Sea ice thickness and freeboard as function of snow and ice properties

Some results of CryoVex 2003 and other field campaigns in the Fram Strait area

S. Sandven, K. Kloster, H. Sagen, V. Alexandrov (NERSC)

S. Gerland and R. Hall (NPI),

R. Forsberg (DNSC) and C. Haas (AWI)

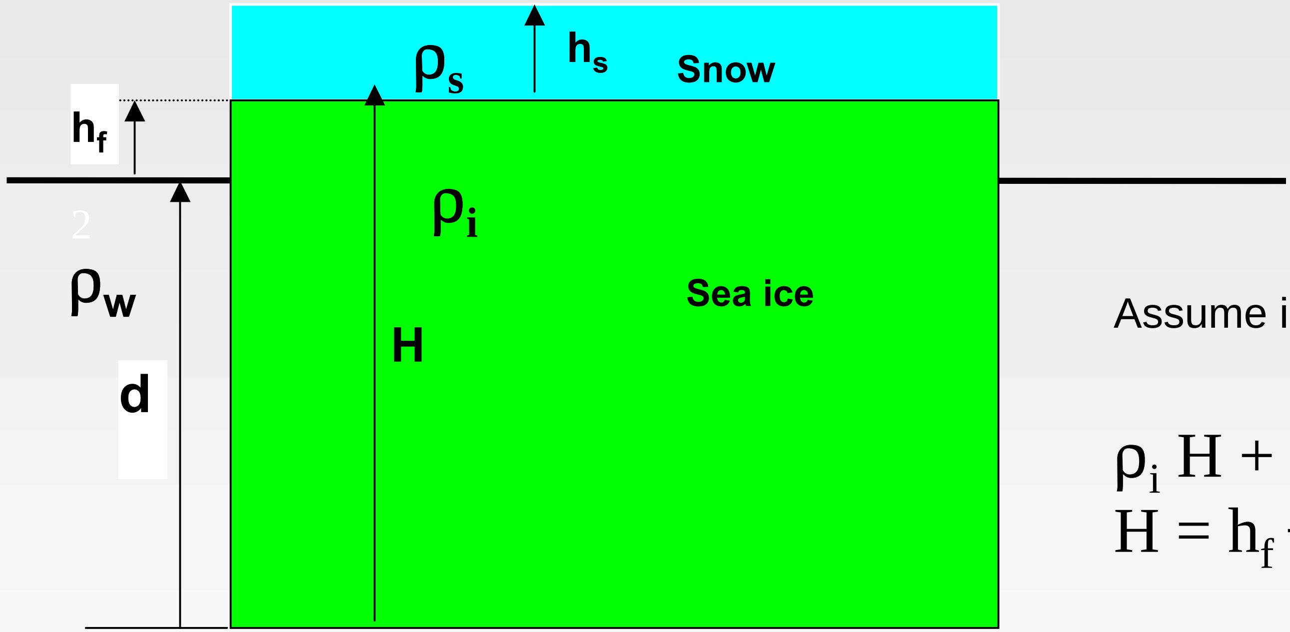
Background and motivation

The physical properties of snow and ice, which vary with season and region, have significant impact on the retrieval of ice thickness from freeboard measurements.

In the CryoVex field campaign in the Fram Strait area in April 2003, several types of snow and ice data were collected from aircraft, helicopter and in situ measurements

The mean and variance of snow and ice density need to be determined, using both new and previous in situ data.

Sea ice thickness (H), freeboard (h_i) and draft (d)



Assume isostatic equilibrium:

$$\rho_i H + \rho_s h_s = \rho_w d$$
$$H = h_f + d$$

Sea ice thickness can be retrieved from ice freeboard using the relation $H=(R+1)h_f$, where $R= \rho_m/(\rho_w-\rho_m)$, ρ_m is the mean density of the snow and ice layer

R = 9.1 assuming no snow (Rothrock)

R = 8.7 Beaufort Sea in Spring [Bourke, Paquette, 1989]

R = 7.8 Direct measurements of draft and freeboard (Wadhams)

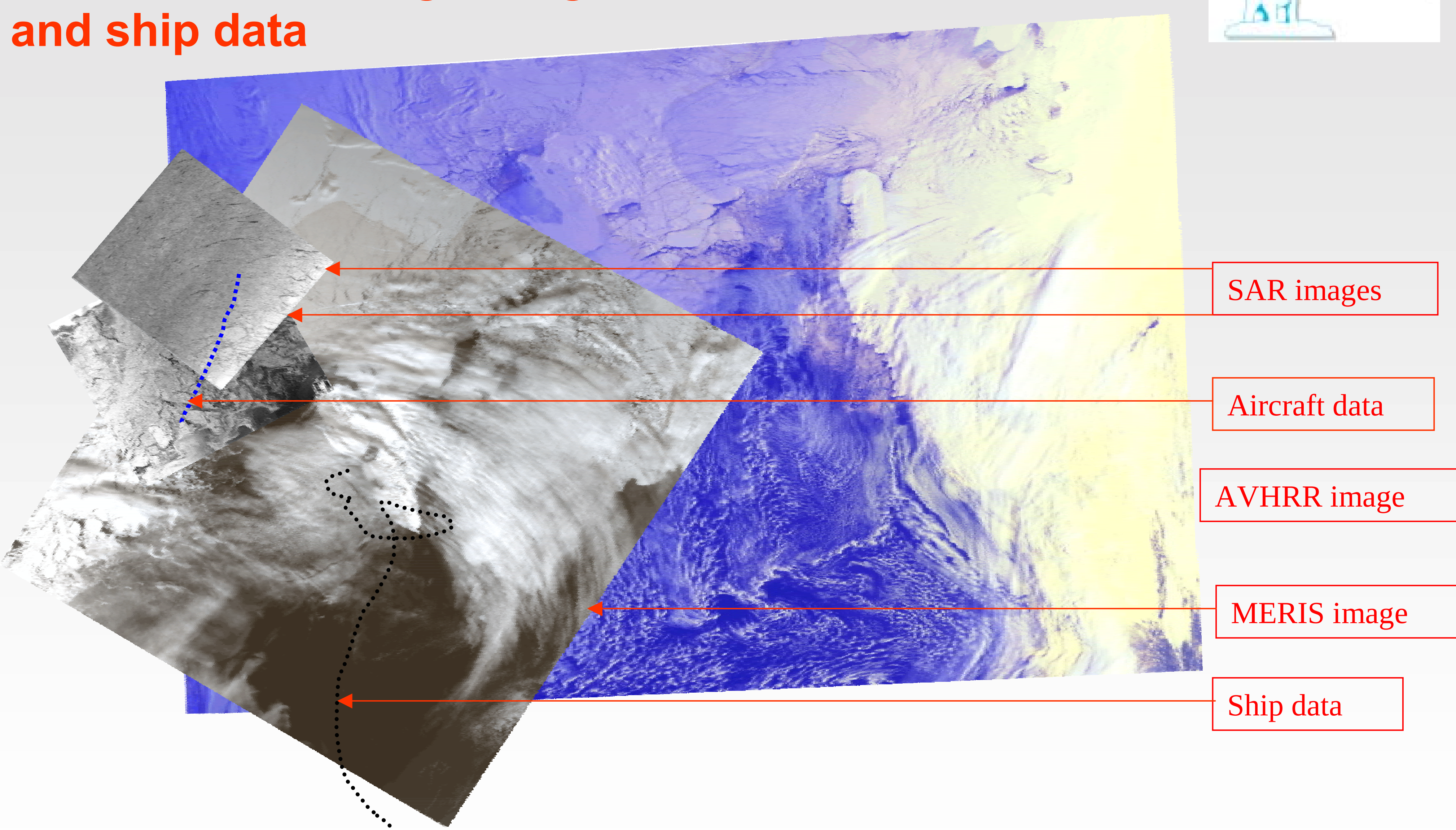
R is dependent on ice thickness

Validation parameters

Table 1

	Volumetric Measurements	Drill holes	Surveying	Scanning Laser	EM Sounding	Video Records
Platform	*In situ - ship*	*In situ - ship*	*In situ – sledge-ship*	*Aircraft*	*Helicopter - ship*	*Aircraft helicopter - ship*
Snow Density	X	X				
Snow Thickness		X				
Ice Density	X	X				
Freeboard		X	X	X	X	
Floe Surface Topography			X	X	X	
Ice Thickness		X			X	
Floe Size Distribution				X	X	X
	AWI, NERSC, NP	AWI, NERSC NP	AWI	KMS	AWI	KMS

Co-location of images, flight tracks and ship data



CRYOVEX experiment 2003

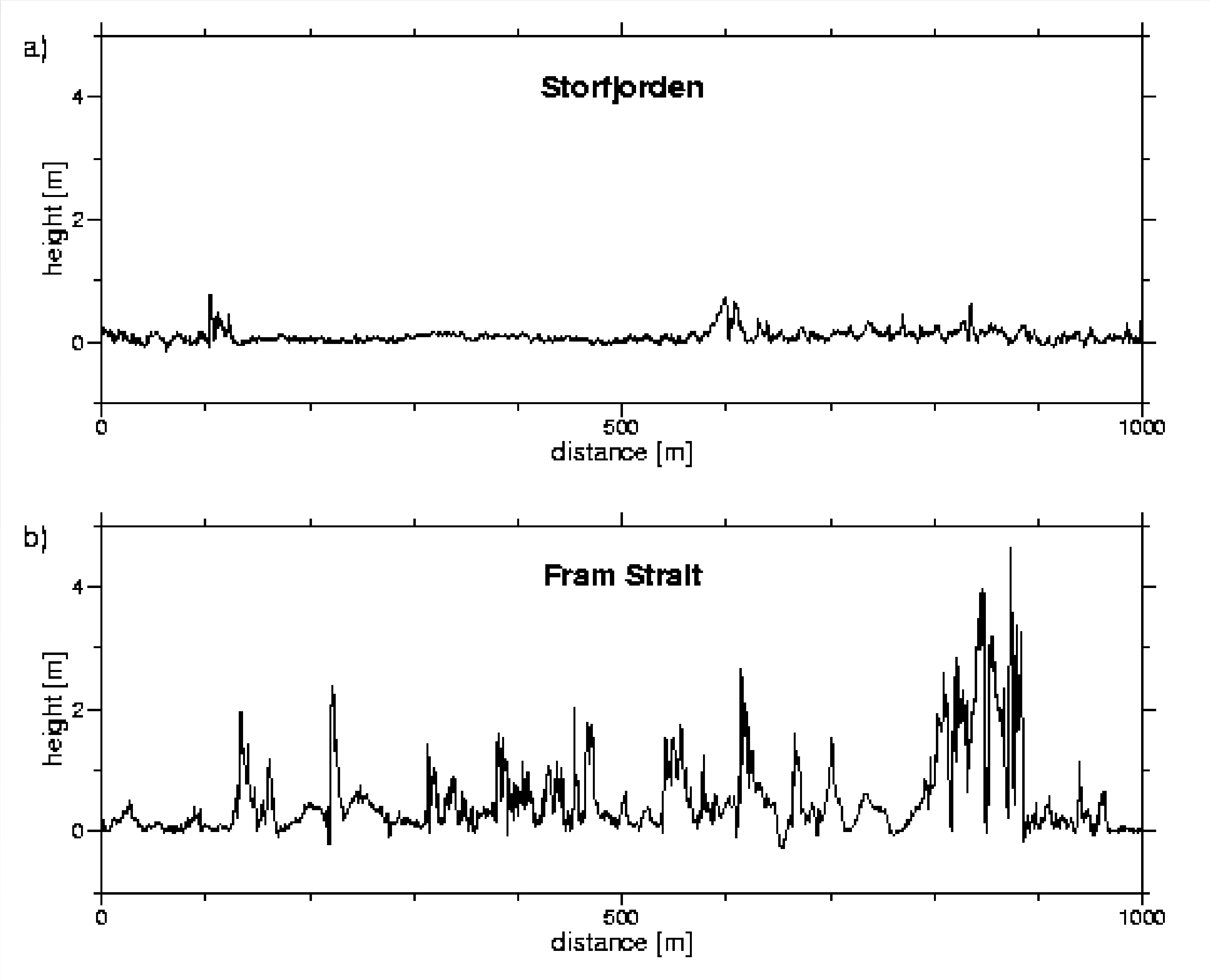
Twin Otter aircraft with laser scanner and D2P radar

R/V Polarstern with helicopter

Example of surface heigth profiles using the HEM system

Firstyear ice

Multiyear ice

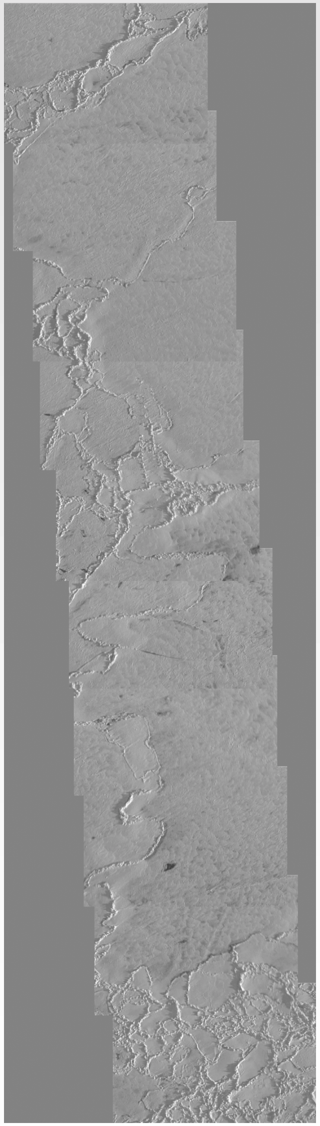


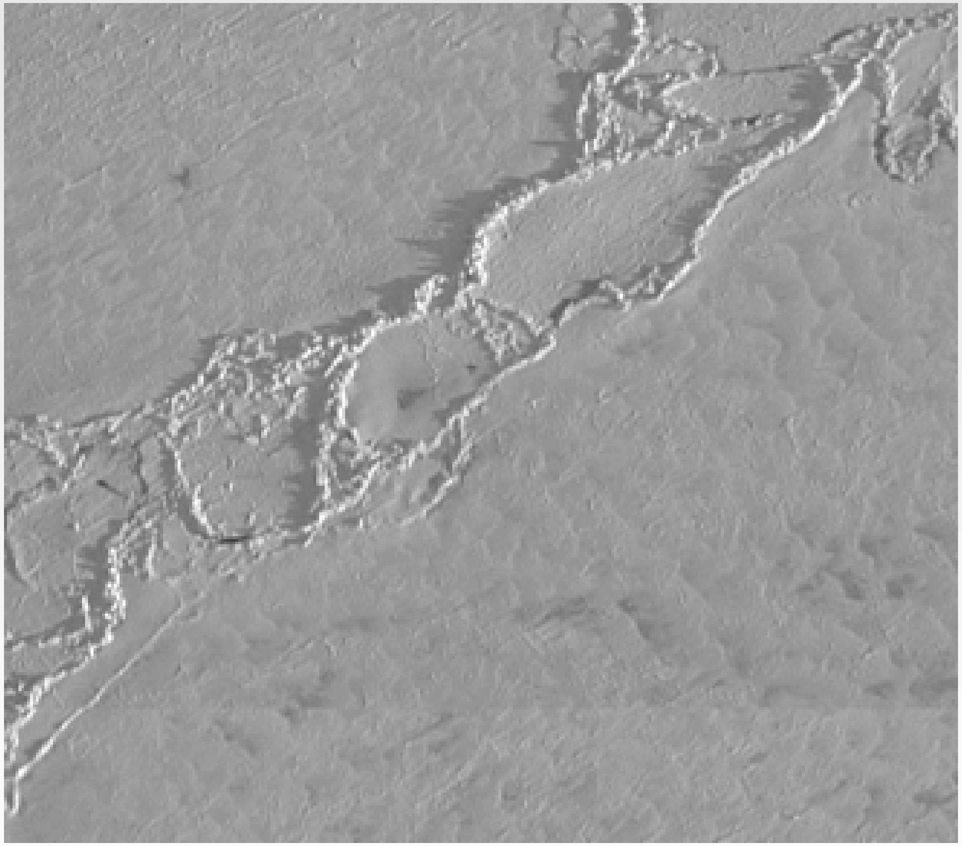
Courtesy: C. Haas

Vertical video of ice surface roughness

Scale: 1500 m x 300 m:

Roughly the CryoSat footprint

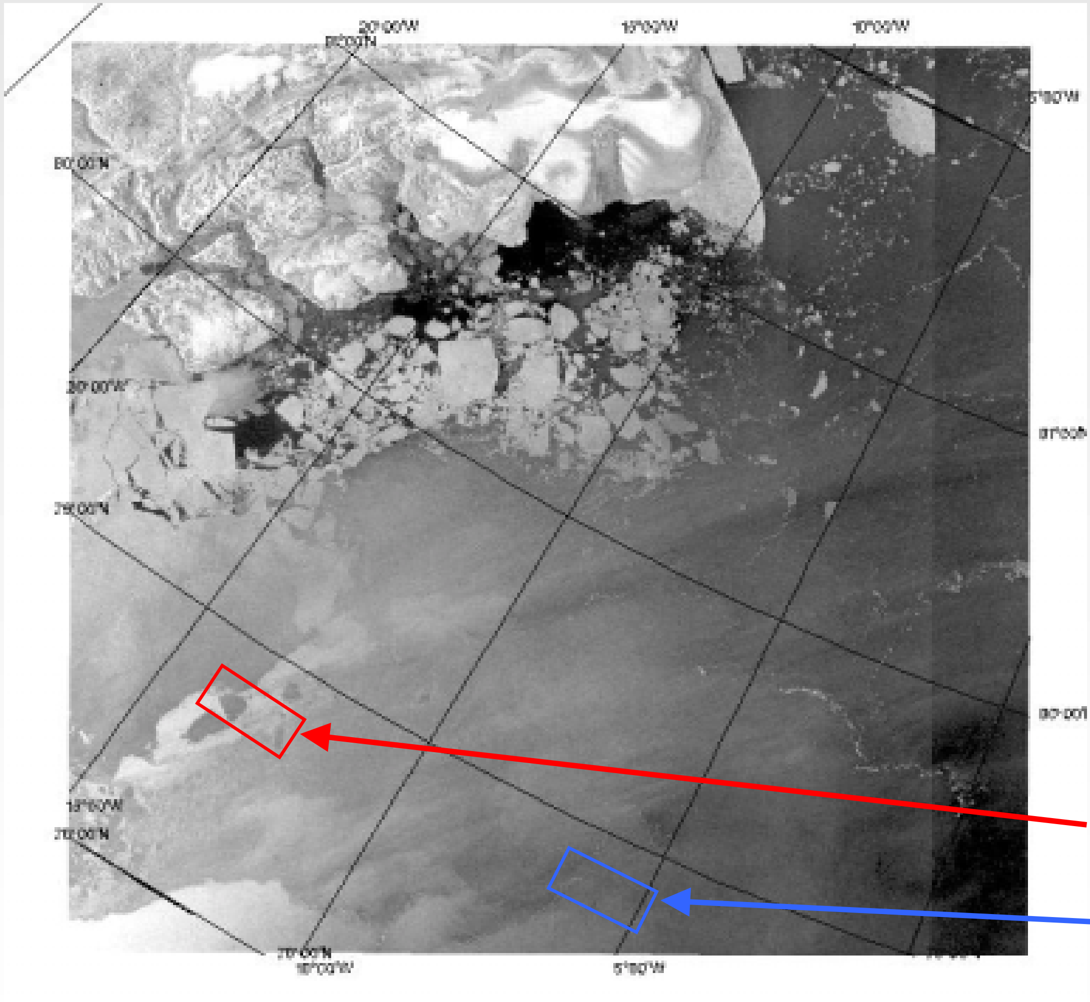




Scale: 300 x 300 m

Example from an area of firstyear ice

NPI *in situ* ice measurements, Fram Strait, September 2003 & 2004



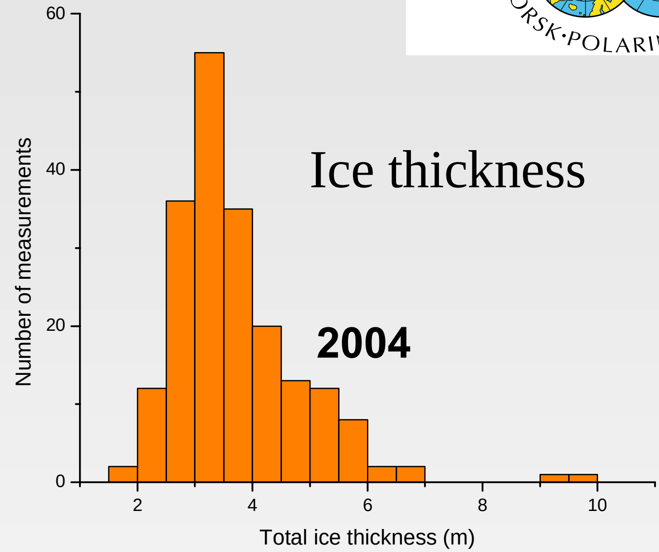
Main area for *in situ* ice work 2004

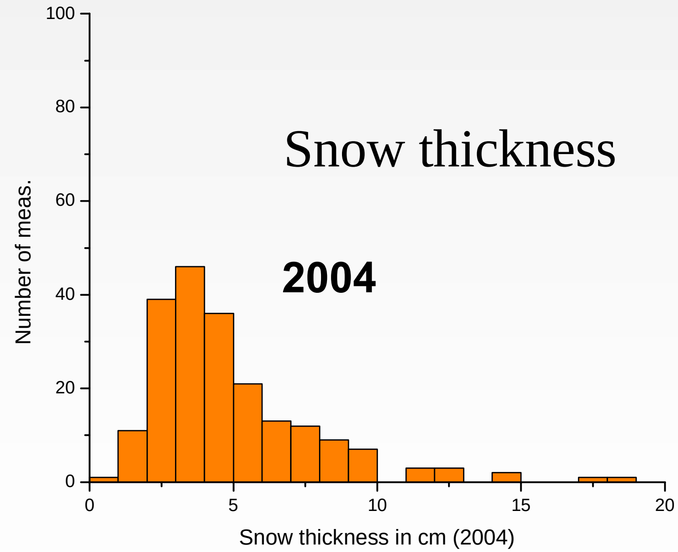
Main area for *in situ* ice work 2003

Photos: H. Goodwin and S. Gerland, NPI

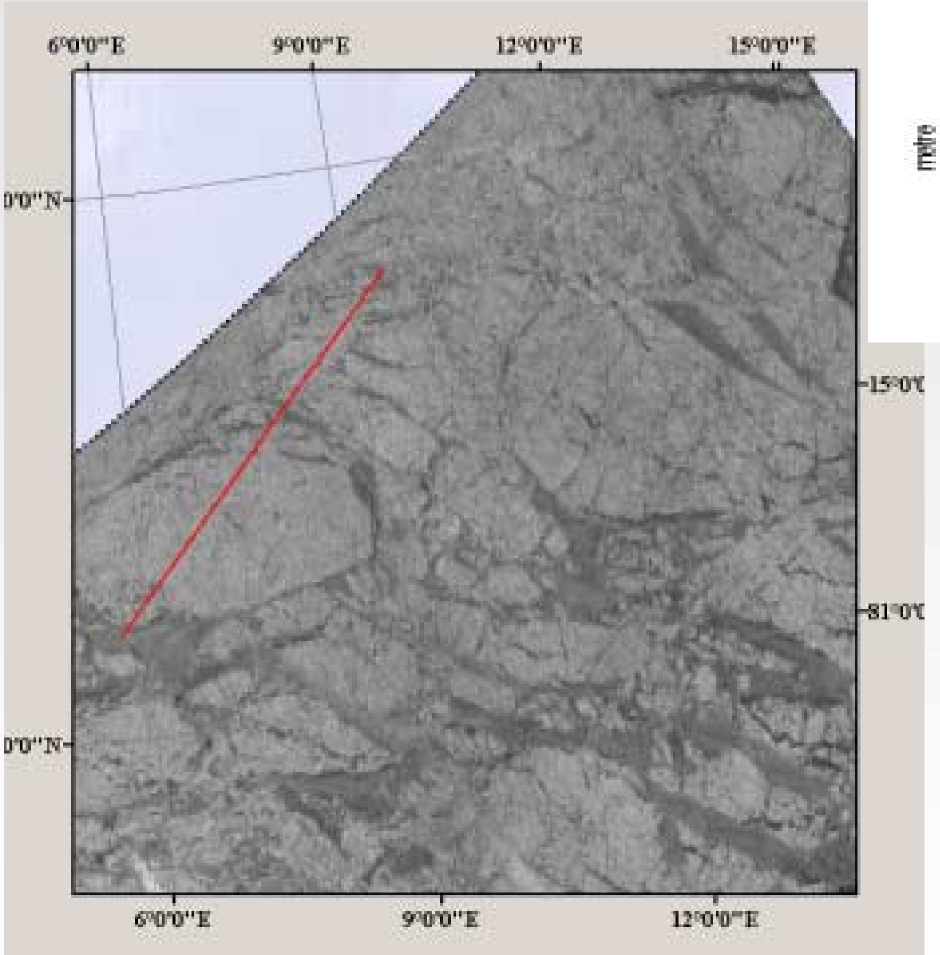
NORSK·POLARINSTITUTT

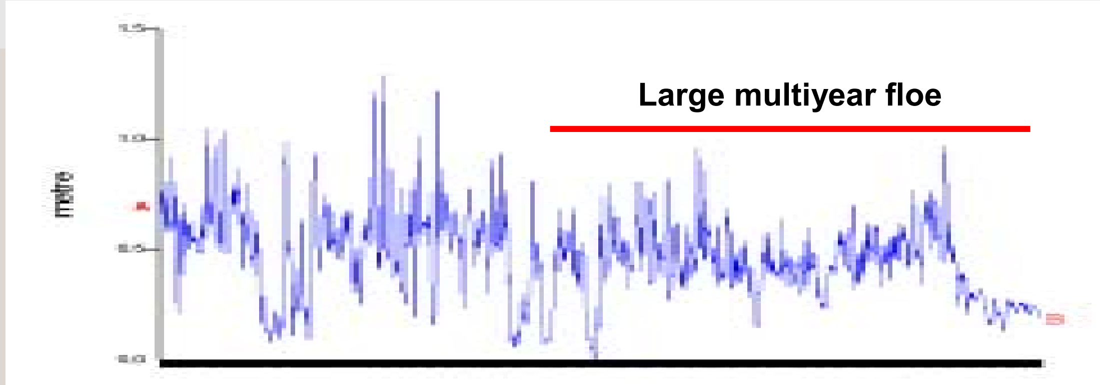
- **Parameters measured:** Snow and ice thickness (drillings and electromagnetics), freeboard, draft, snow density, snow grain size, snow classification
- **Snow density** was 390 kg m^{-3} on average (2004)
- **Ice crusts** at the snow surface were observed
- *In situ* measurements will be continued, they can be used in CryoSat CalVal issues, and they support NPI's longterm monitoring of ice draft (upward looking sonar) in the Fram Strait
- See also workshop poster "Combined sea ice thickness investigation …" by S.Gerland, R.Hall, E. Hansen & T.B. Løyning

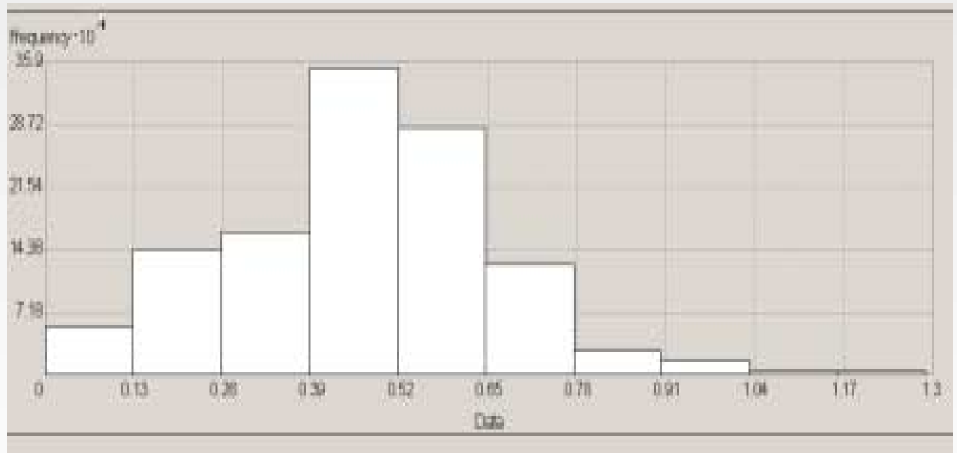




Laser profile colocated with SAR image on 11 April

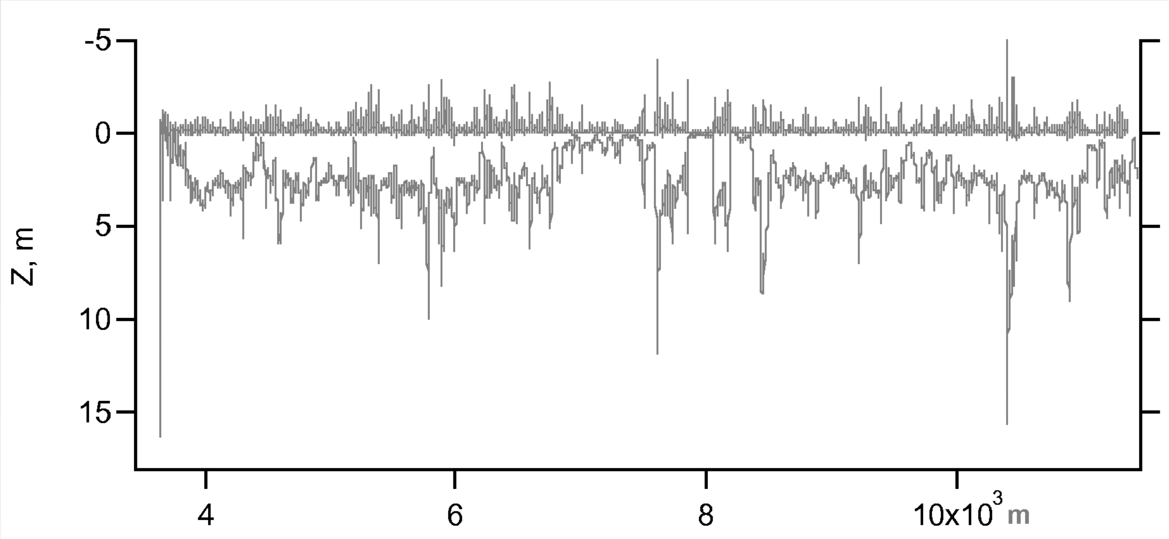






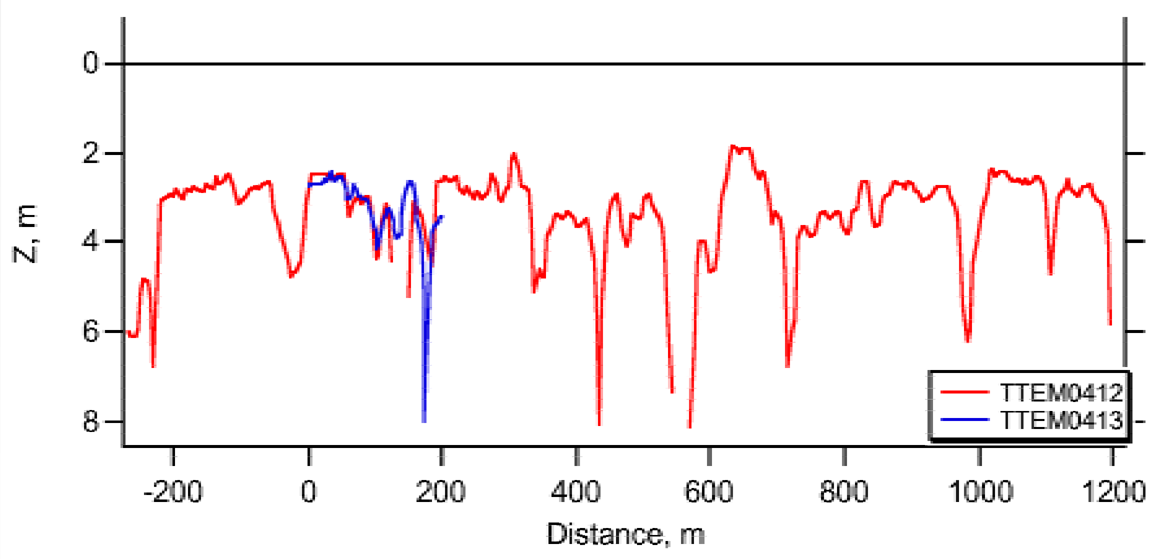
Average freeboard = 0.55 m

HEM data and sledge EM data from 11 April



Surface topography from helicopter laser: 40 km

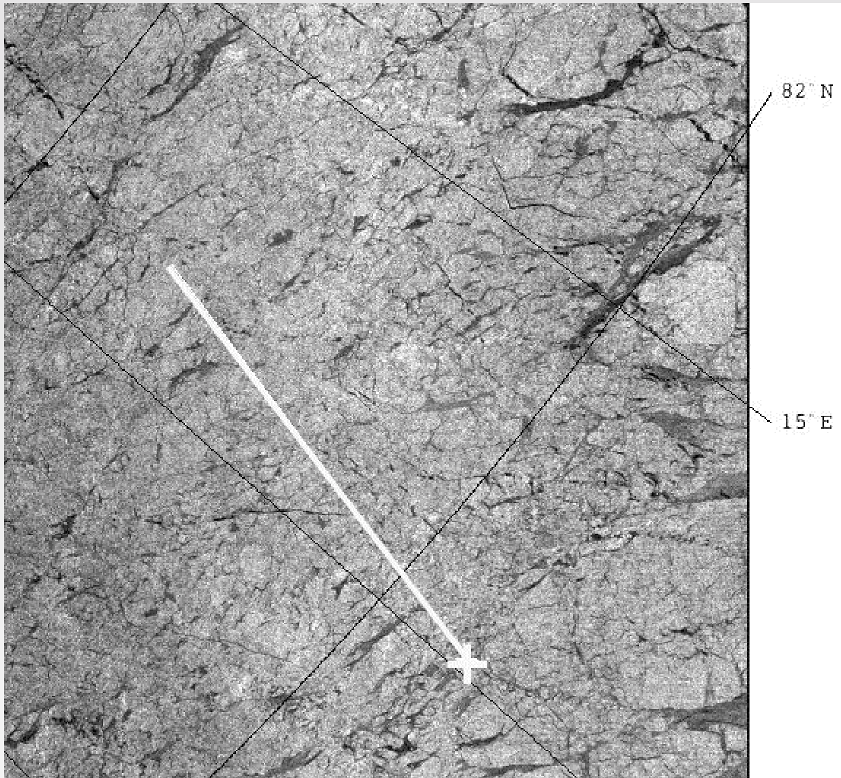
Ice draft from helicopter EM



Ice draft from HEM compared with sledge EM data: 1.4 km

Courtesy: C. Haas

D2P + Laser profile on 15 April

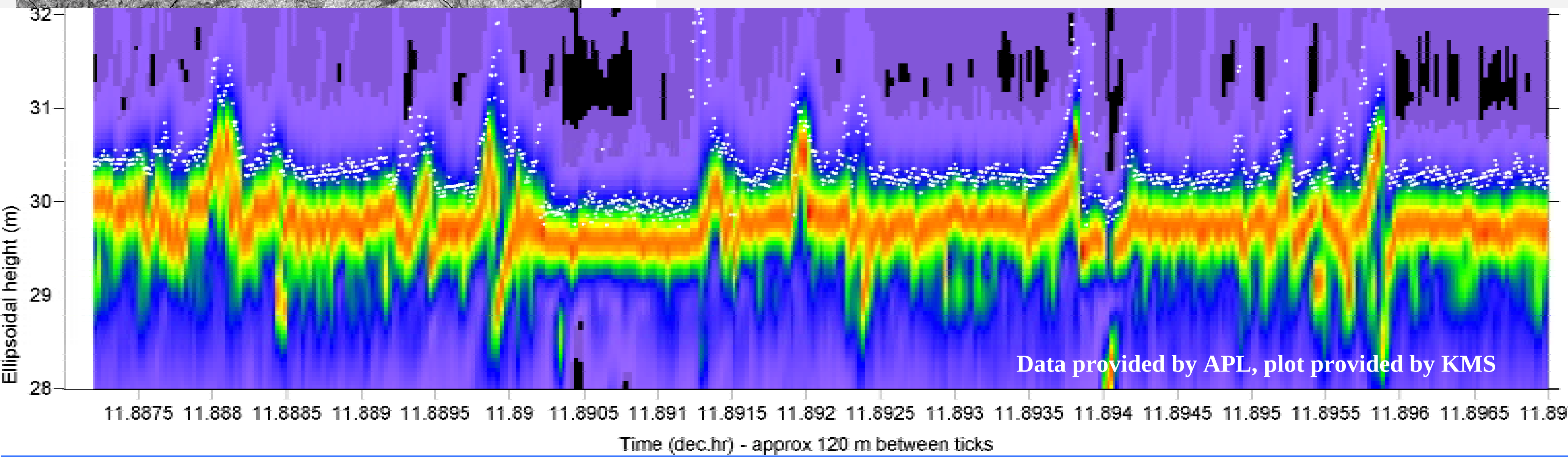


Whole flight line north of Polarstern: 100 km

Example of radar and laser profile: 2.4 km

D2P radar amplitude: colour scale (ice surface)

Laser profile: white dots (snow surface)



How much effect can snow have on ice freeboard ?

Russian studies (i.e Mironov, 1995, Romanov, 1995, Warren et al., 1999) over several decades give information on the seasonal and regional variability.

For ice thickness H ≈ 2 m, the freeboard is typically 20 - 30 cm, depending on snow cover and density

Effective freeboard and thickness are defined to take into account of the show cover:

$h_{ef} = h_f + \rho_s h_s / \rho_I$ $\qquad$ $H_{ef} = h_{ef} + d$

Snow cover can add up to 17 cm for MY ice and 10 cm for FY ice in effective freeboard

Monthly snow data for MY ice and the effect on freeboard

Month	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July
Snow depth (cm) Loschilov 1964	5	11	18	21	24	26	29	31	36	38	34	2
Snow depth (cm) Warren et al. 1999	3	11	19	23	25	27	30	32	34	34	30	6
Snow density (gcm^{-3})	0.10	0.18	0.22	0.25	0.29	0.29	0.31	0.32	0.32	0.31	0.34	0.40
Ice freeboard due to snow (cm)	-0.50	-1.90	-3.90	-5.10	-6.80	-7.40	-8.80	-9.70	-11.30	-11.60	-11.30	-0.80

For the mpnth of April the following regional variabilities are found (Romanov, 1995):

Region	Snow depth (cm), average	Snow depth (cm), interannual variability	Freeboard due to snow (cm), average	Freeboard due to snow(cm), interannual variability
Central Arctic	36	10	-11.3	-3.1
Greenland 1	30	20	-9.4	-6.3
Greenland 2	60	30	-18.8	-9.4
Canadian Arctic 1	20	10	-6.3	-3.1
Canadian Arctic 2	30	10	-9.4	-3.1

Example of calculated thickness from nominal snow, ice and freeboard data

Assumed freeboard (ice only) : 0. 30 m

Snow depth = 35 cm (from Romanov)

Snow density = 360 kg/m^3

Water density = 1028 kg/m3

Result: Hi = 3.1 m for ρ_ι=887 kg/m^3

Sensitivity to snow layer:

$\underline{+}$ 0.10 cm in snow thickness leads to $\underline{+}$ 0.26 cm in ice thickness

In situ snow/ice data from CRYOVEX (1)

One MY floe NW of Polarstern (Long Ice Station)

Freeboard (snow+ice) = 0.5 m (from aircraft data

Ice density = 0.920 (typical MY meltponds)

and 0.8335 (observed)

Date	Time	Latitude	Longitude	Snow depth (cm)	Snow load (Kg/m2)	Hi F=0.5; ρi=0.920	Hi F=0.5; ρi=0.8335
07.04	15.00	81.54	09.35	18	68	3.36	
07.04	15.00	81.54	09.35	22	87	3.18	
08.04	15.00	81.54	09.35	25	96	2.99	
08.04	15.00	81.54	09.35	30	97	2.56	
10.04	10.00	81.49	09.31	10	33	3.76	
12.04	11.00	81.49	09.31	35	129	2.4	
12.04	11.00	81.49	09.31	22	81	3.13	
12.04	16.00	81.49	09.31	20	88	3.36	
14.04	10.00	81.49	09.31	14	53	3.59	
14.04	14.00	81.49	09.31	07	18	3.90	
14.04	17.00	81.49	09.31	45	154	1.74	
15.04	17.00	81.47	10.16	13	53	3.67	
15.04	17.00	81.47	10.16	22	60	2.95	
17.04	11.00	81.45	09.55	10	31	3.75	
17.04	11.00	81.45	09.55	30	123	2.78	
Average				**22**	**78**	**3.10**	**1.88**

Calculated and observed ice thickness

Calculated thickness:

1. Freeboard (snow + ice) for MY ice from the long laser profile on 11 April: 0. 55m

Snow depth = 22 cm

Snow load = 78 kg/m2, giving snow density of 360 kg/m^3

Water density = 1028 kg/m3

Result: Hi = 3.5 m for ρ_{ι}=910 kg/m^3 and 2.2 m for ρ_{ι} = 836 kg/m^3

2. Freeboard (snow + ice) for MY ice from the dense survey around Polarstern: 0.65 m $\pm$ 0.2 m

Similar calculation gives Hi = 4.4 m for ρ_{ι}=910 kg/m^3 and 2.7 m for ρ_{ι} = 836 kg/m^3

Observed thickness: 2.06 $\pm$ 0.17 m from EM profiles

Snow depth statistics for MY ice in the Cryovex area

Snow property	Minimum	Average	Maximum	CryoVex obs
Depth (Level ice)	25 cm	35 cm	45 cm	22±14 cm 11±8 cm
Depth (Ridges)	40 cm	100 cm	150 cm	No obs
Snow tongues (height-length)	45 cm / 15 m	70 cm / 30 m	100 cm / 45 m	No obs
Sastrugi snow depth & area (%)	40 cm & 40 %	55 cm & 50 %	60 cm & 70 %	No obs
Ice thickness	150 cm	240 cm	300 cm	206 cm
FY ice area (%)	15 %	40 %	70 %	< 15 %

From Romanov 1995

Sensitivity of ice thickness retrieval to ice density

MY with hummocks

MY observed in CRYOVEX

Frequently used value (Eicken 1995):

0.88 ± 0.02

MY with meltponds

Ice density	0.78	0.80	0.82	0.84	0.86	0.88	0.90	0.92	0.94
Hi (m)	1.48	1.60	1.76	1.95	2.18	2.47	2.86	3.39	4.16

Kg/m^3 x 10^3

Questions:

1. Is there any trend in the amount of MY ice with hummocks ?
2. Will there be more MY ice with refrozen meltponds due to more summer melt ?

Conclusions

1. We need to establish better statistics on snow and ice density for various ice regions in the Arctic -> establish retrieval errors
2. If global warming continues in the Arctic, the snow and ice properties will change and statistics based on old data may become biased
3. New in situ measurements are needed across the Arctic Ocean: I.e. International Polar Year