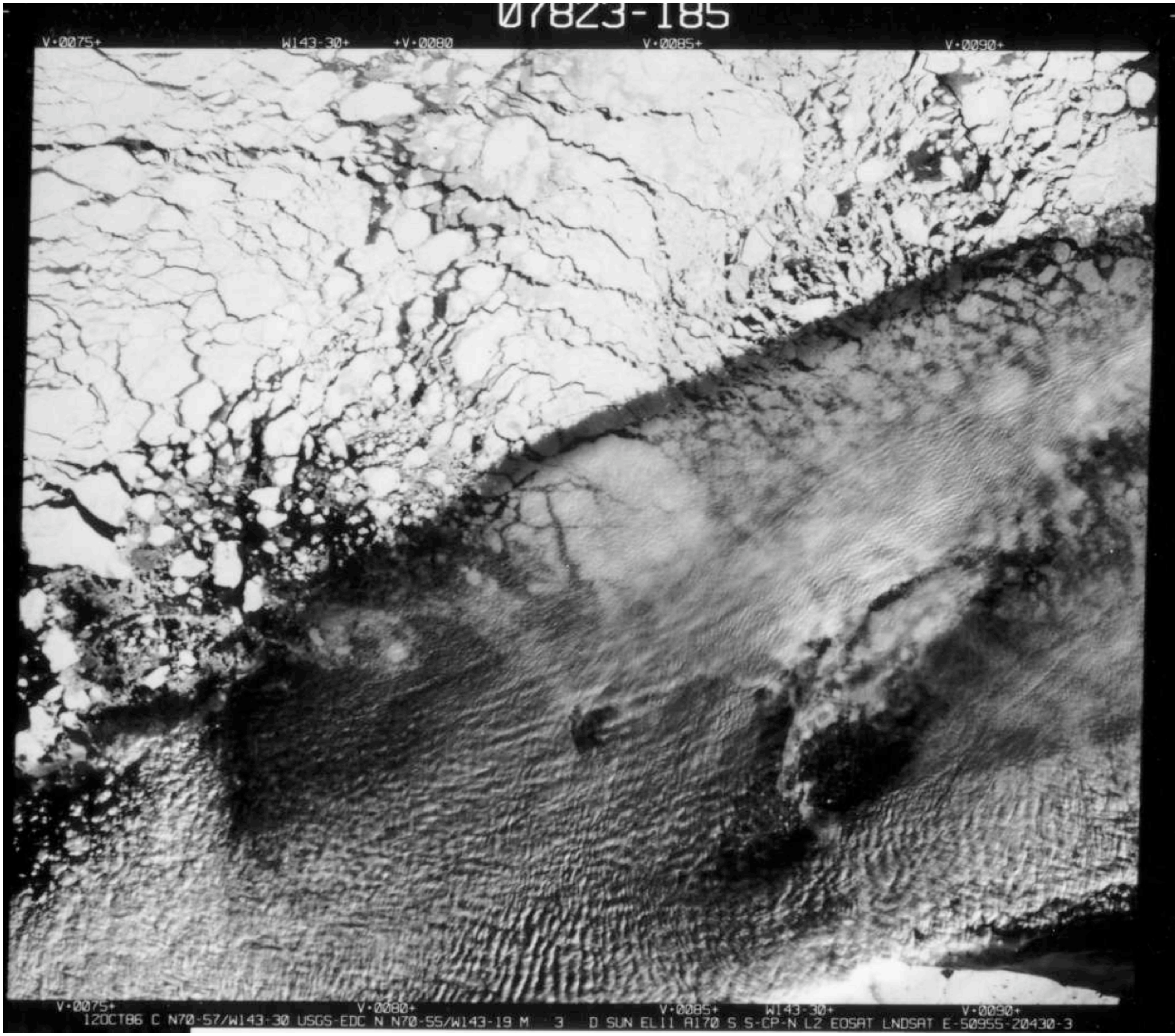
Ground-Based Infrared Remote Sensing of Cloud Properties over the Antarctic Plateau. Part II: Cloud Optical Depths and Particle Sizes

Ashwin Mahesh,* Von P. Walden,+ and Stephen G. Warren



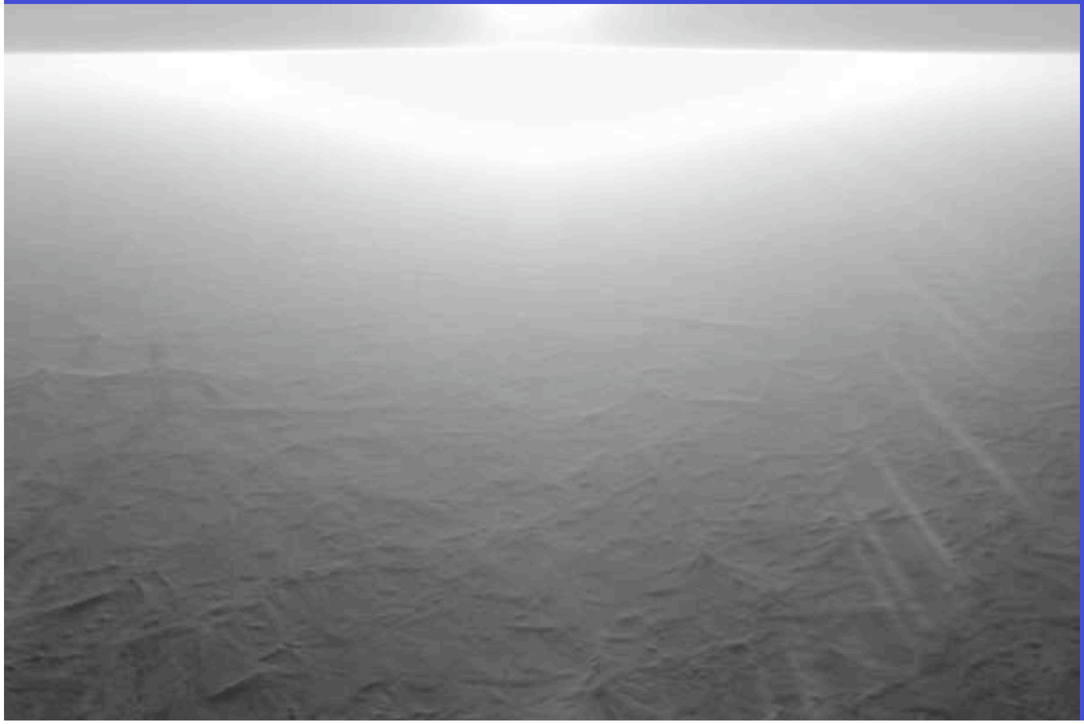
From upward-looking infrared interferometer.

Consistent with solar transmittance measurements by Kuhn (1977) at Plateau Station.



Cloud over snow-covered sea ice (Landsat)

(Welch and Wielicki, 1989)



Hudson & Warren, submitted to JGR.

Spectral and Broadband Longwave Downwelling Radiative Fluxes, Cloud Radiative Forcing, and Fractional Cloud Cover over the South Pole

MICHAEL S. TOWN

J. Climate, 2005, 2007

Precipitable water

Summer	1.6 mm
Winter	0.4 mm

Clear-sky longwave fluxes (2/3 from water vapor, 1/3 from CO_2)

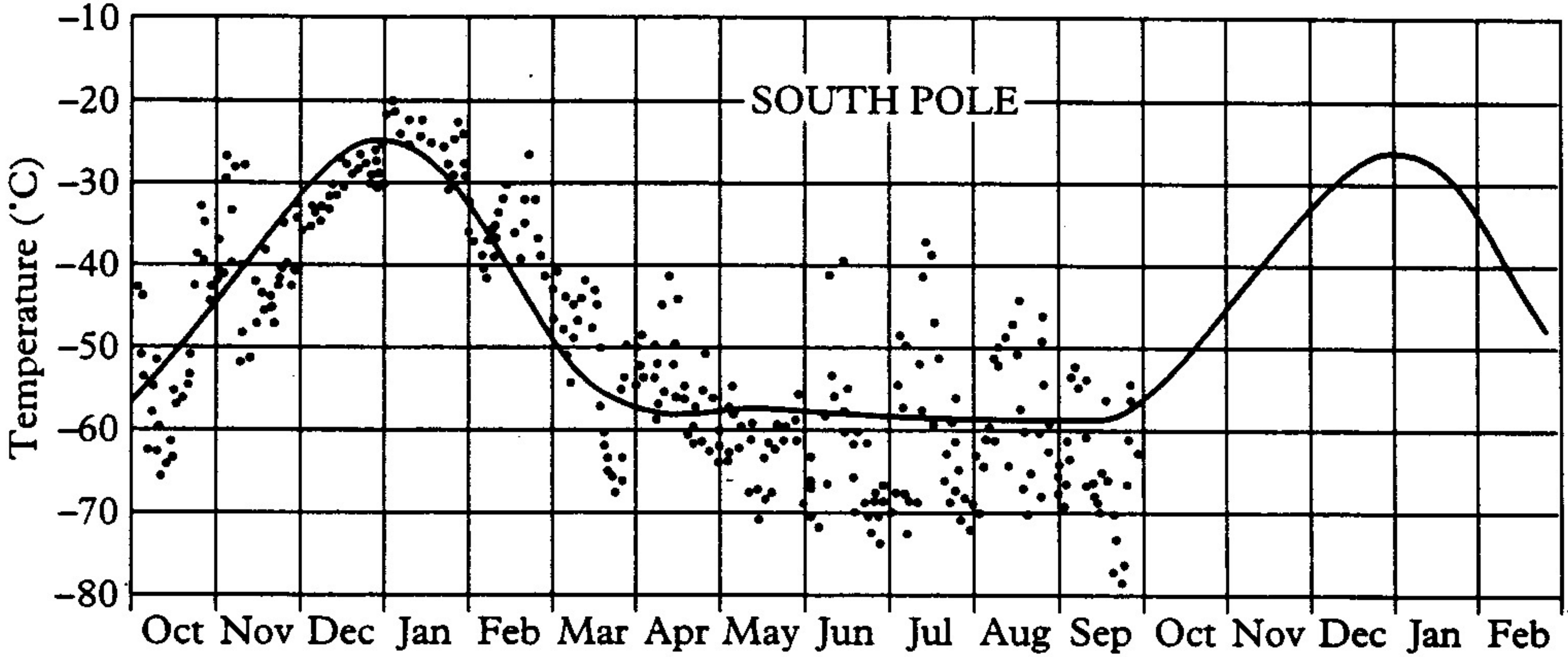
Summer	110-125 W m^{-2}
Winter	60-80 W m^{-2}

Cloud cover	Summer	45-50 %
	Winter	55-60%

Longwave cloud radiative forcing *(W m^{-2})*

	downward	*net*
South Pole	18	10
Global	46	46 (Kiehl & Trenberth, 1997)
Global		29 (Stackhouse, yesterday)

Snow surface is warmer under clouds *by* 0.5-1 K (summer)
3-4 K (winter)



ANTARCTICA. Figure 2. *Surface air temperatures at South Pole Station.* Solid line: 20-year mean for each day. Dots: daily mean temperatures for the year October 1985–September 1986.

[redacted]

Hudson and Brandt
J. Climate 2005

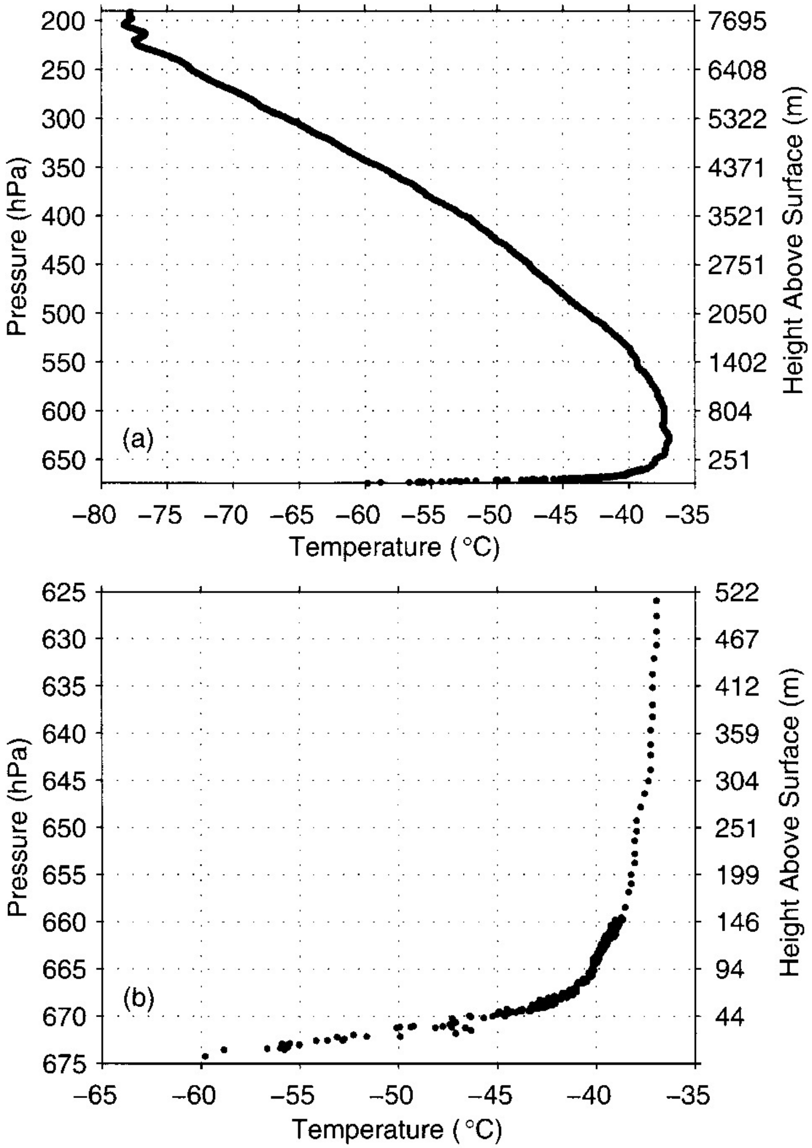


FIG. 3. Temperature profile measured at South Pole Station on 25 Sep 2001. Data above 660 hPa are from a routine radiosounding with an RS80; those below 660 hPa are from a tethered sounding with an RS80. (a) The full tropospheric sounding is shown, and (b) the lowest 500 m are enlarged. The surface pressure was 674 hPa.

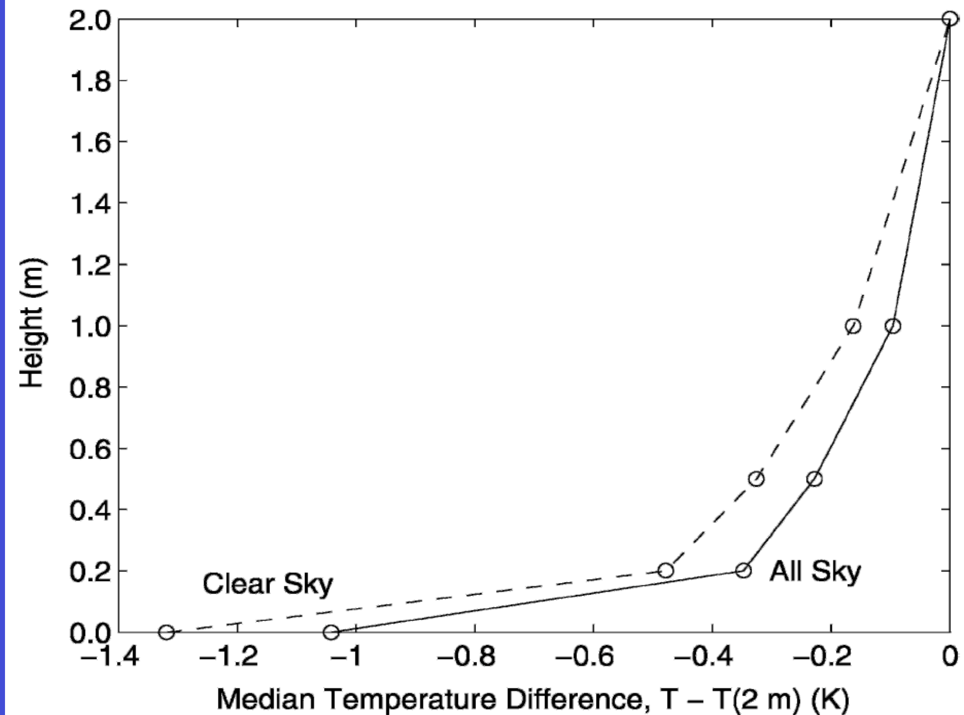
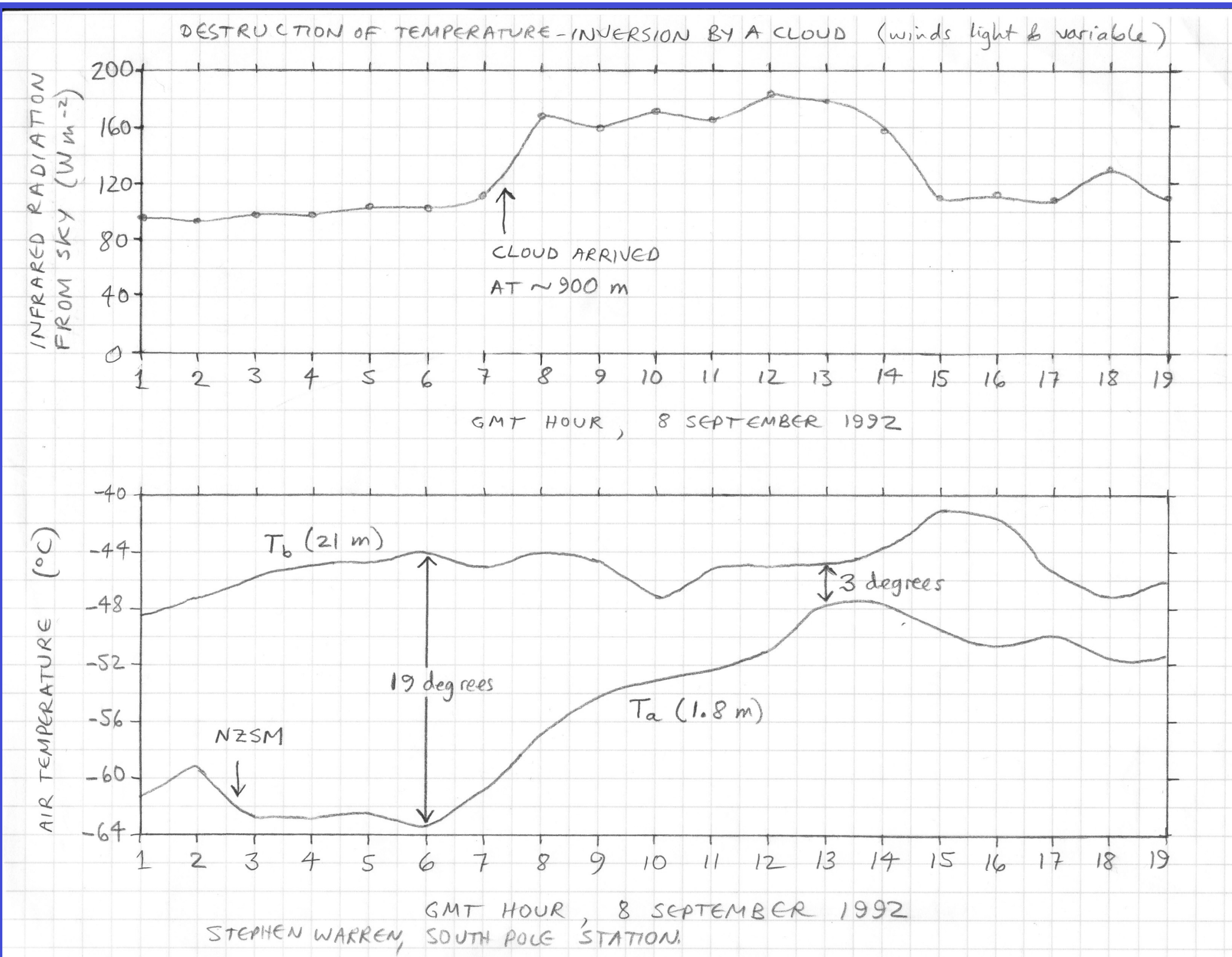
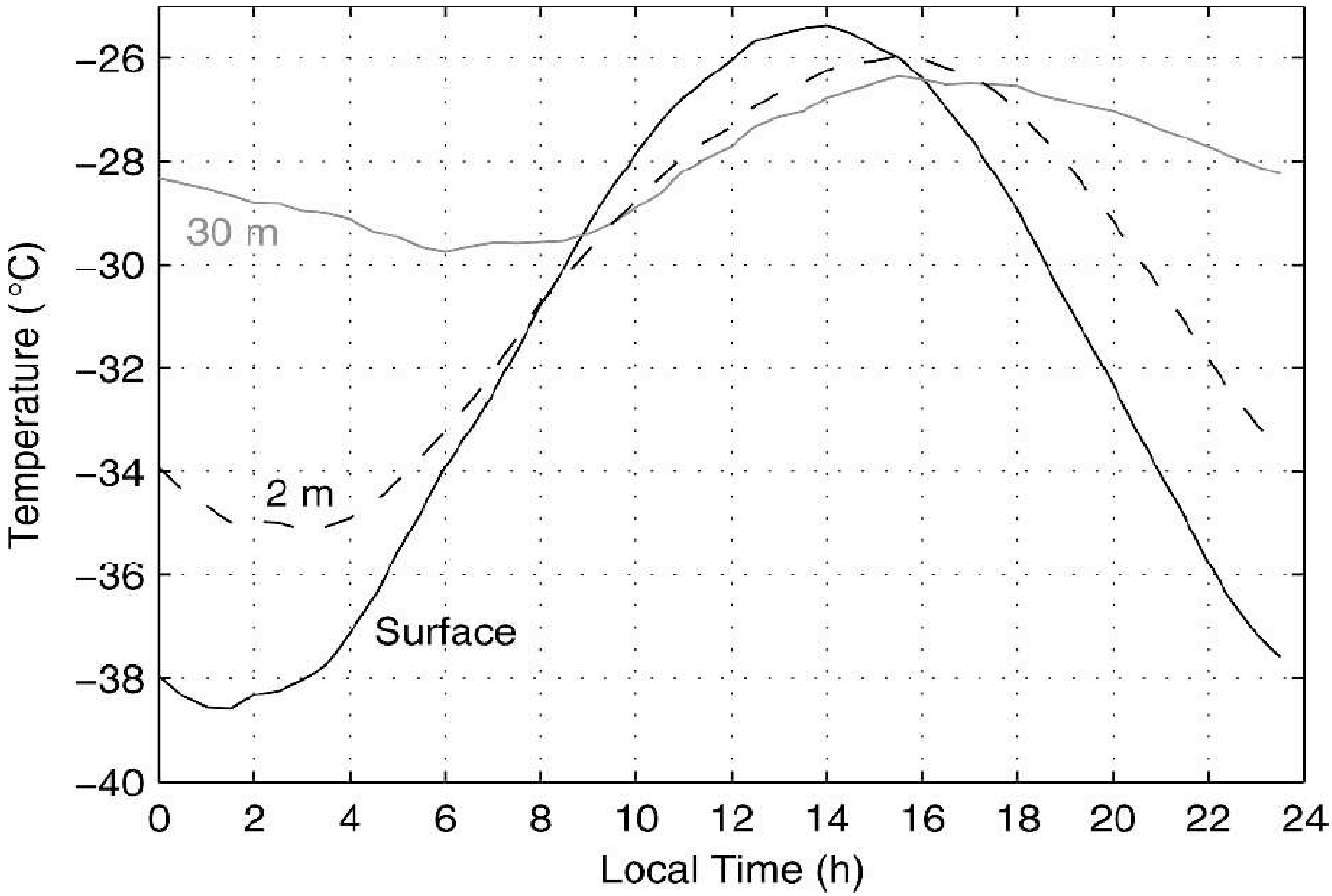
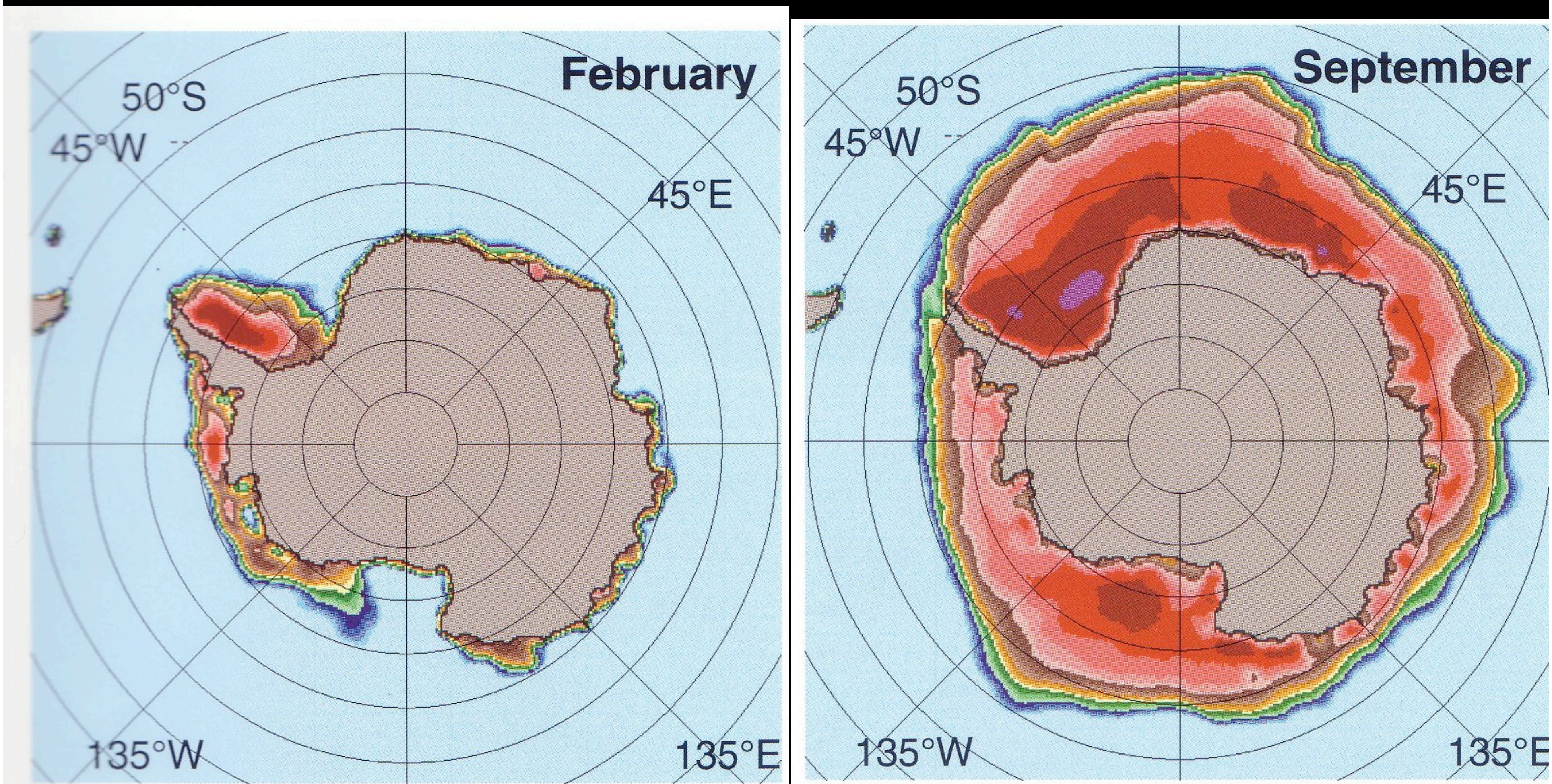


FIG. 13. Median temperature difference relative to 2 m. Data are from South Pole during the 2001 polar night. Separate profiles are shown for the overall median (All Sky, solid line) and the clear-sky median (dashed line).

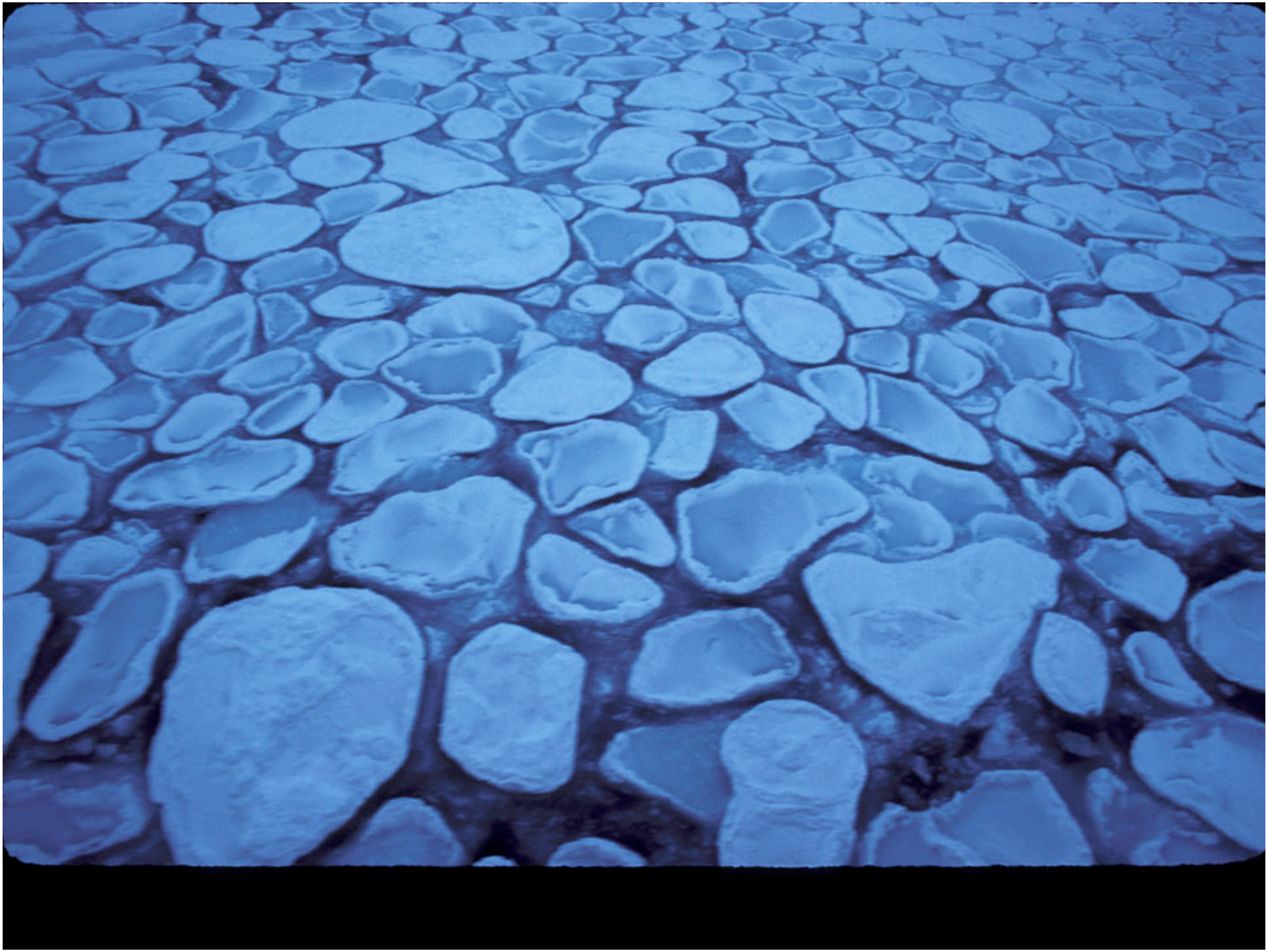

DESTRUCTION OF TEMPERATURE-INVERSION BY A CLOUD (winds light & variable)
INFRARED RADIATION FROM SKY (W m⁻²)
200
160
120
80
40
0
CLOUD ARRIVED
AT ~ 900 m
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
GMT HOUR, 8 SEPTEMBER 1992
AIR TEMPERATURE (°C)
-40
-44
-48
-52
-56
-60
-64
Tb (21 m)
3 degrees
19 degrees
Ta (1.8 m)
NZSM
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
GMT HOUR, 8 SEPTEMBER 1992
STEPHEN WARREN, SOUTH POLE STATION.

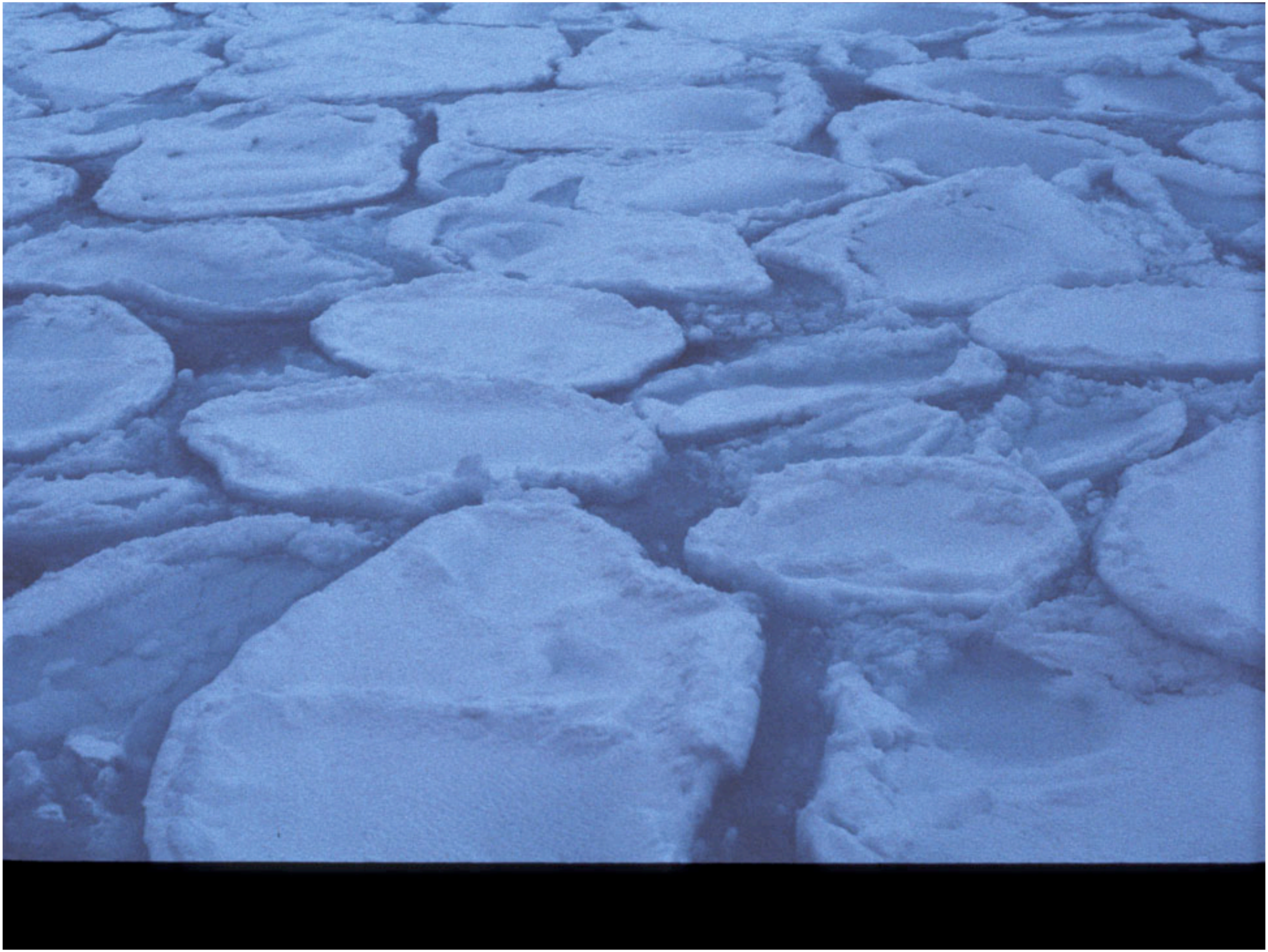


Diurnal cycle of temperatures in summer
at Dome C, 75°S (Hudson & Brandt, 2005)

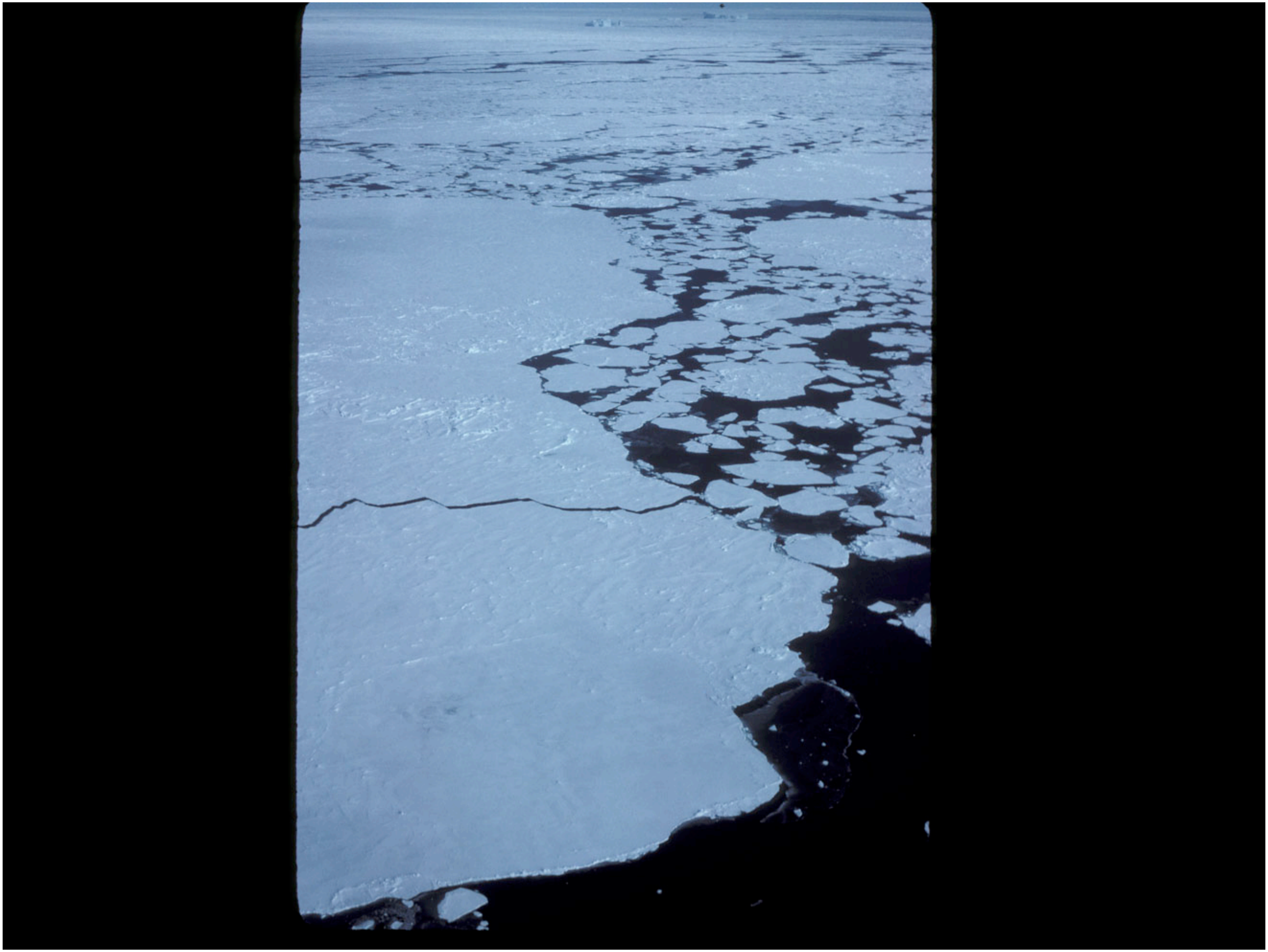

February
50°S
45°W
45°E
135°W
135°E
September
50°S
45°W
45°E
135°W
135°E

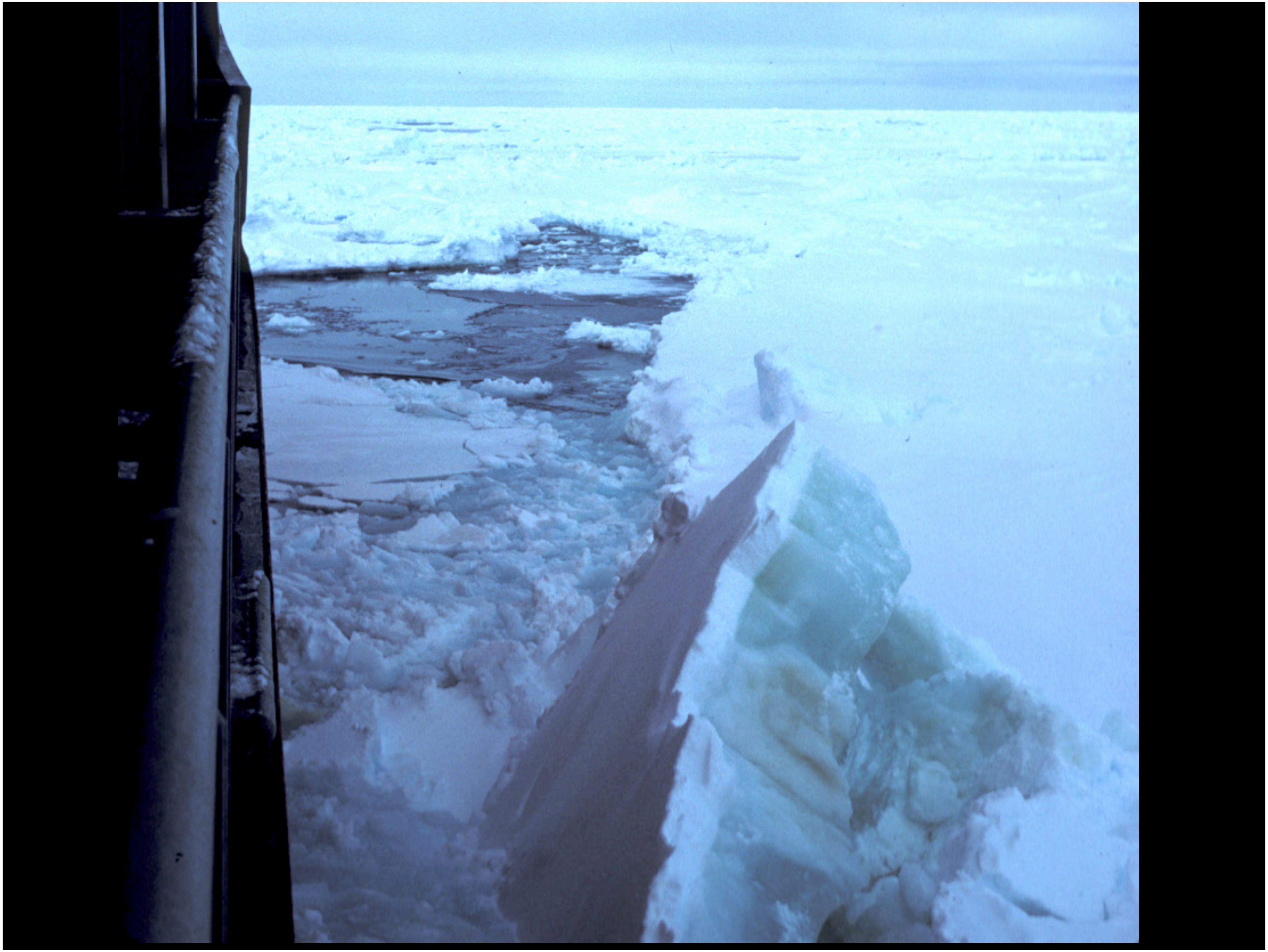

ICEBIRD



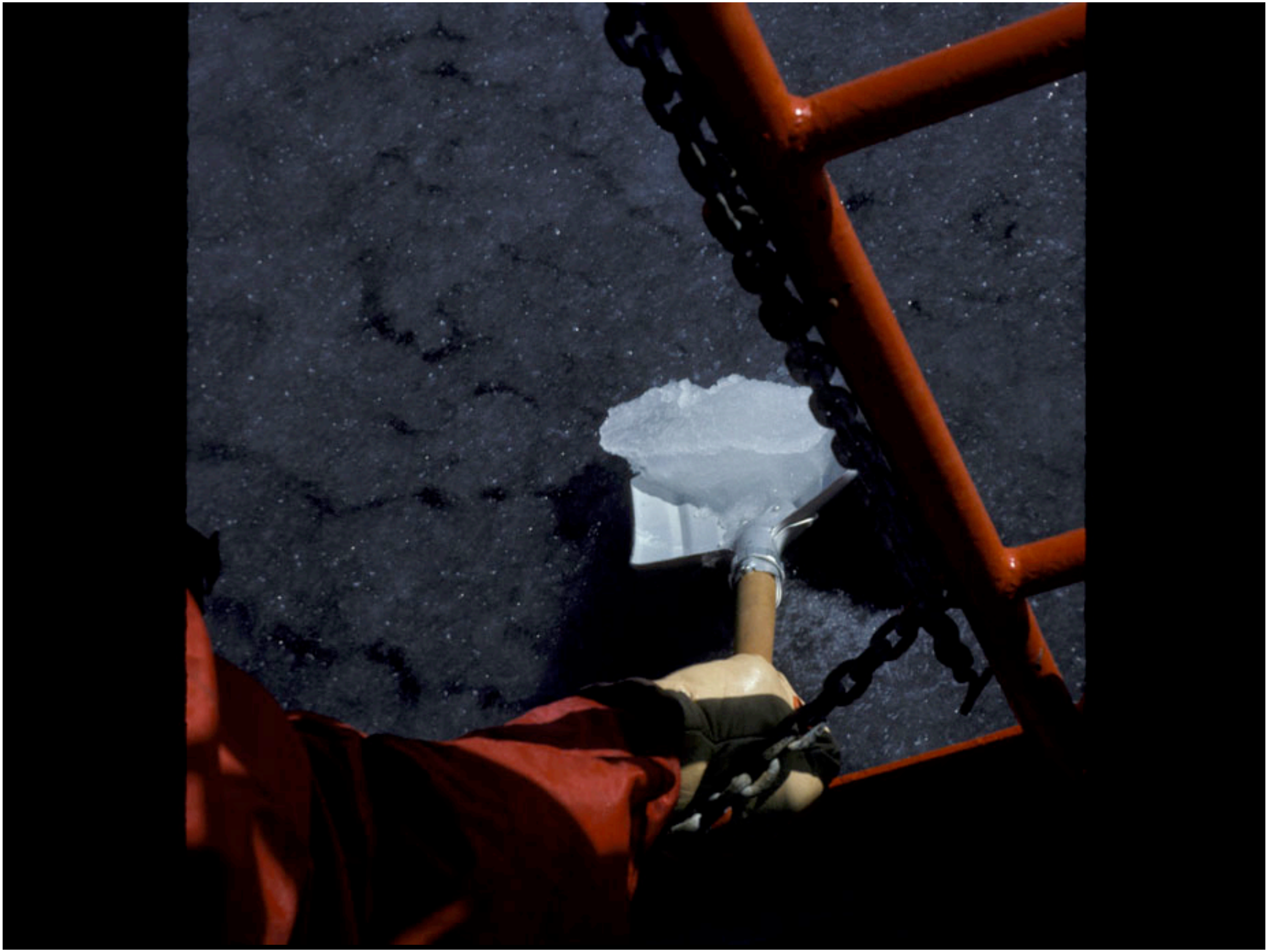


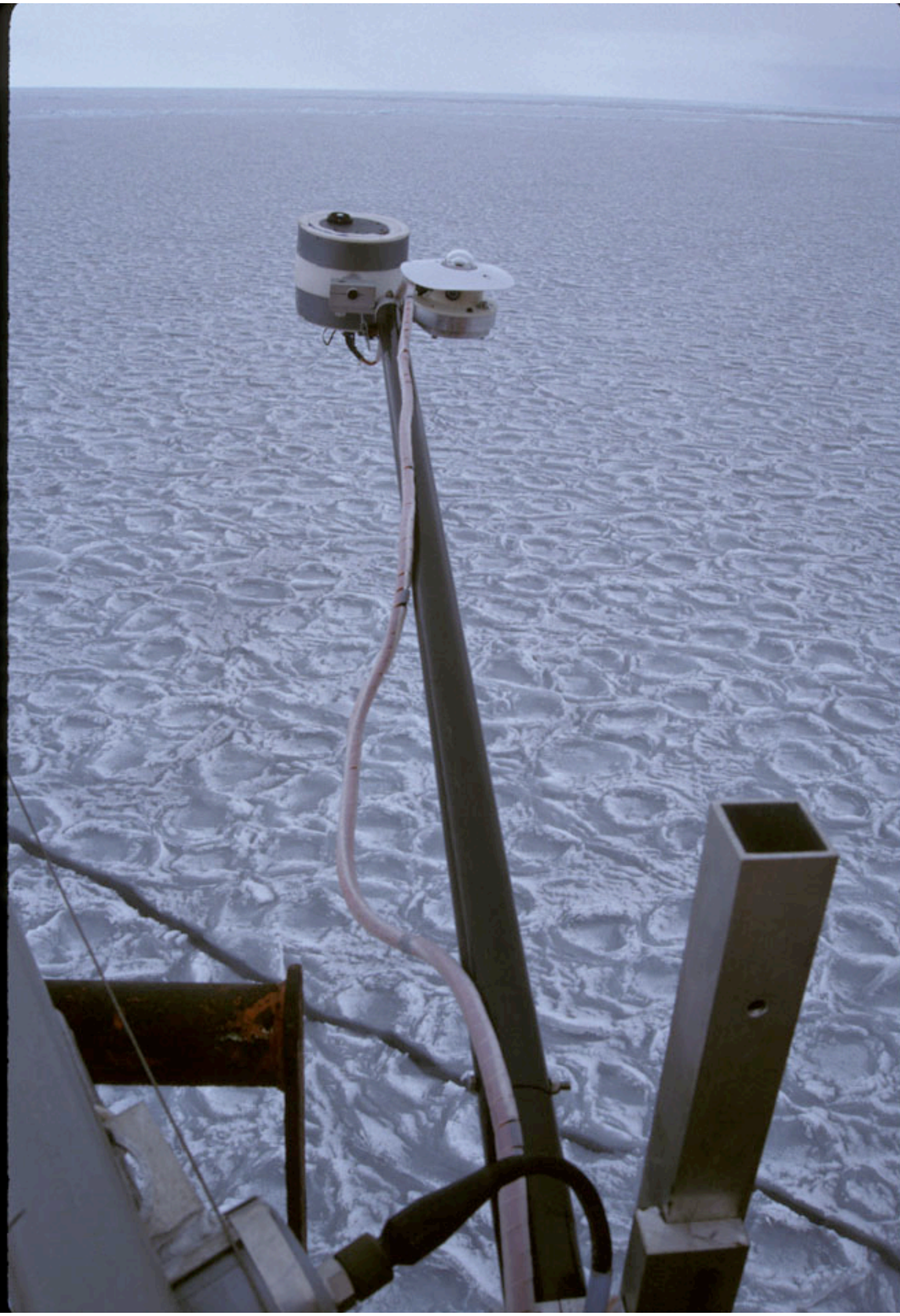

HELICOPTER
RESOURCES






AUSTRALIAN
antarctic
Territory
1997
$1.05
ANARE: Sea Ice Research





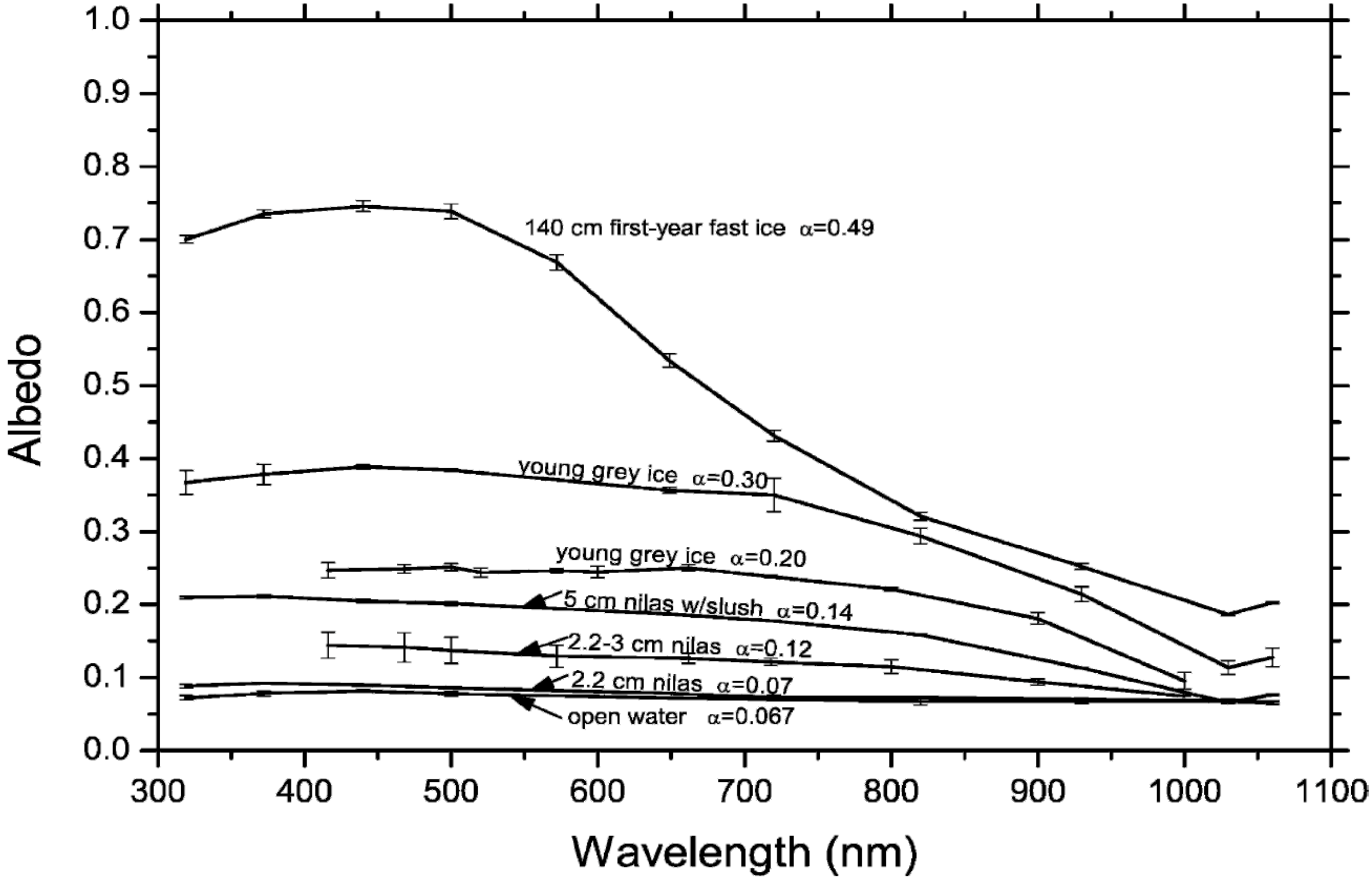


FIG. 1. Spectral albedos of snow-free ice and open water. Measurements from the 1996 voyage begin at 320 nm; those from the 1988 voyage begin at 420 nm. Broadband solar albedo α is also given. Ice thickness Z_i is given, except for two ice types that were observed only from

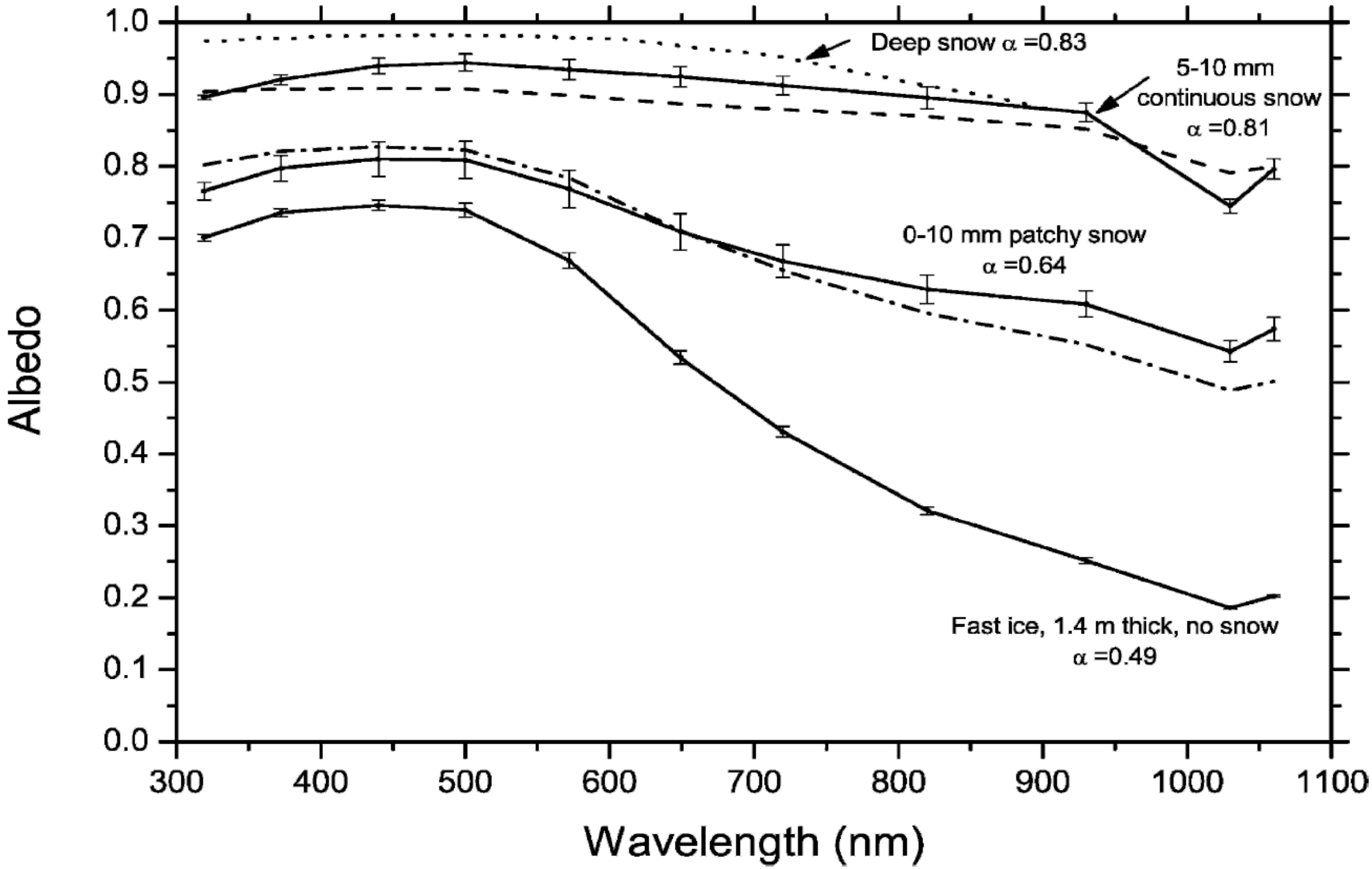


FIG. 2. Effect of a thin snow cover on the albedo of thick cold fast ice near Davis Station, 30 Oct 1996. The air temperature was −5°C. The lower curve is the same as the upper curve in Fig. 1, for bare ice that is 1.4 m thick. Nearby, the ice was covered with patchy snow or continuous snow; their albedos are also shown. The topmost curve, for deep snow on the

TABLE 1. Representative all-wave solar albedos of surface types in the East Antarctic sea ice zone in spring and summer. Values in bold are derived from measurements; all others were interpolated or extrapolated using Fig. 5. The seasons are indicated by SON and DJF.

				Thin snow (<3 cm)				Thick snow (>3 cm)			
		No snow		Clear		Cloudy		Clear		Cloudy	
Ice type	Ice thickness (cm)	Clear	Cloudy	SON	DJF	SON	DJF	SON	DJF	SON	DJF
Open water	0	**0.07**	**0.07**	—	—	—	—	—	—	—	—
Grease	<1	**0.09**	**0.09**	—	—	—	—	—	—	—	—
Nilas	<10	**0.14**	**0.16**	**0.42**	**0.39**	**0.45**	**0.42**	—	—	—	—
Young grey ice	10–15	**0.25**	**0.27**	0.55	0.51	0.59	0.56	0.72	0.67	0.76	0.72
Young grey-white ice	15–30	0.32	0.34	0.64	0.59	0.68	0.64	0.76	0.70	0.81	0.76
First-year ice <0.7 m	30–70	0.41	0.45	**0.74**	**0.69**	**0.79**	**0.74**	0.81	0.75	0.87	0.82
First-year ice >0.7 m	>70	**0.49**	**0.54**	**0.81**	**0.75**	**0.87**	**0.82**	**0.81**	**0.75**	**0.87**	**0.82**

Surface Albedo of the Antarctic Sea Ice Zone

RICHARD E. BRANDT AND STEPHEN G. WARREN

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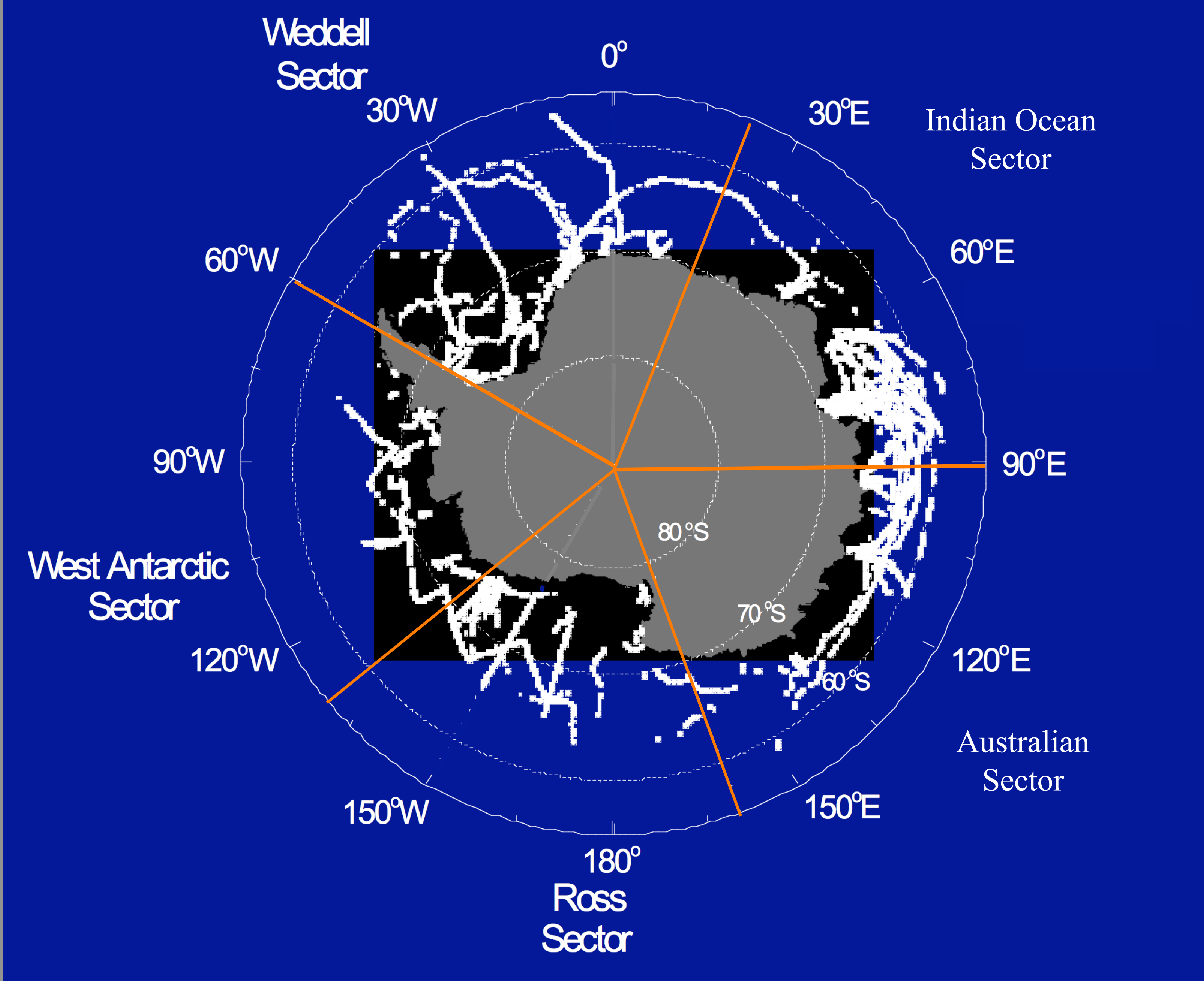
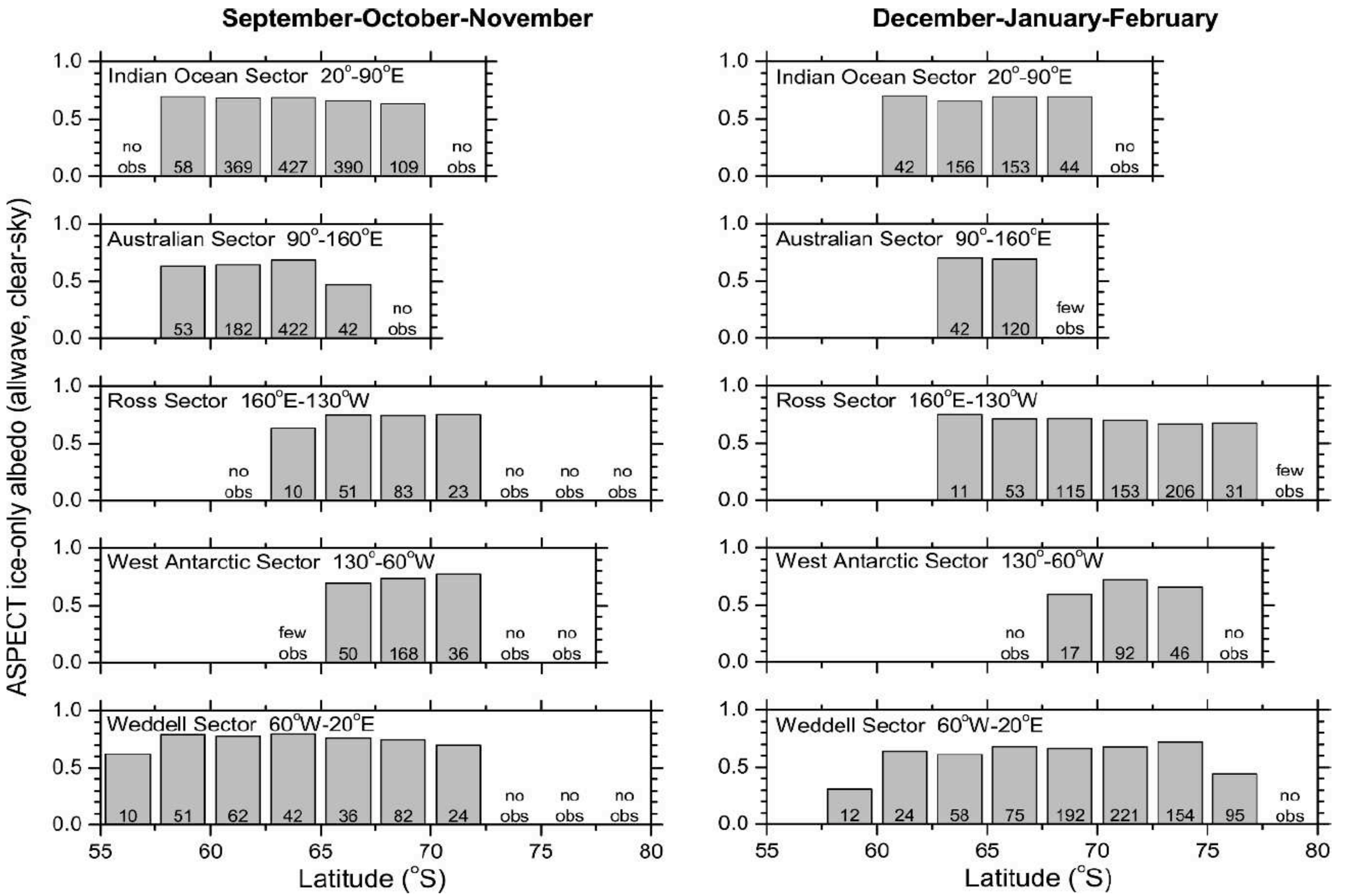
(Manuscript received 30 September 2004, in final form 28 February 2005)

ASPeCt ship tracks for SON and DJF





Ice-only albedos

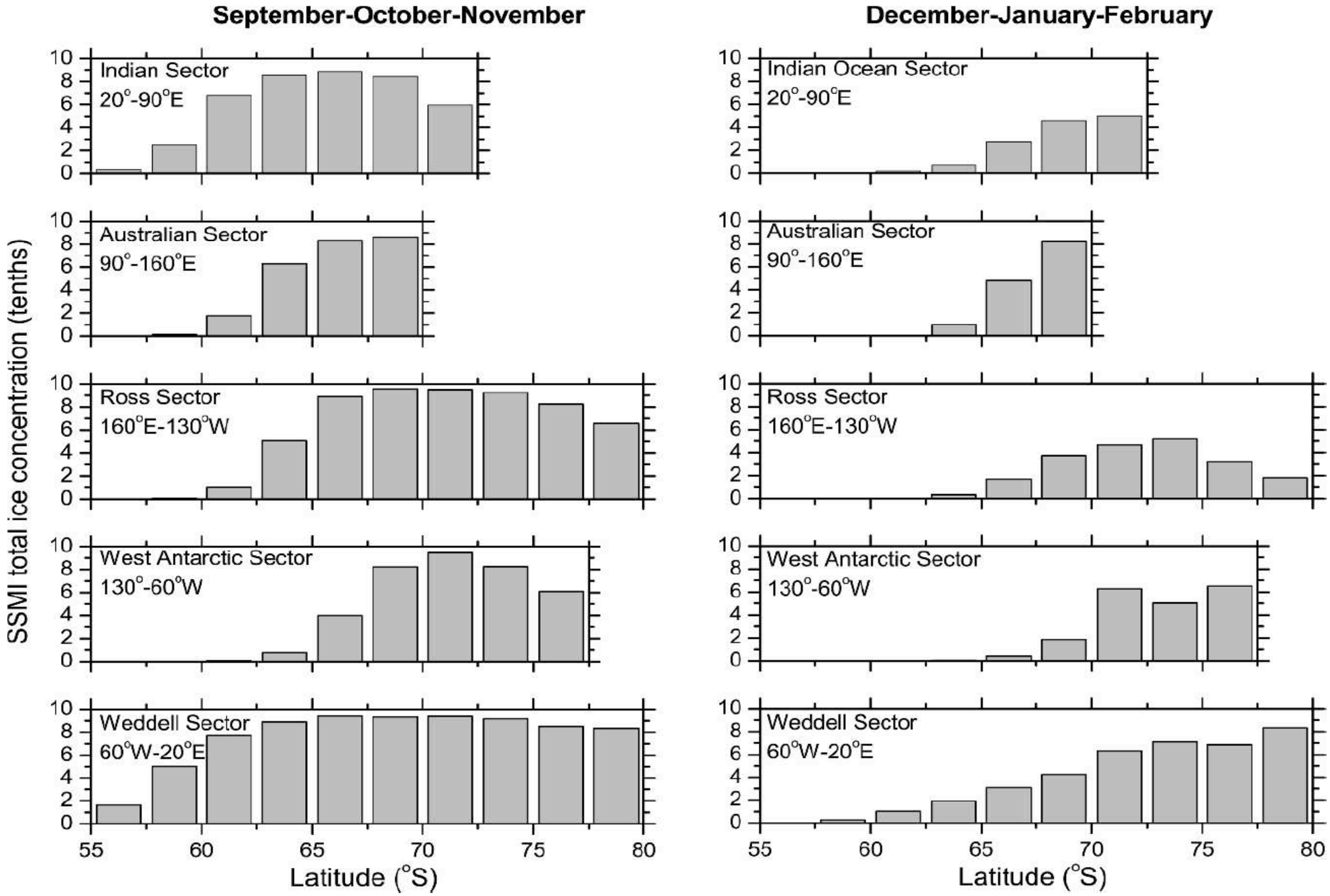


FIG. 9. Average ice concentration as a function of latitude, from satellite passive microwave observations by the SSM/I instrument, using the bootstrap algorithm, for the years 1988–2000. Plots are shown for two seasons for each of the five sectors.

Ice concentration

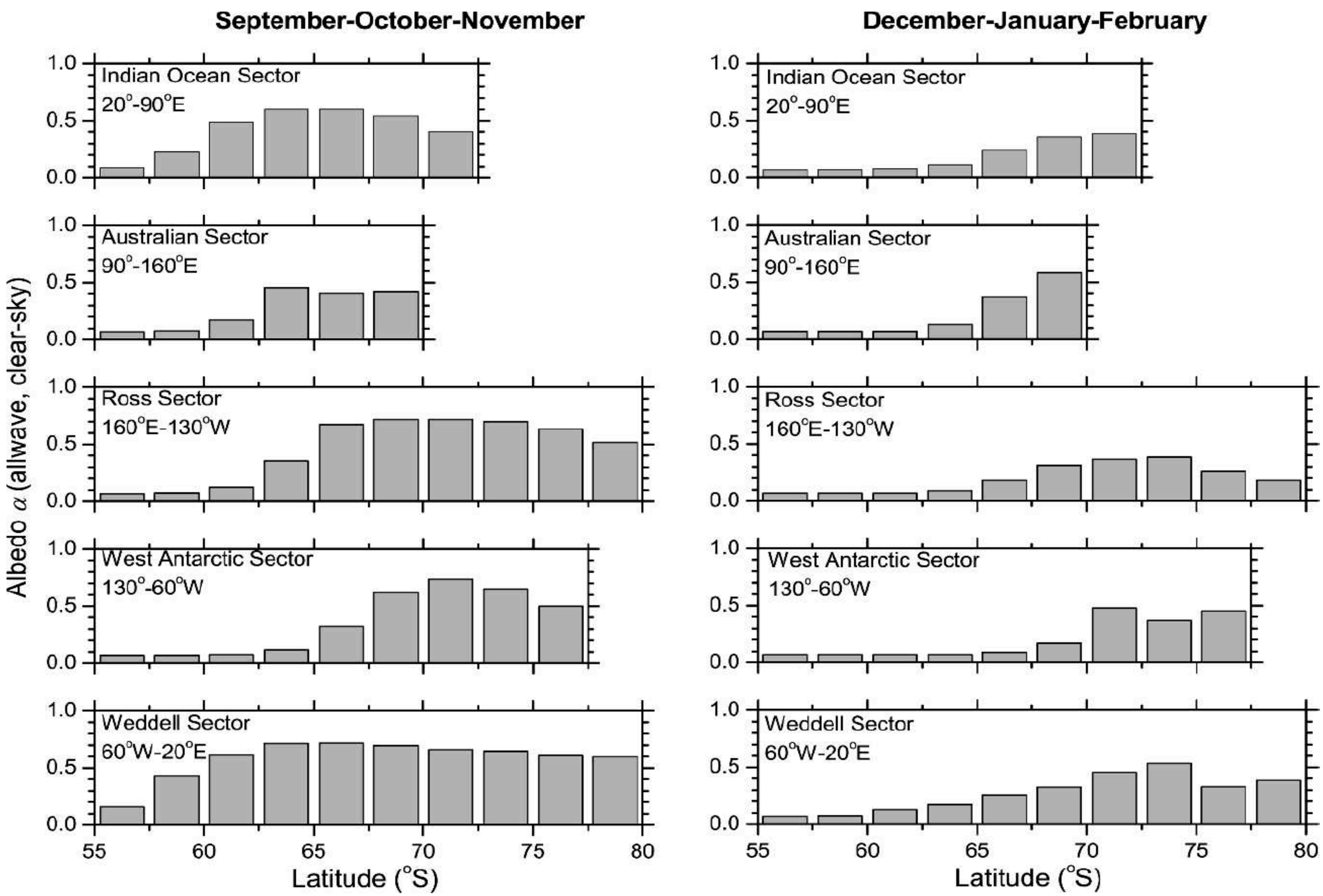


FIG. 10. Average broadband solar albedo as a function of latitude, including both ice and water, combining ASPeCt ice-only albedos from Fig. 7 together with SSM/I ice concentrations

Area-average albedos (ice and water)

Clouds over Antarctic sea ice (Melanie Fitzpatrick)

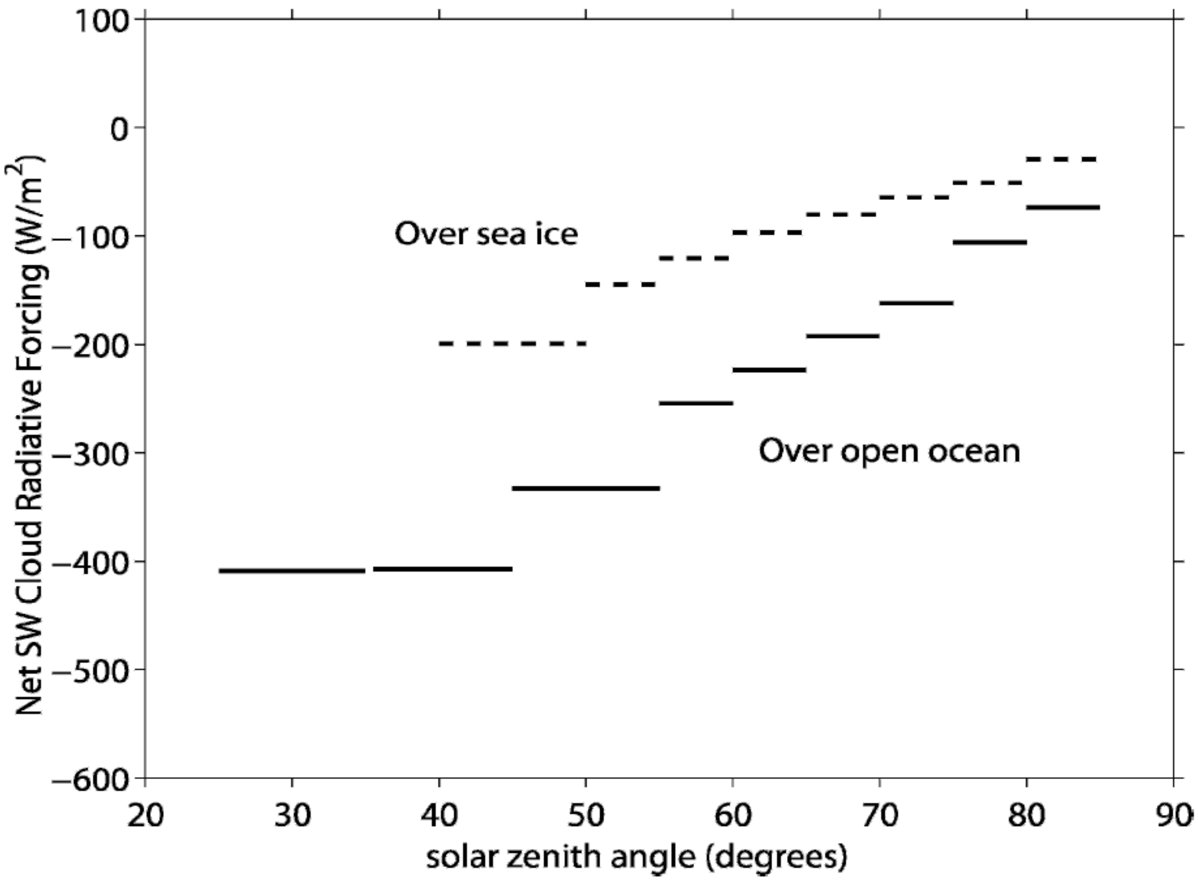
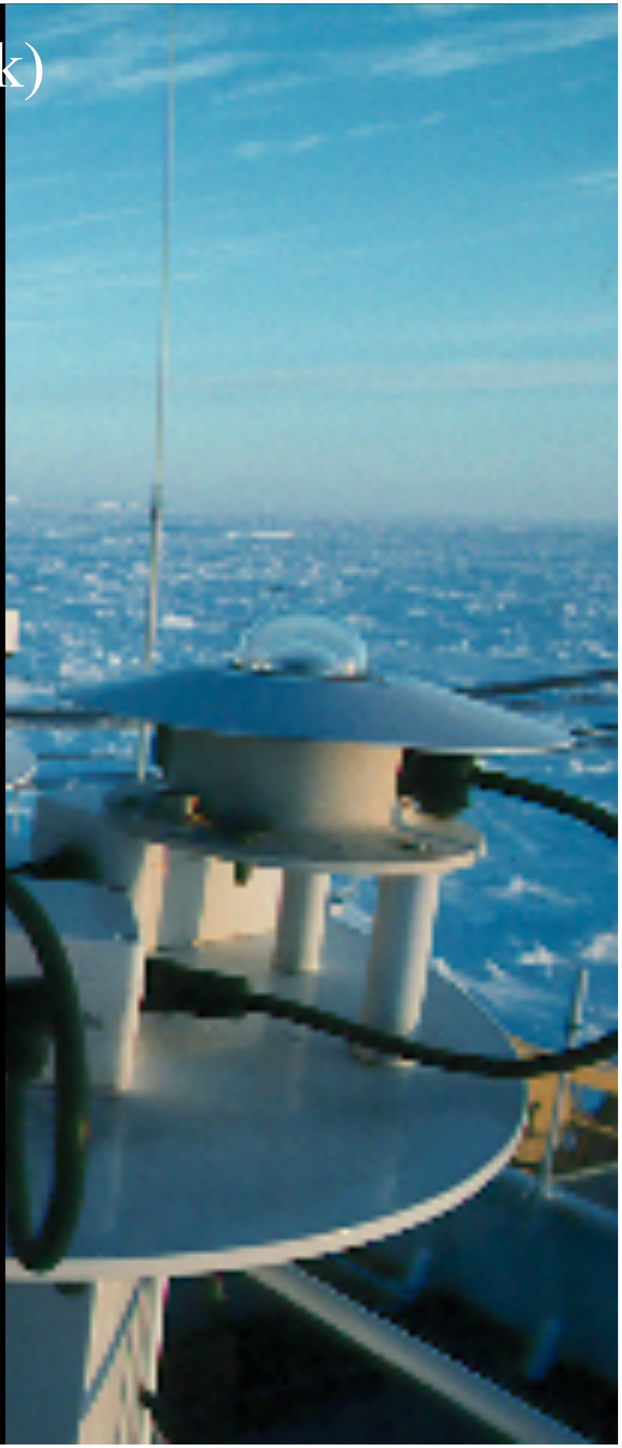


FIG. 11. Net shortwave cloud radiative forcing (CRF_n) at the surface obtained by multiplying the downward shortwave cloud radiative forcing by $(1 - \alpha)$, where α is the surface albedo. Each average (for a solar-zenith-angle bin) is the difference in net shortwave irradiance between all conditions and clear conditions. Data are from the 1996 spring voyage. CRF_n is smaller over sea ice due to both the higher surface albedo and the less frequent occurrence of clouds.



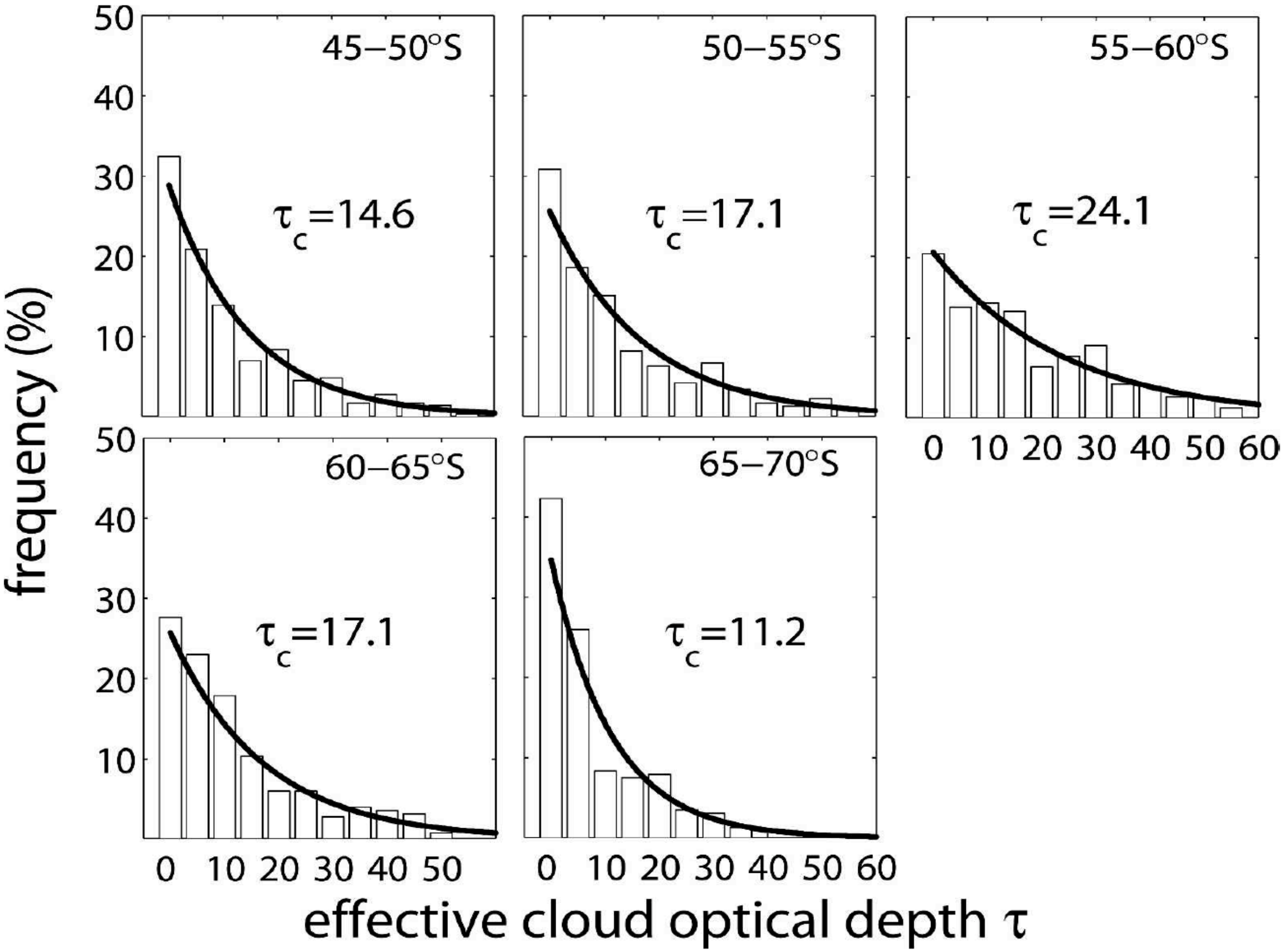


FIG. 14. Cloud optical depth for different latitude intervals for all voyages of the *Aurora Australis* between 1991 and 2002 with concurrent observations of ocean, sea ice, and cloud conditions. The observations include all seasons and as such are biased toward spring and summer when a greater number of voyages occurred. The number of observations for each season and each latitude interval are shown in Table 2. Exponential fits are also given, where $f(\tau) = \tau_c^{-1} \exp(-\tau/\tau_c)$. The values shown in the figure are percentages for bins of width $\Delta\tau = 5$.

Clouds over Southern Ocean in spring and summer (Fitzpatrick and Warren, 2005).

Similar values were found in Arctic summer by Lubin and Simpson (1997)

The Relative Importance of Clouds and Sea Ice for the Solar Energy Budget of the Southern Ocean

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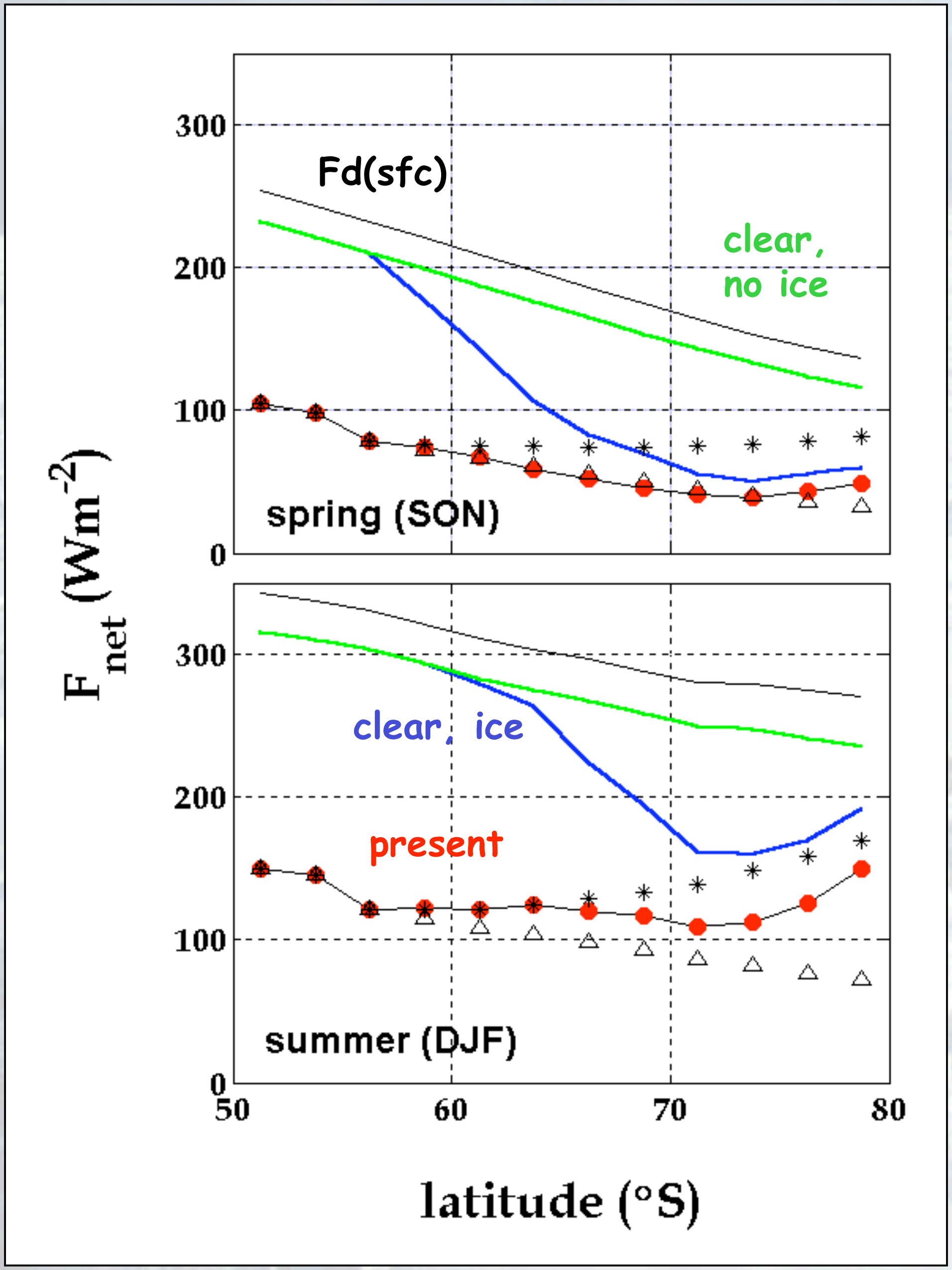
(Manuscript received 14 March 2006, in final form 20 June 2006)

Relative Importance of Sea Ice and Cloud



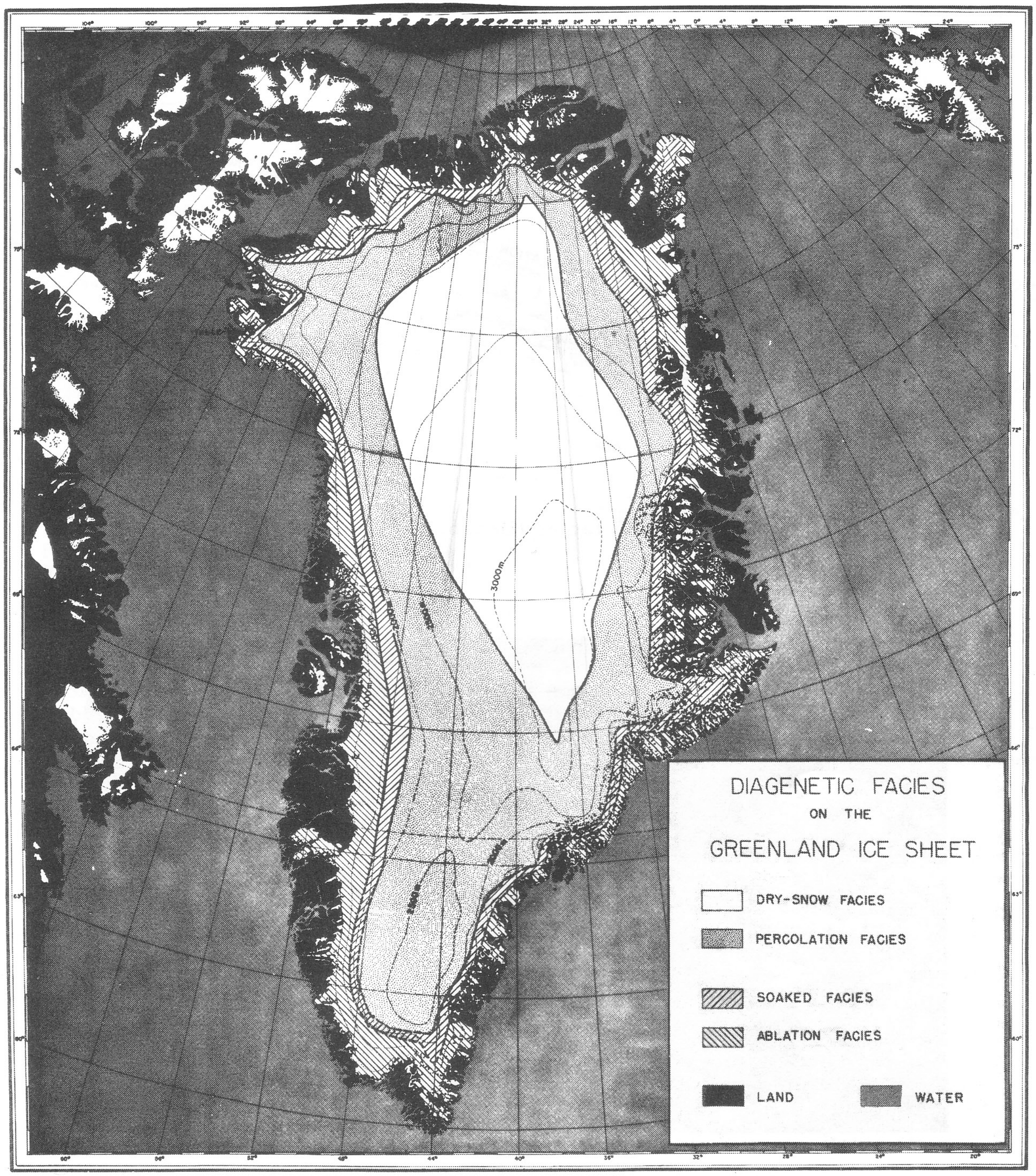
Mean F_{net} (area-weighted)

Sea-ice effect
spring: -60 Wm^{-2}
summer: -30 Wm^{-2}

Cloud and ice effect
spring: -115 Wm^{-2}
summer: -150 Wm^{-2}

(averaged over Southern Ocean 50-80 S)

The Arctic is different.

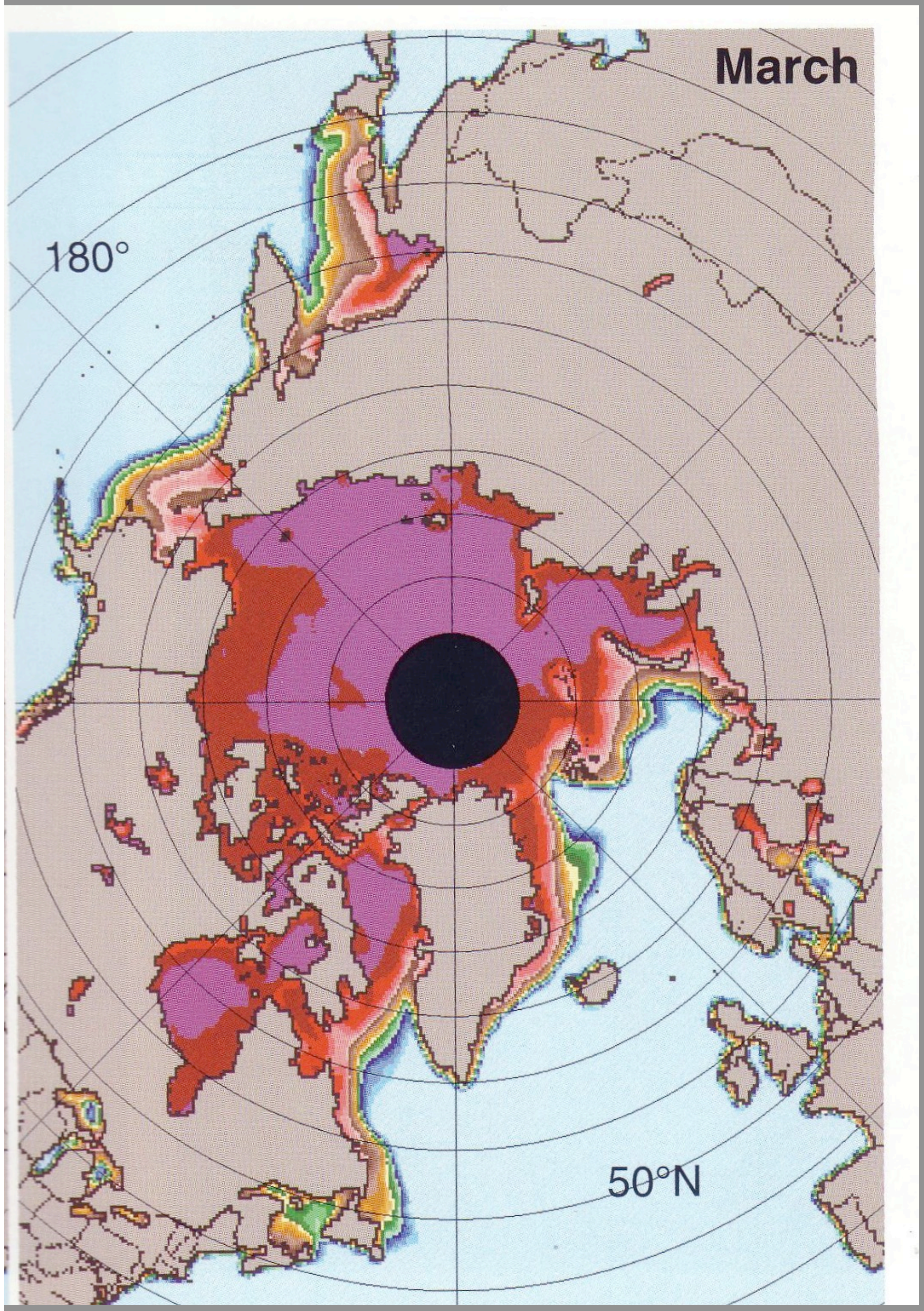


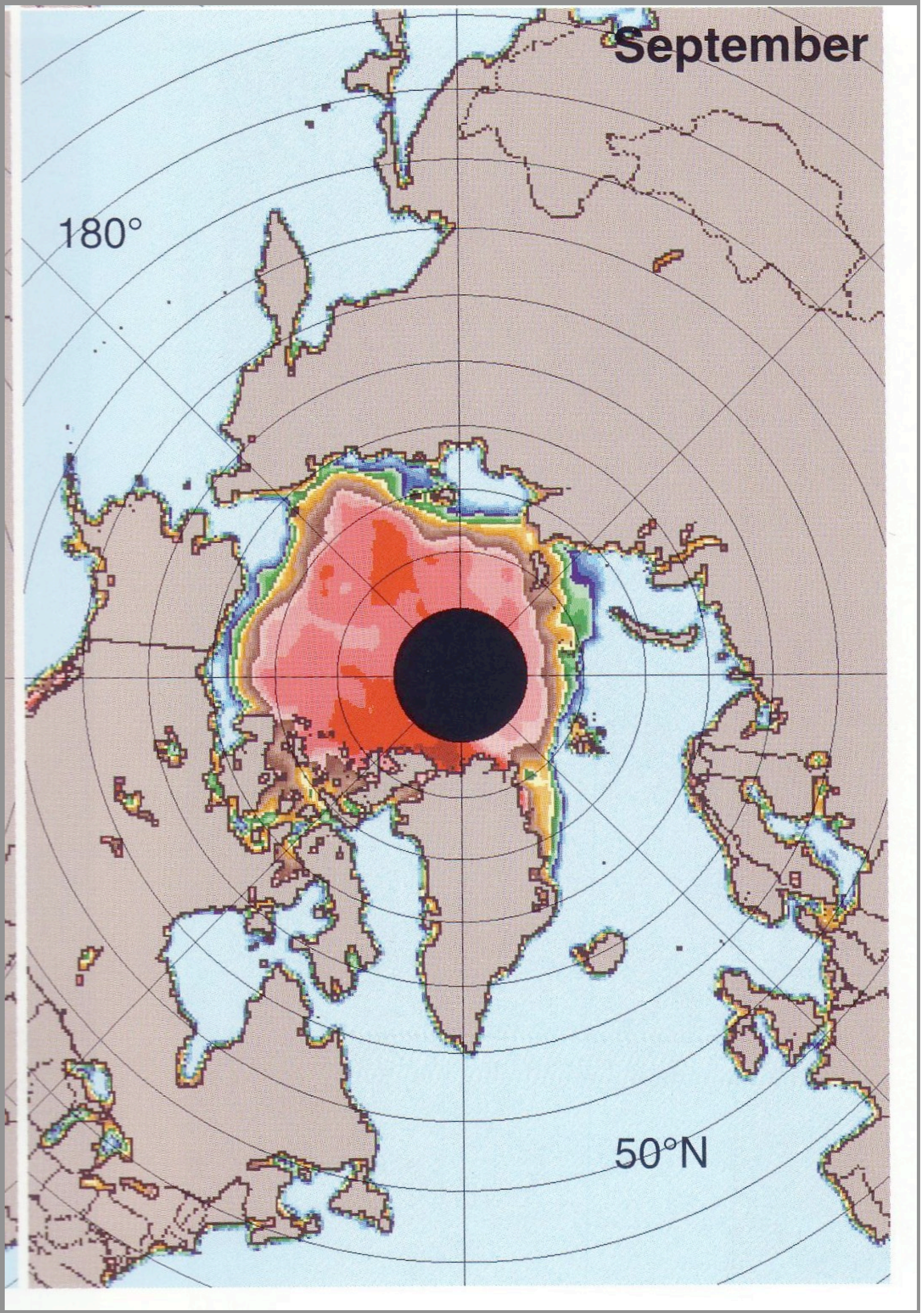
Benson, 1960:

Some melting occurs over 70% of the ice sheet.

Northeast Greenland in August 2006


Northeast Greenland: Debris-covered ice, meltwater stream


March
180°
50°N


September
180°
50°N

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

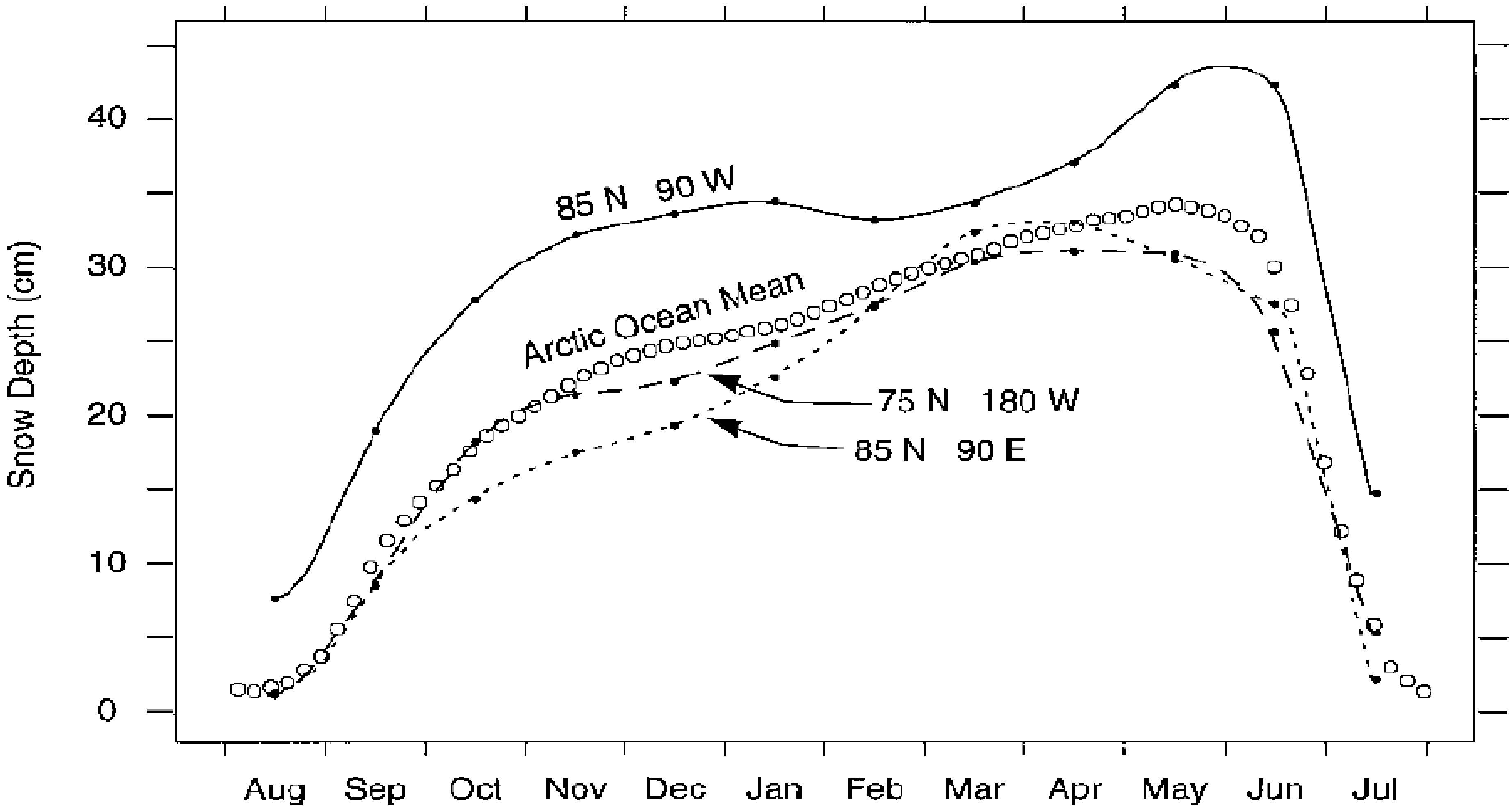


FIG. 13. Seasonal cycles of snow depth on multiyear Arctic sea ice. The mean of all NP stations that sampled complete years (Aug–Jul) is shown, as well as the seasonal cycles at three locations (values taken from Fig. 9).

Warren et al. *J. Climate*, 1999

Puddles on snow-free Arctic sea ice in summer

Black carbon in Arctic snow

Stephen Warren, Thomas Grenfell
University of Washington, Seattle

Antony Clarke
University of Hawaii

Clarke & Noone, *Atmos. Environ.*, 1985

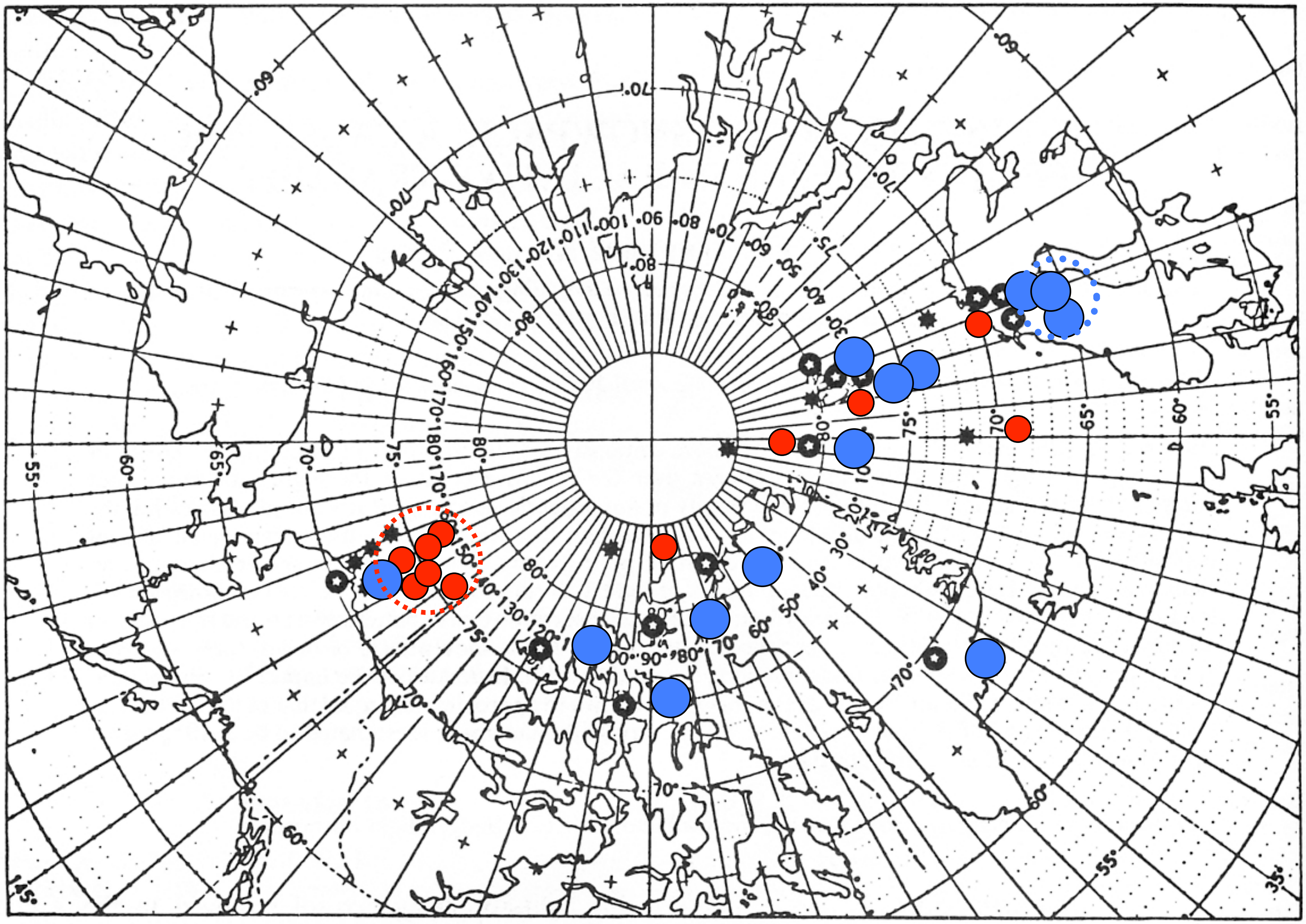
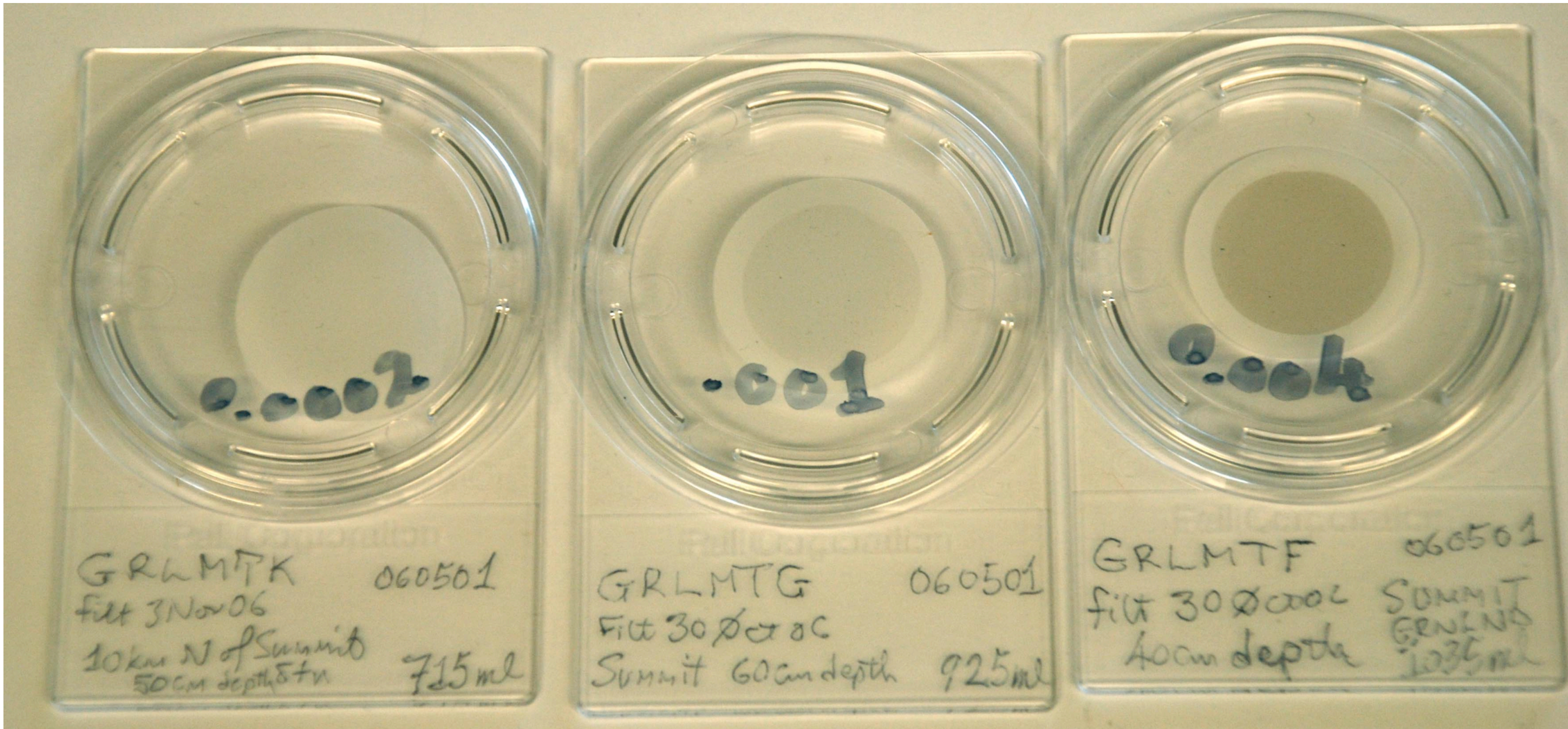


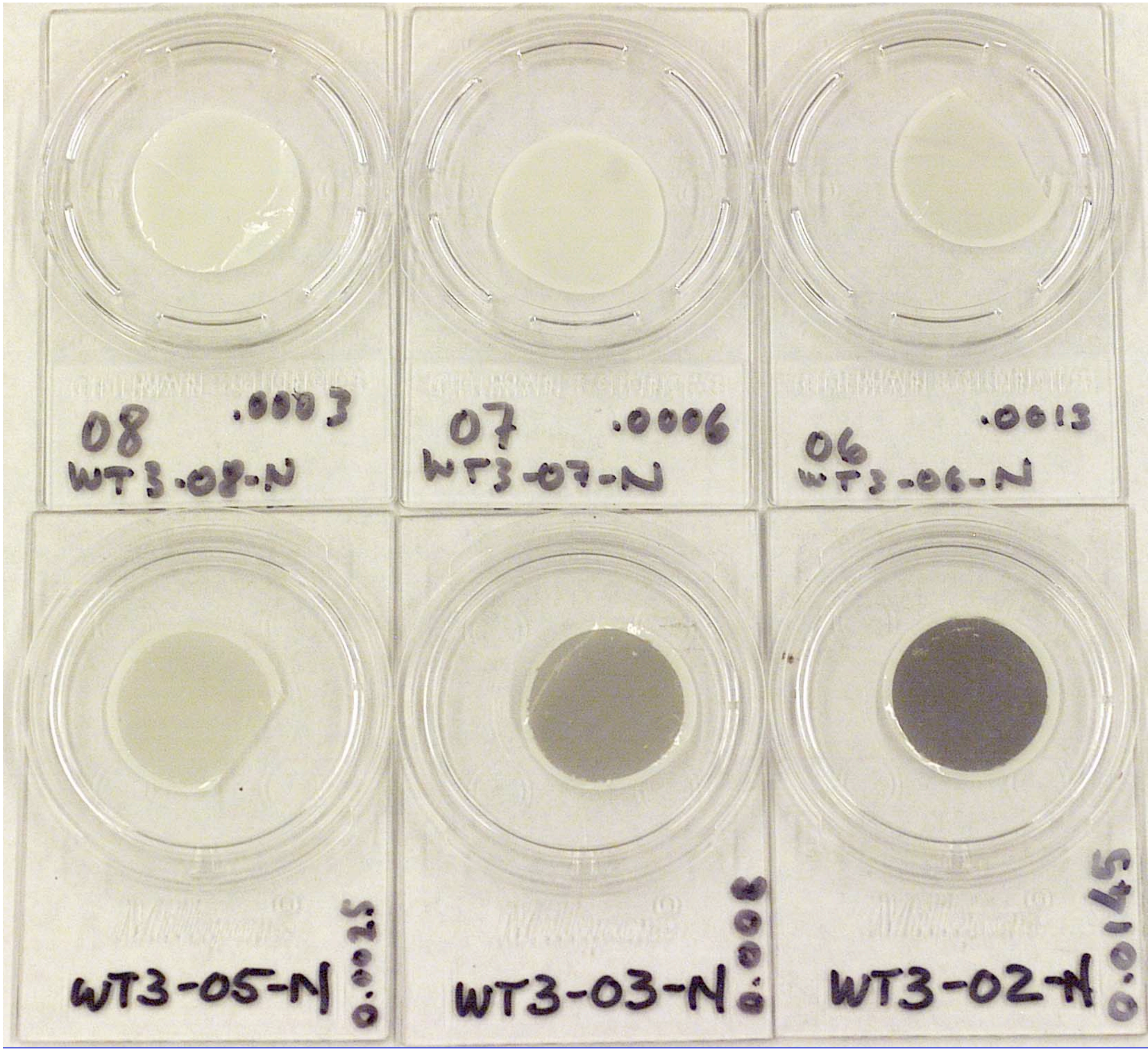
Fig. 1. Map of Arctic sampling locations for the University of Washington atmospheric (●) aircraft samples and snowpack (●) samples for 1983 and 1984.

1983

Most within 5-50 ppb

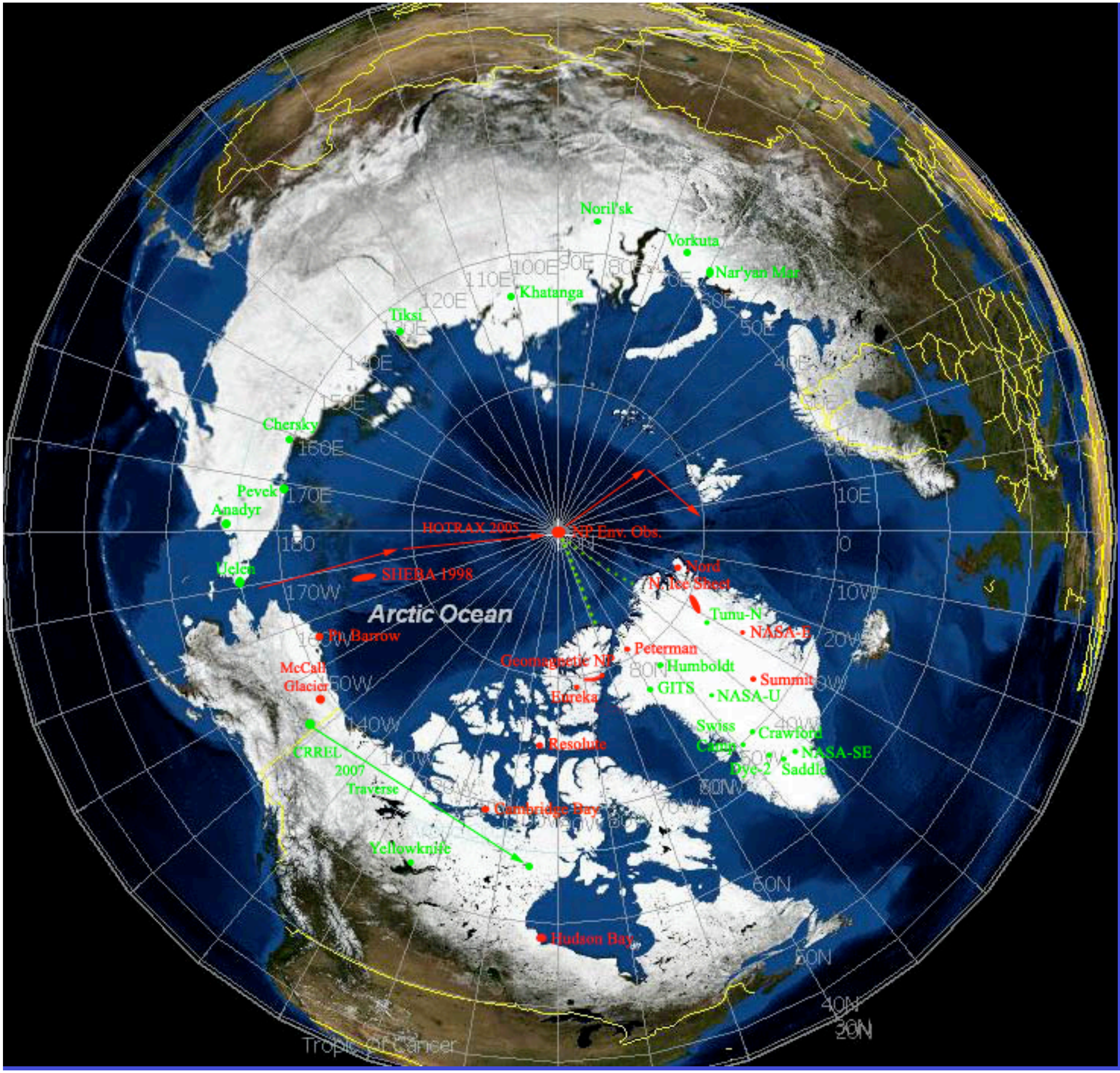

PARAFILM


.001
0.004
GRLMTK 060501
filt 3Nov06
715ml
GRLMTG 060501
Summit 60cm depth 925ml
GRLMTF 060501
SUMMIT
40cm depth



BC standards made by Tony Clarke

"Monarch -71 soot"



NSF project began 2006

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.