Snow, climate and ecosystems

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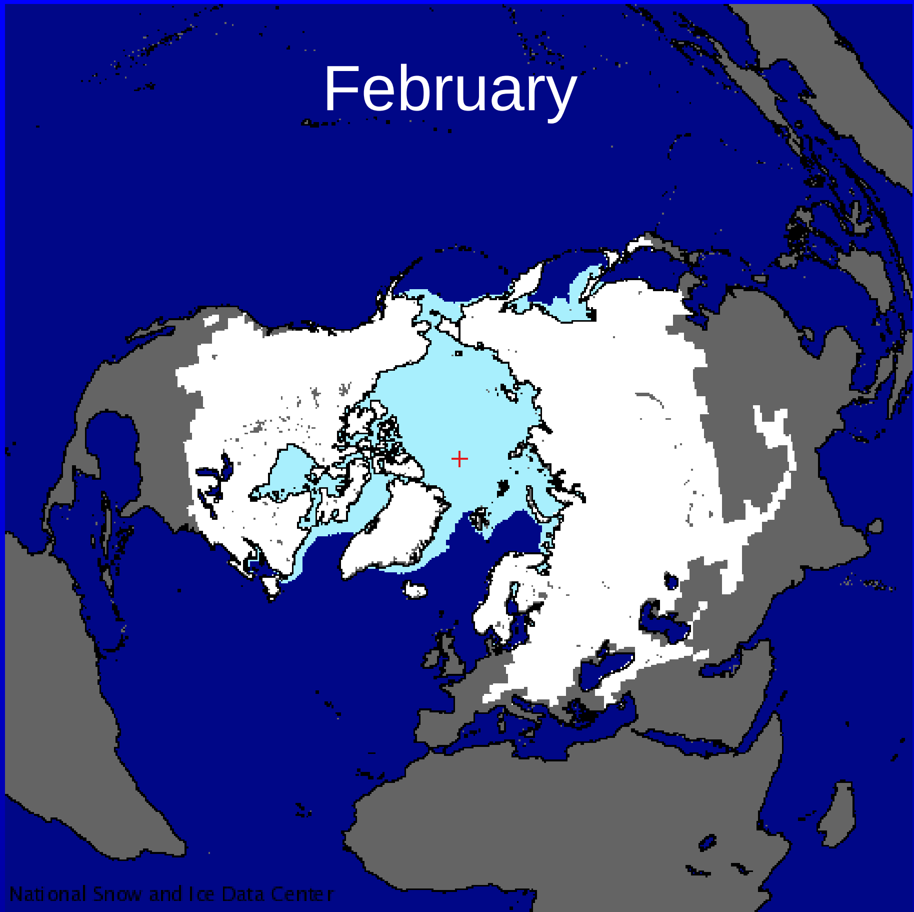
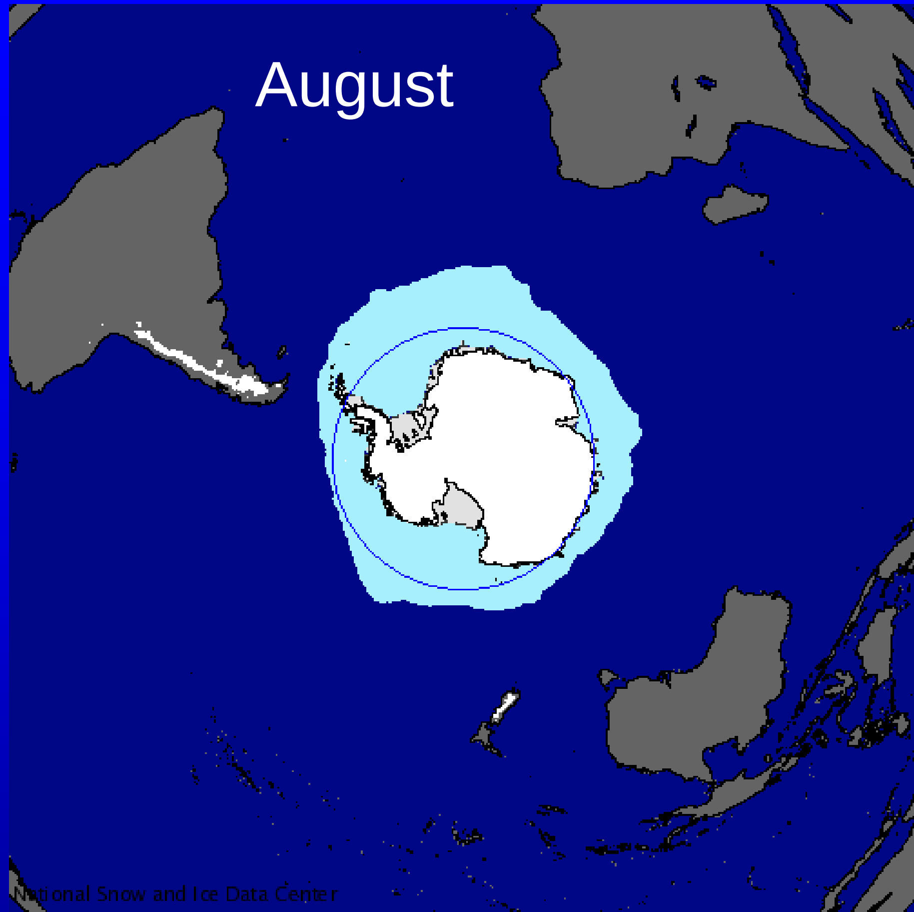


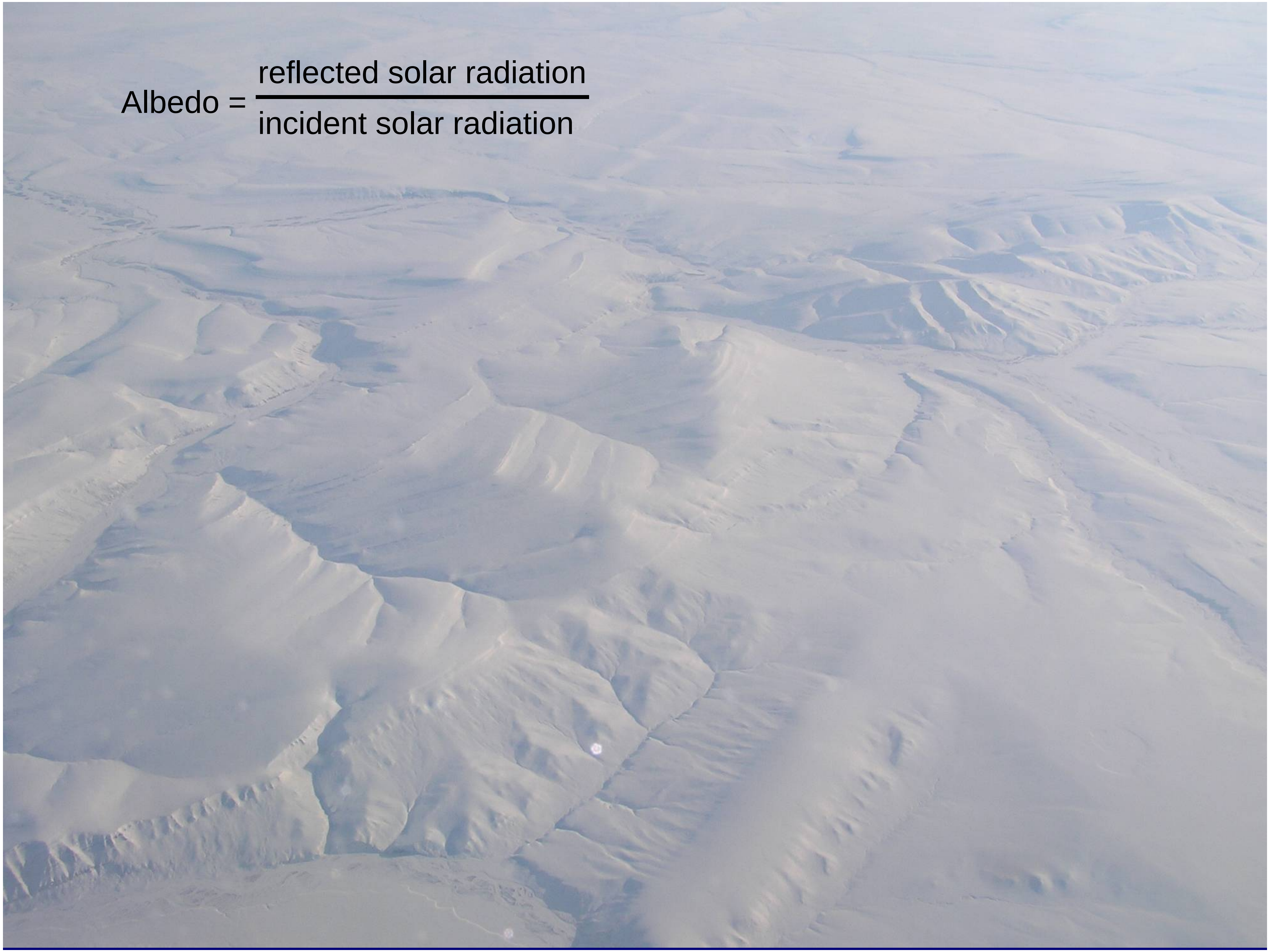


North Hemisphere : 254 10^6 km^2
Continents : ≈ 100 10^6 km^2
Continental snow cover, February : 42 10^6 km^2

Earth, February : snow covers 14% of the Earth surface

1 – Snow affects the albedo of the surface

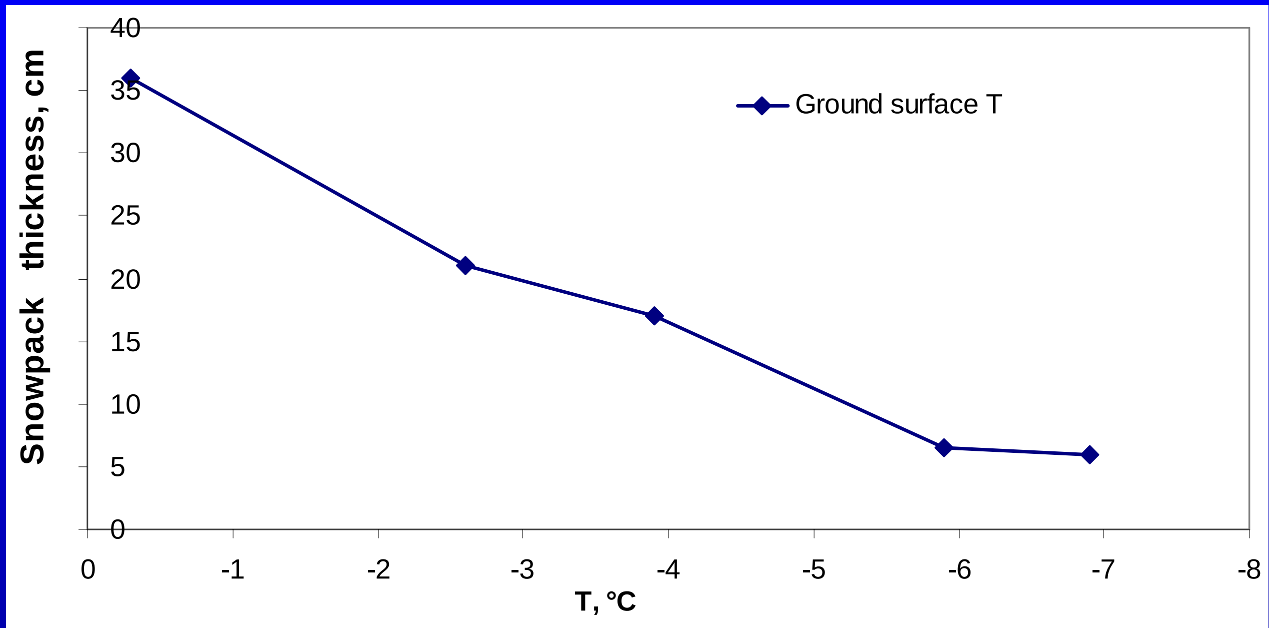
$$\text{Albedo} = \frac{\text{reflected solar radiation}}{\text{incident solar radiation}}$$

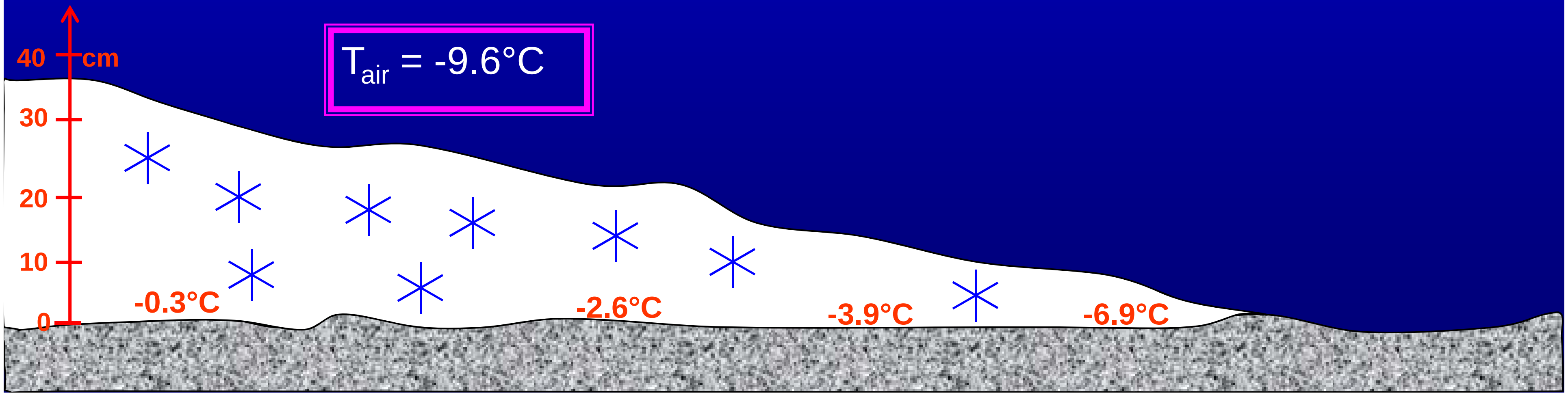


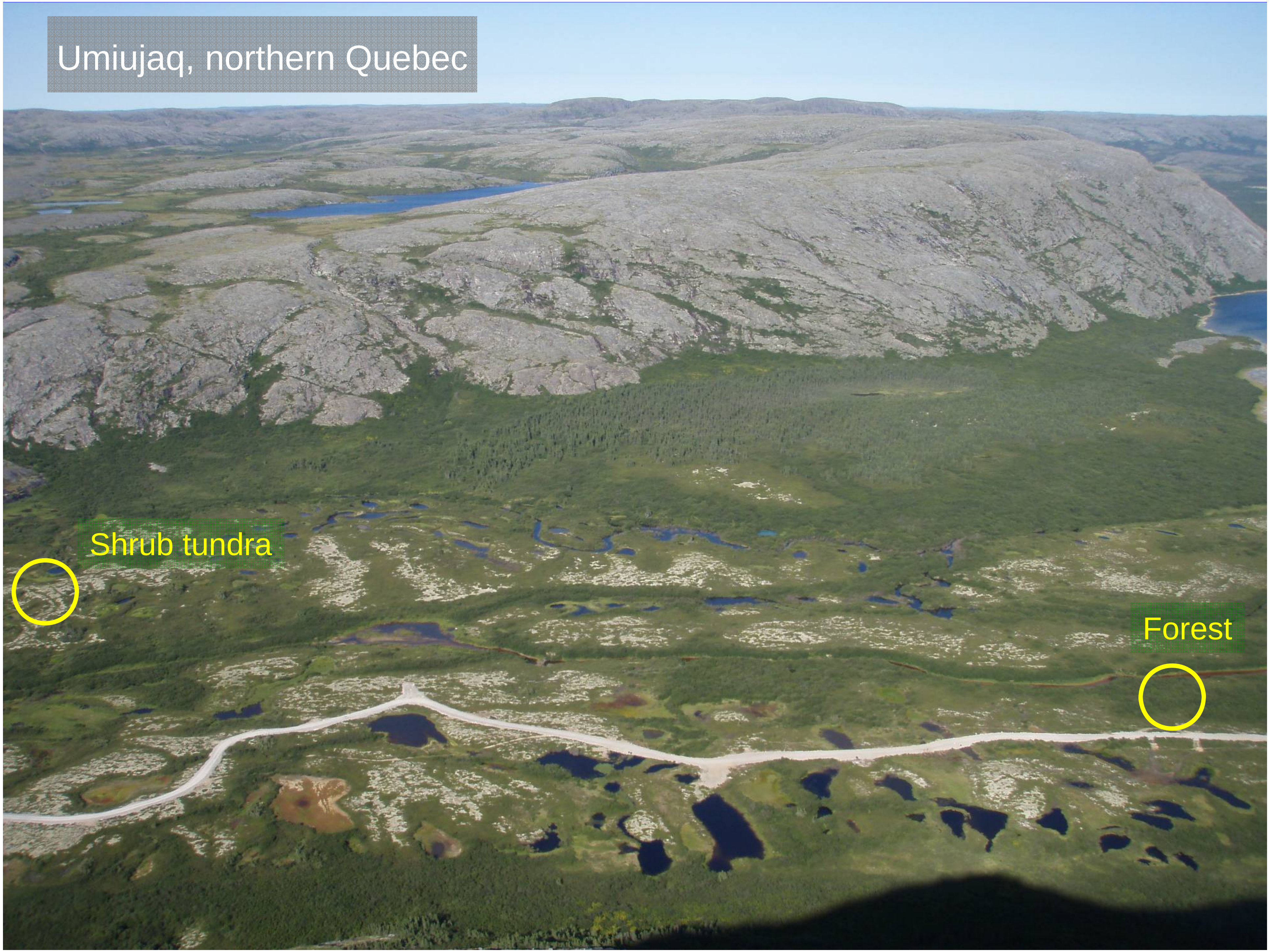
2 – Snow affects the temperature of the underlying soil

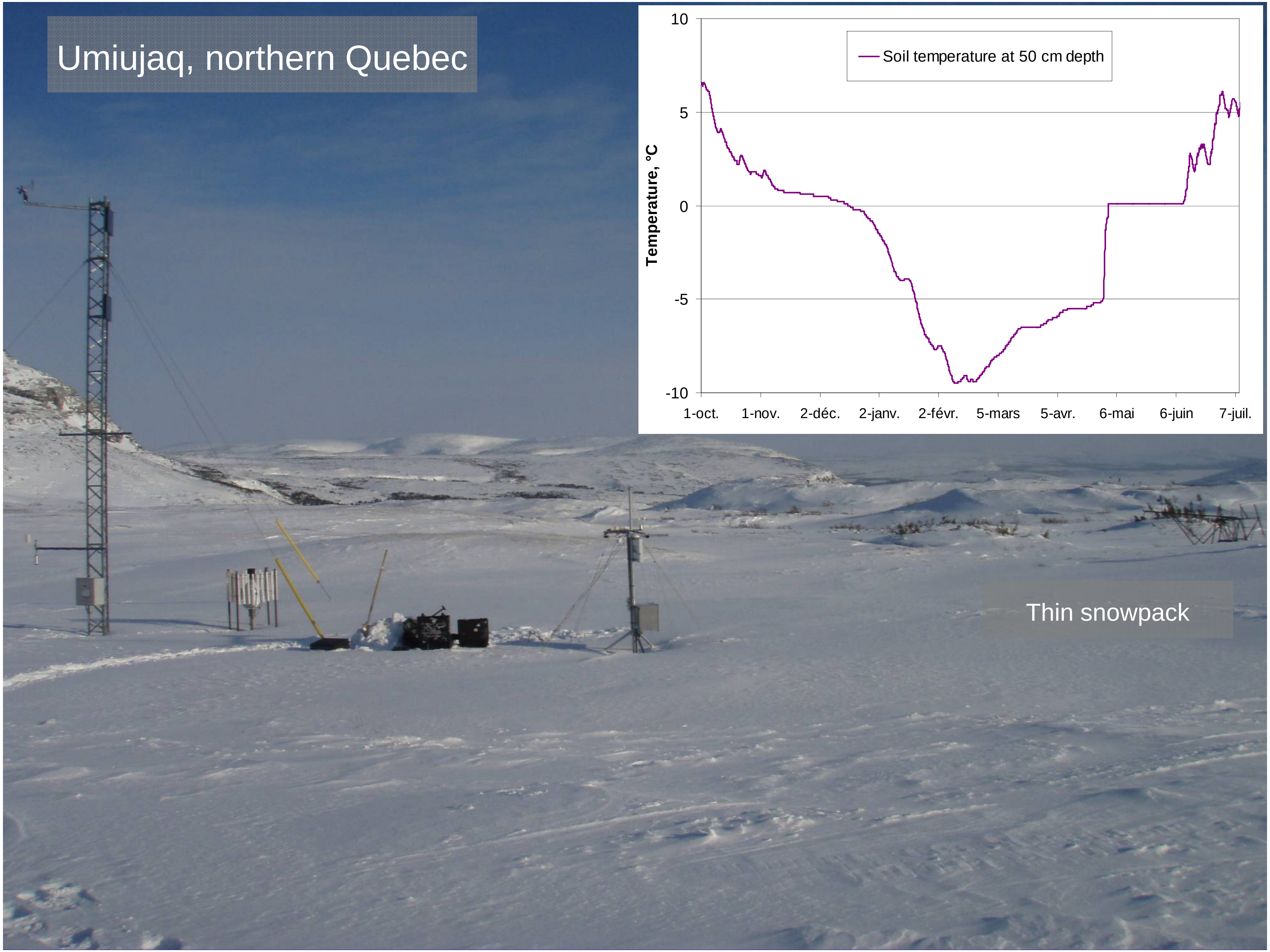
Soil temperature is not a simple function of air temperature

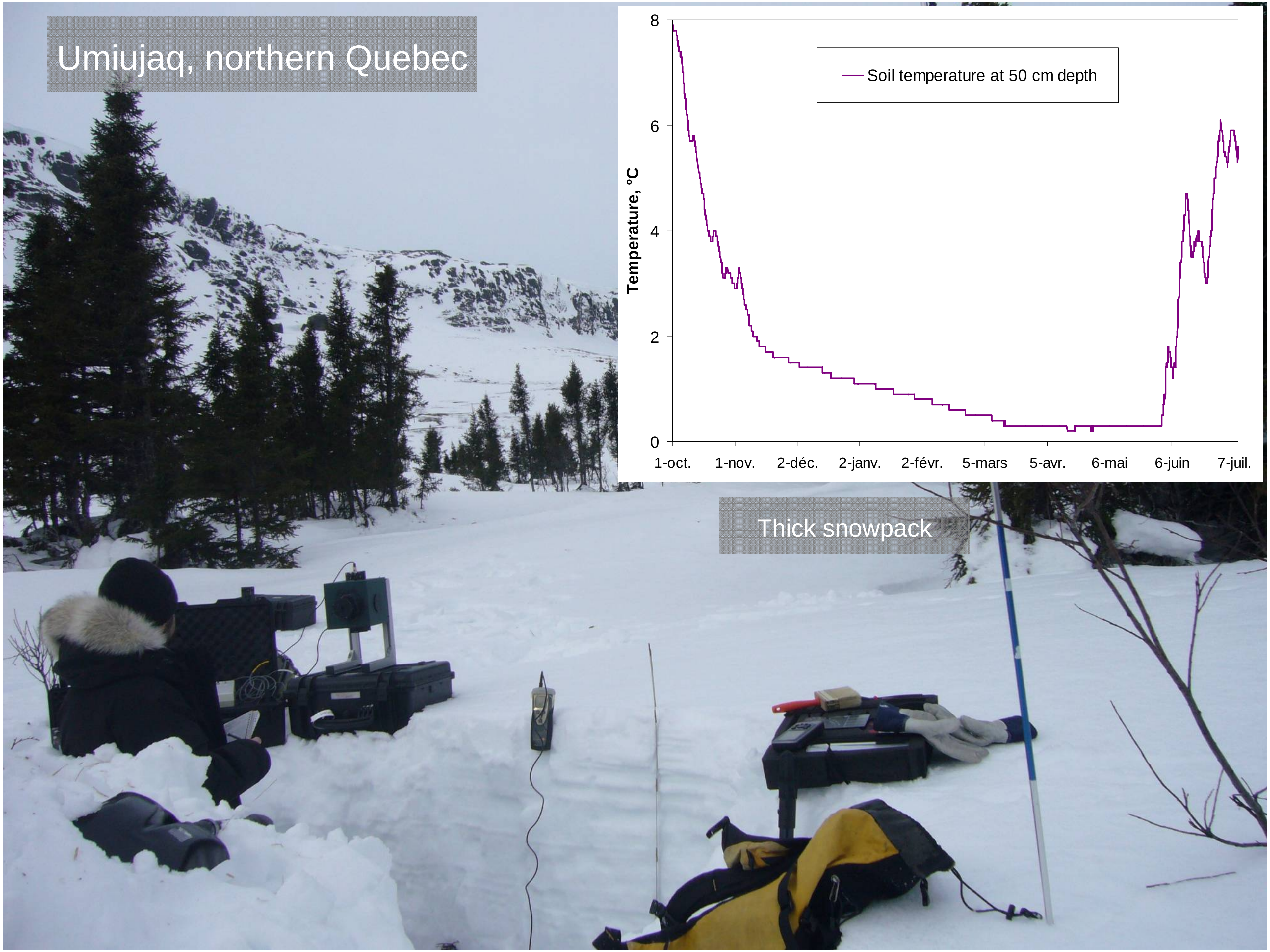
Lautaret pass, Alps, 2100 m, 21 March 2008



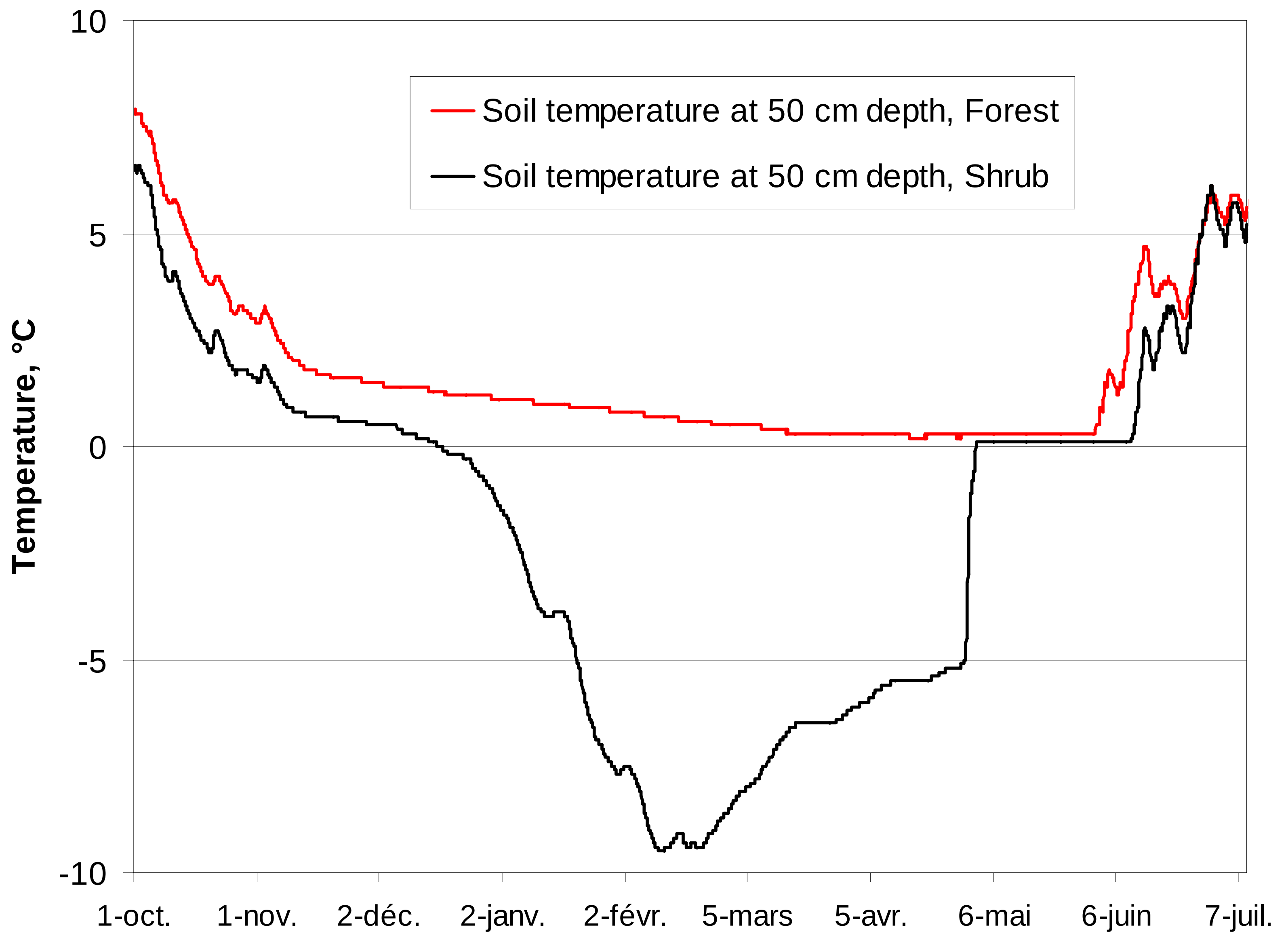



Umiujaq, northern Quebec
Shrub tundra
Forest


Umiujaq, northern Quebec
Soil temperature at 50 cm depth
Temperature, °C
10
5
0
-5
-10
1-oct.
1-nov.
2-déc.
2-janv.
2-févr.
5-mars
5-avr.
6-mai
6-juin
7-juil.
Thin snowpack



Umiujaq, northern Quebec
Soil temperature at 50 cm depth
Temperature, °C
0
2
4
6
8
1-oct.
1-nov.
2-déc.
2-janv.
2-févr.
5-mars
5-avr.
6-mai
6-juin
7-juil.
Thick snowpack

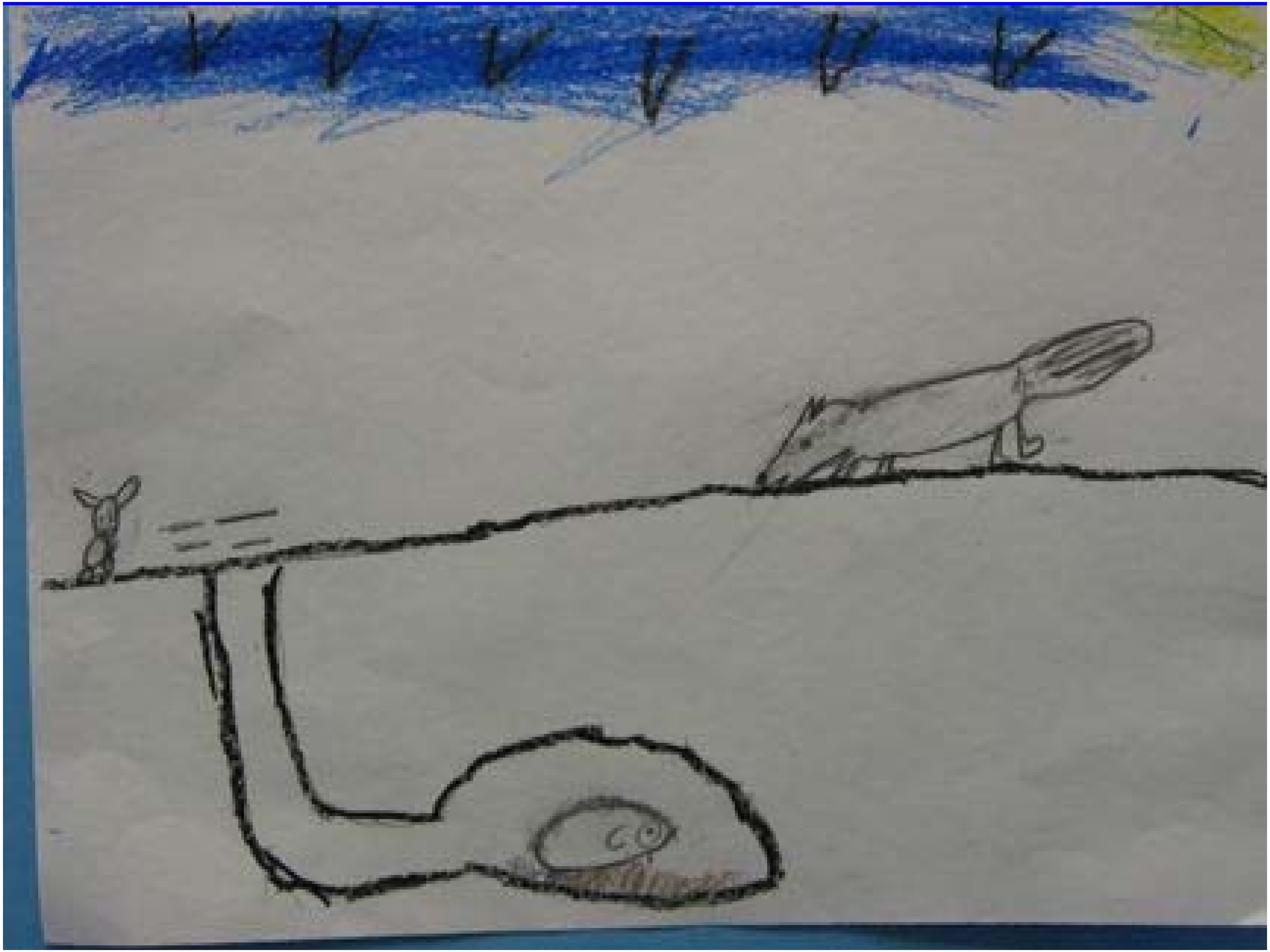


Snow prevents ground freezing

Impact on nutrient cycling and carbon accumulation

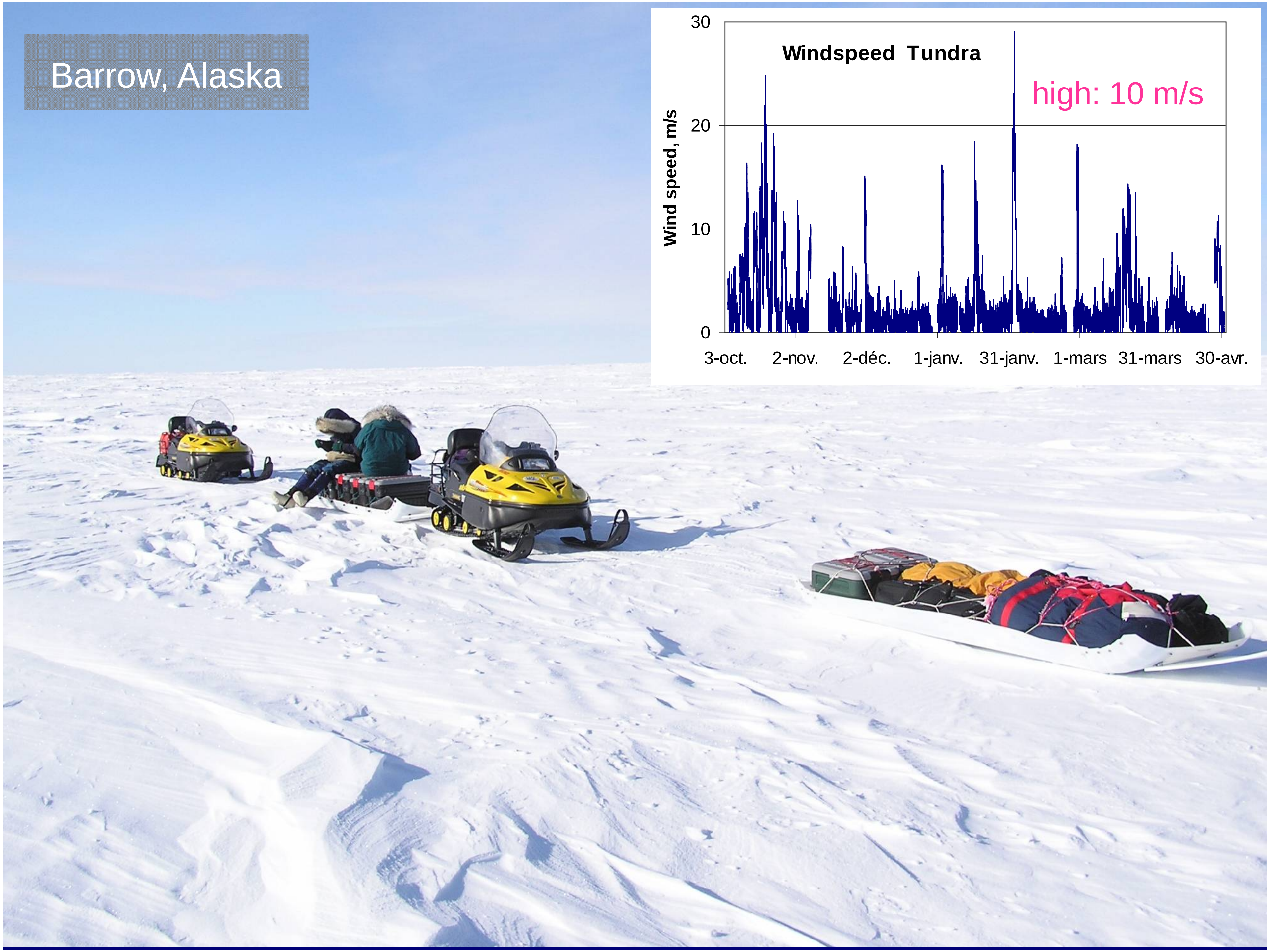
3 – Snow affects wildlife

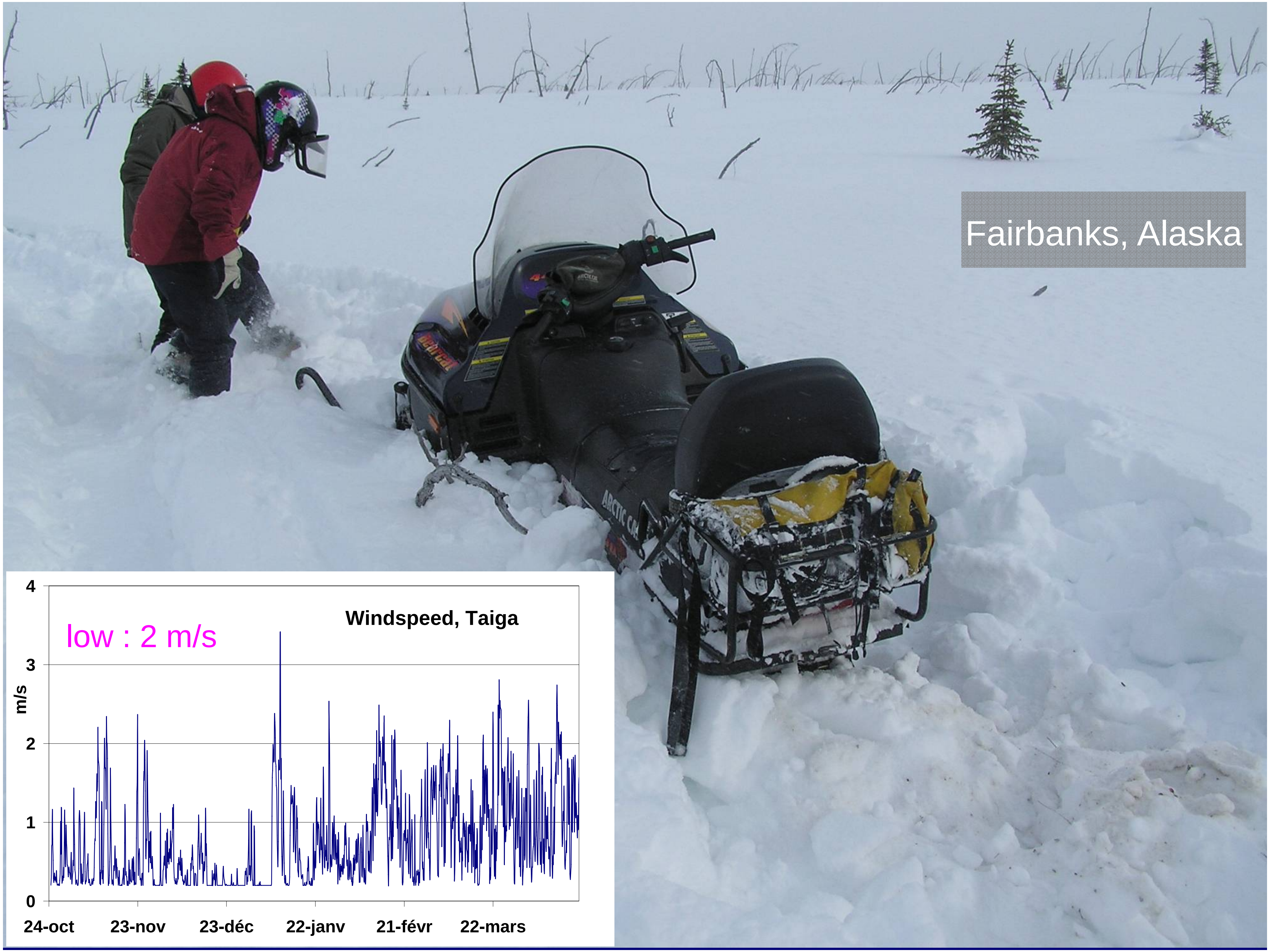
Snow and wildlife




© Bruce G. Marcot

4 – Climate affects snow

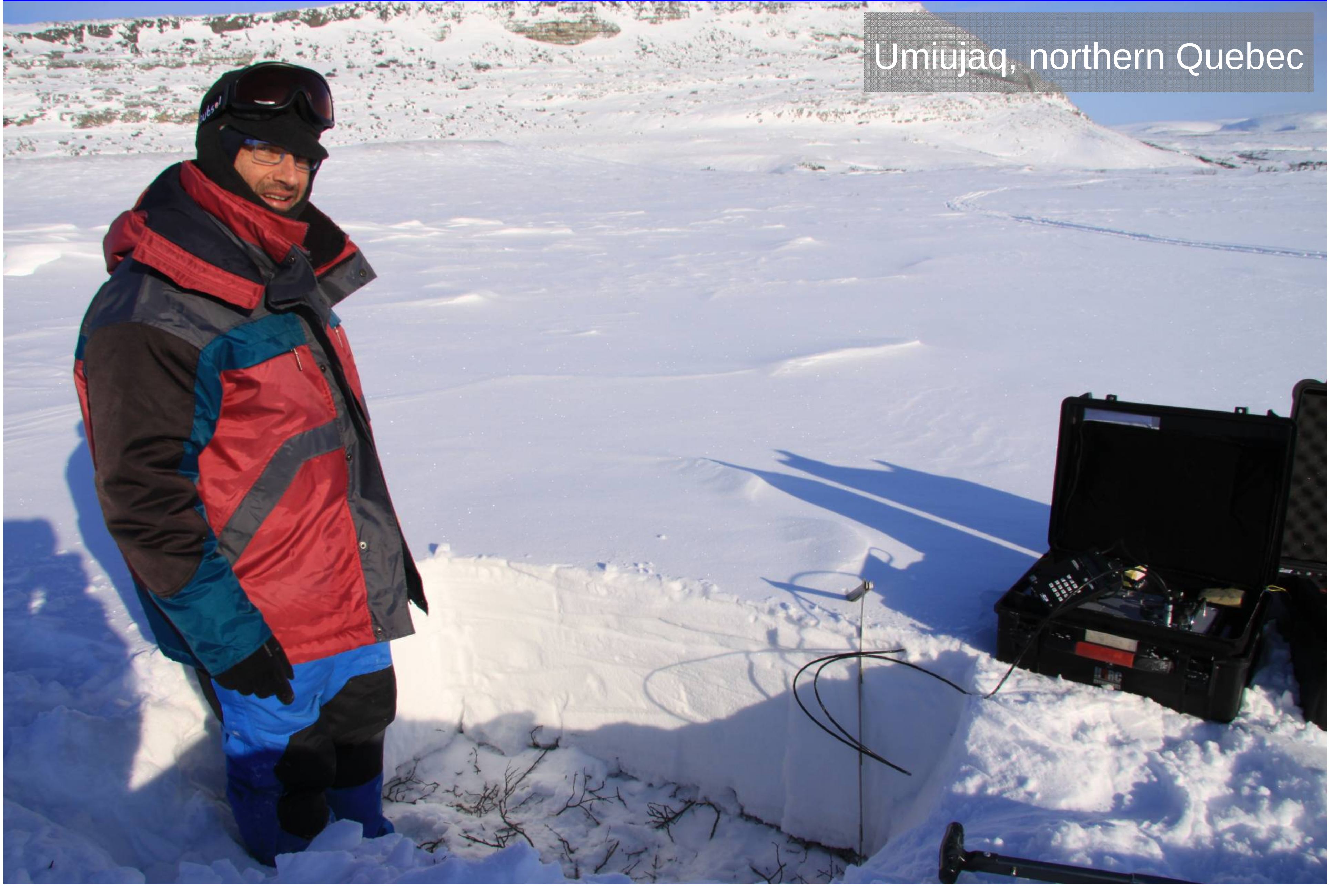

Barrow, Alaska
Windspeed Tundra
high: 10 m/s
Wind speed, m/s
30
20
10
0
3-oct.
2-nov.
2-déc.
1-janv.
31-janv.
1-mars
31-mars
30-avr.



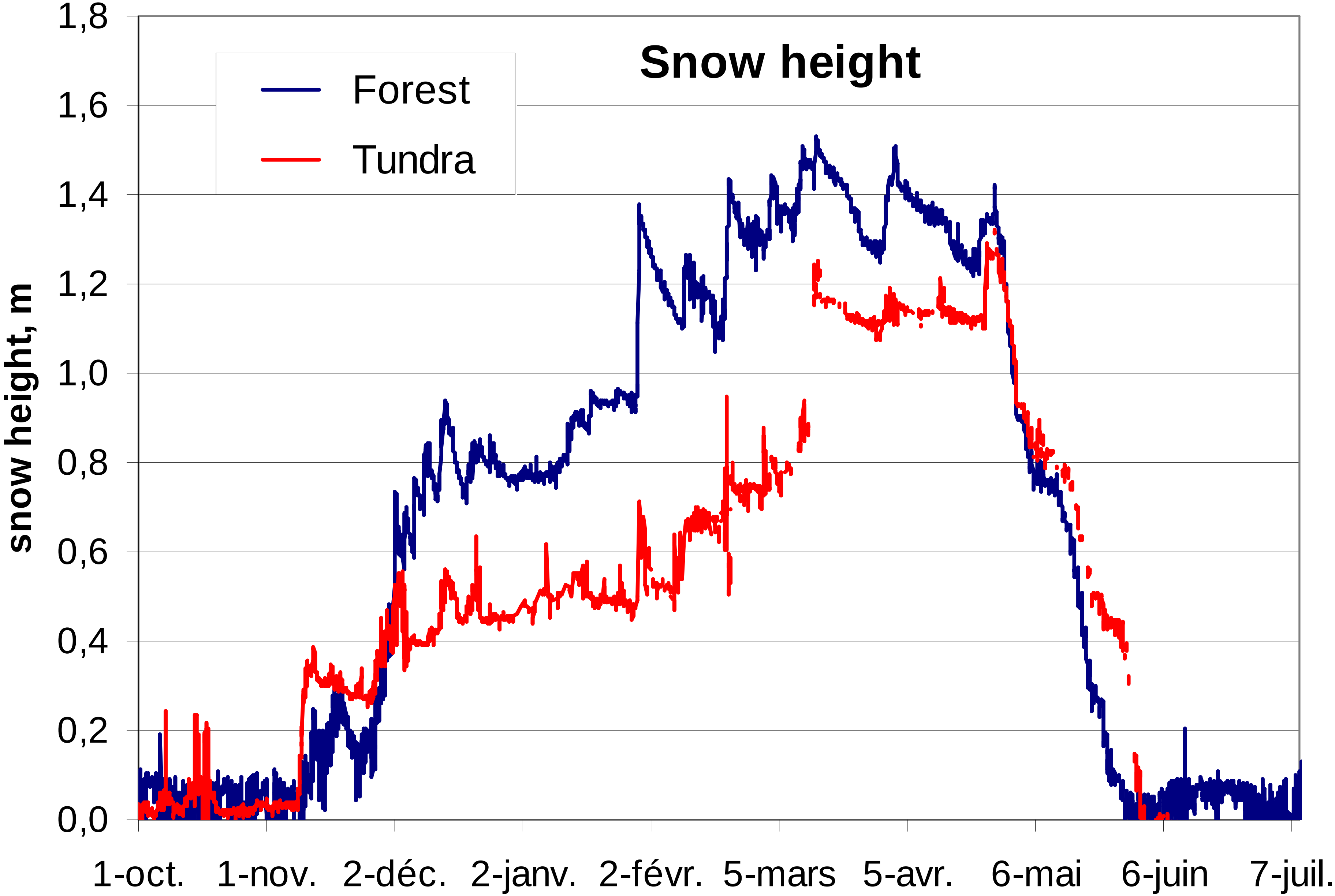
Fairbanks, Alaska
Windspeed, Taiga
low : 2 m/s
m/s
0
1
2
3
4
24-oct
23-nov
23-déc
22-janv
21-févr
22-mars

5 – Vegetation affects snow

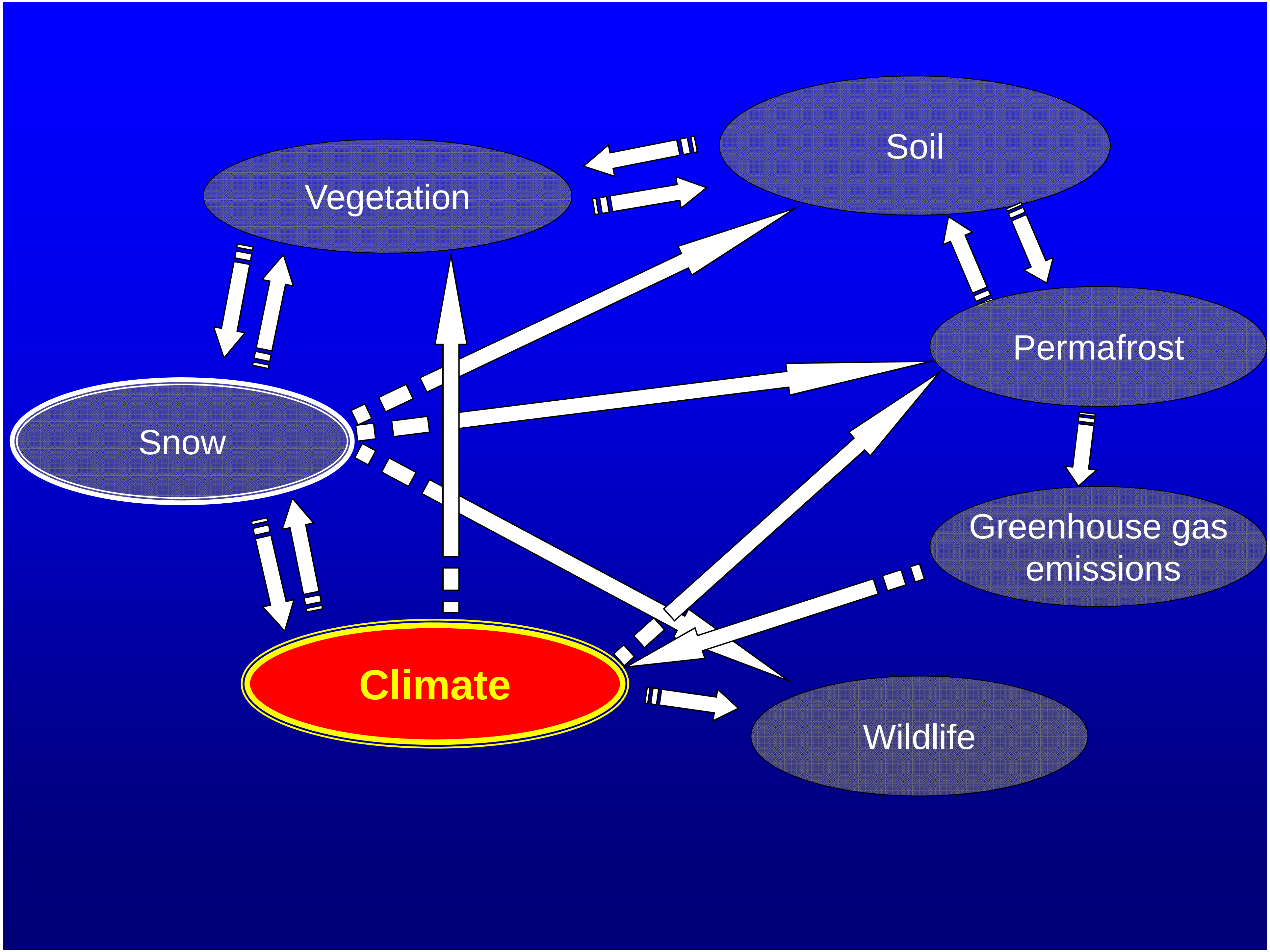
Thin snowpack on tundra




Thick snowpack in forest
Umiujaq, northern Quebec



Snow height
Forest
Tundra
snow height, m
1,8
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
1-oct.
1-nov.
2-déc.
2-janv.
2-févr.
5-mars
5-avr.
6-mai
6-juin
7-juil.


Soil
Vegetation
Permafrost
Snow
Greenhouse gas emissions
Climate
Wildlife

Outline

→ How climate affects snow physical properties

→ Snow metamorphism

→ Snow-albedo feedback 1: sea ice and snow thermal conductivity

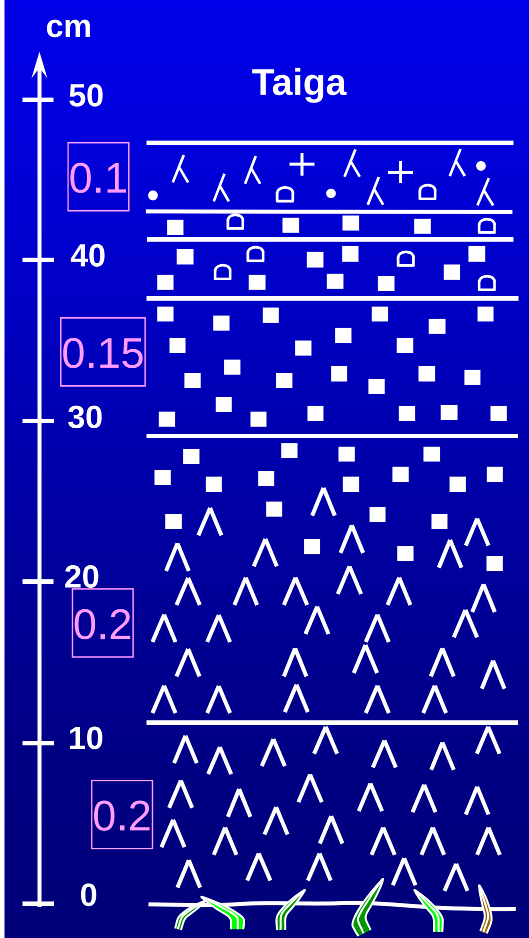
→ Snow-albedo feedback 2: precipitation and the albedo of Antarctica

→ Snow-albedo feedback 3: permafrost, vegetation and snow

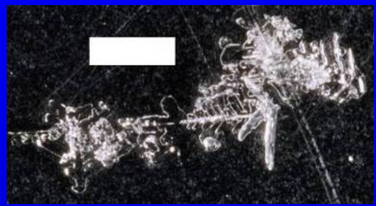
→ Conclusions


Finnish Lapland
Taiga snow
∧ Depth hoar

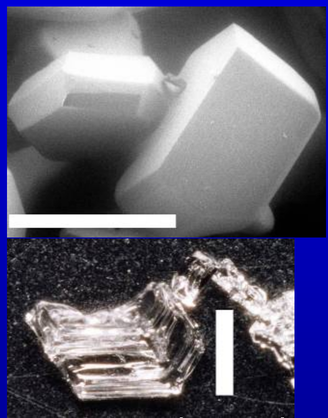
Taiga snowpack



+ Fresh snow

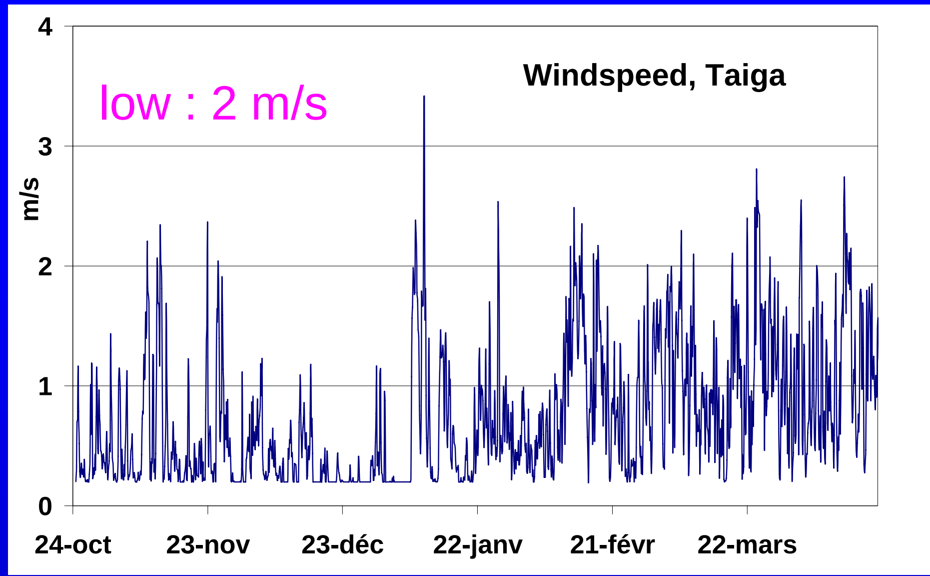


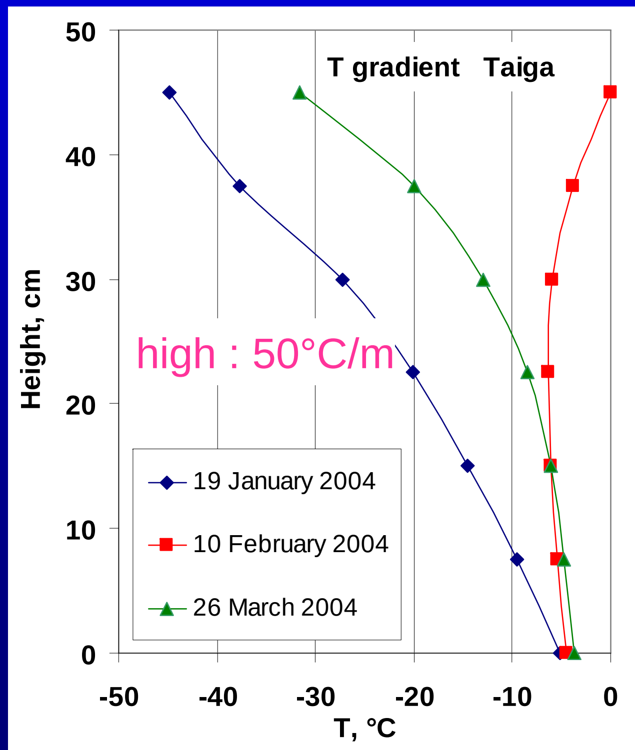
Decomposing crystal



■ Faceted crystal

Λ Depth hoar



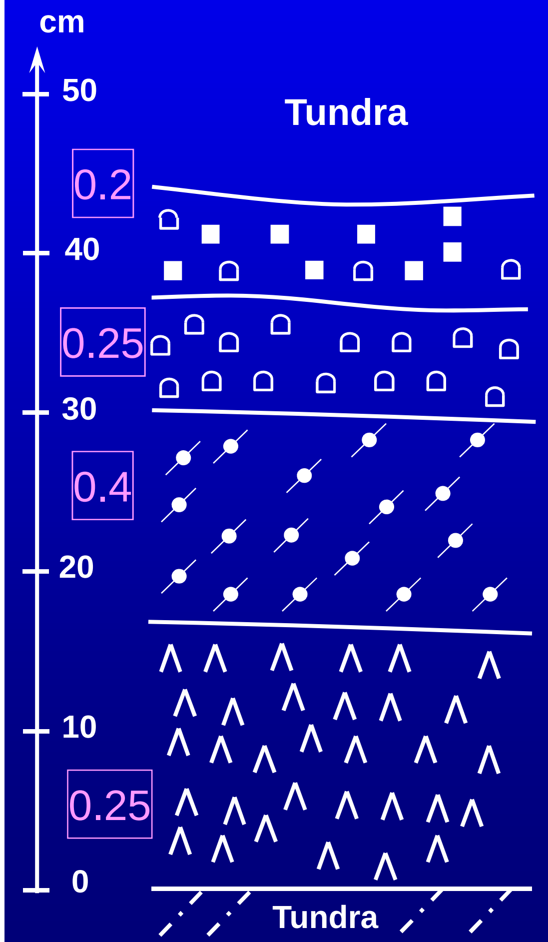


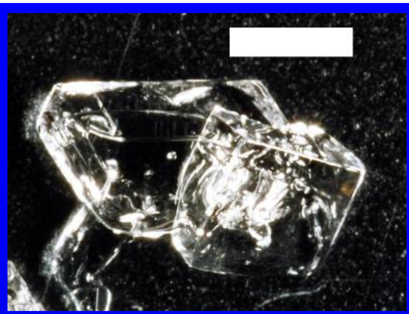
Tundra snow

Barrow, Alaska

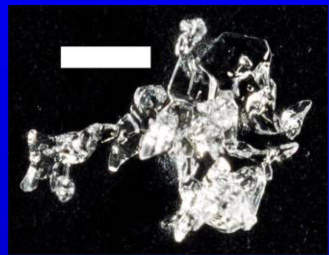
Wind crust

Tundra snowpack

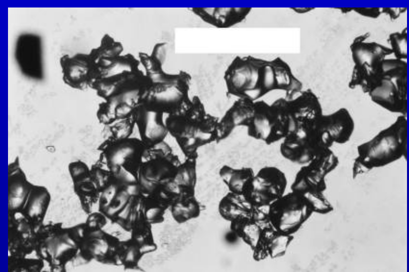




■ Faceted crystal

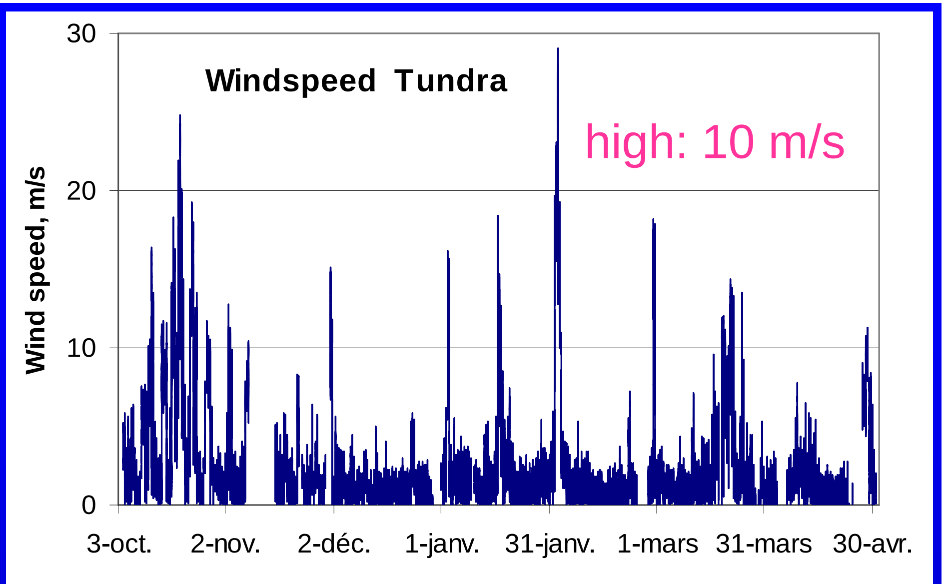


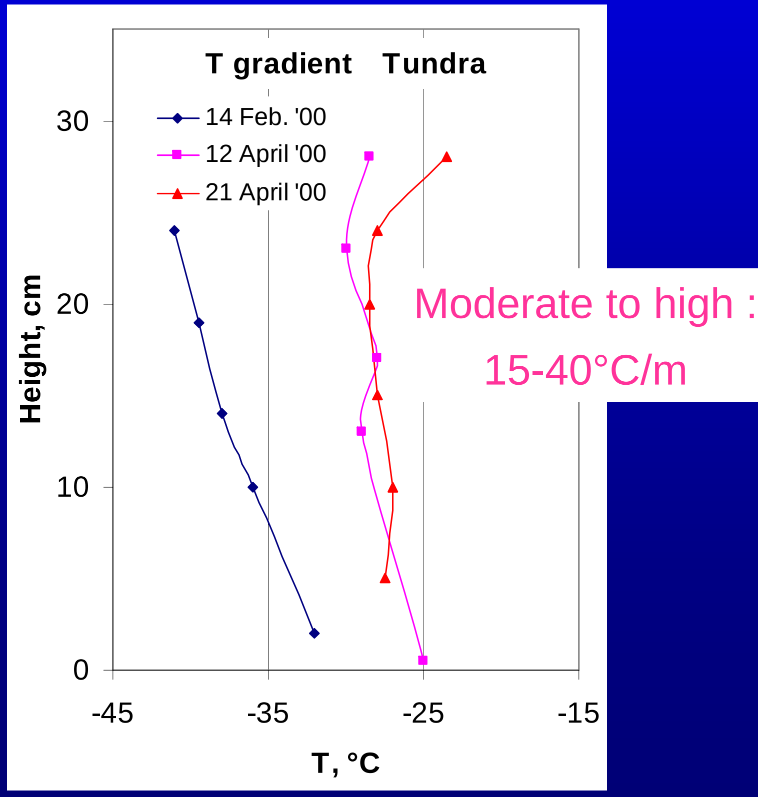
Mixed forms



Wind crust

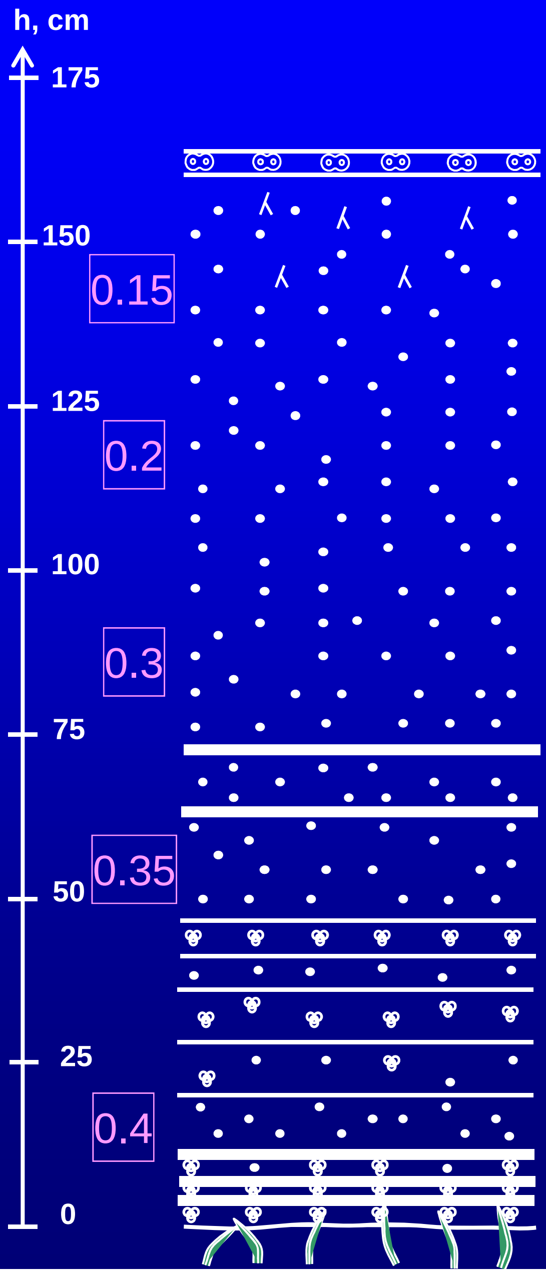
Λ Depth hoar

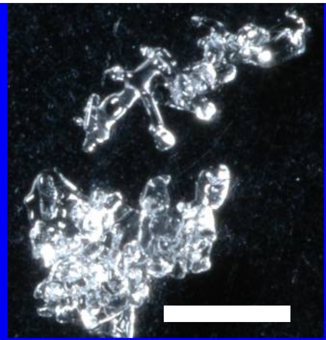




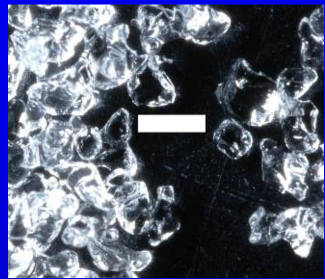

Alpine / maritime snowpacks

Maritime / Alpine snowpacks

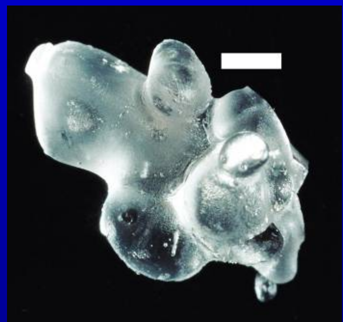




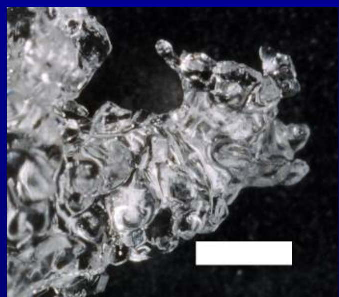
Decomposing crystals



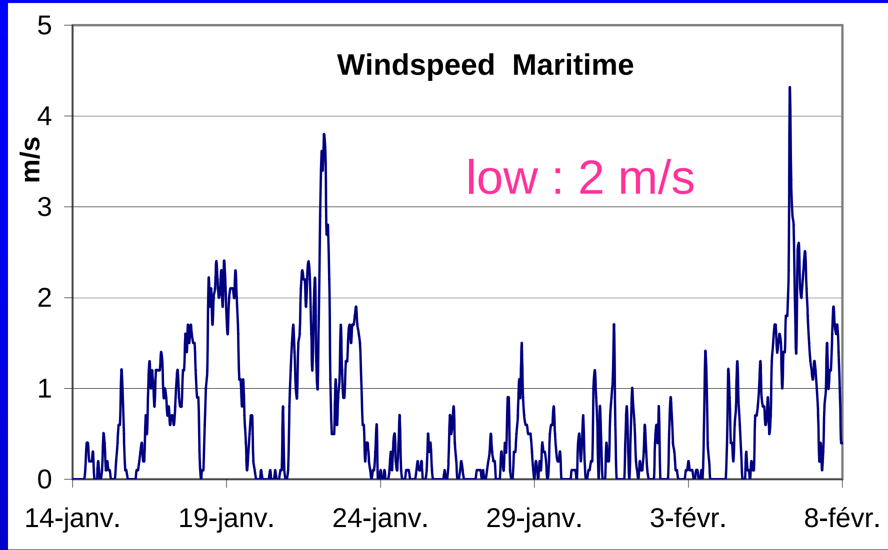
Small rounded grains

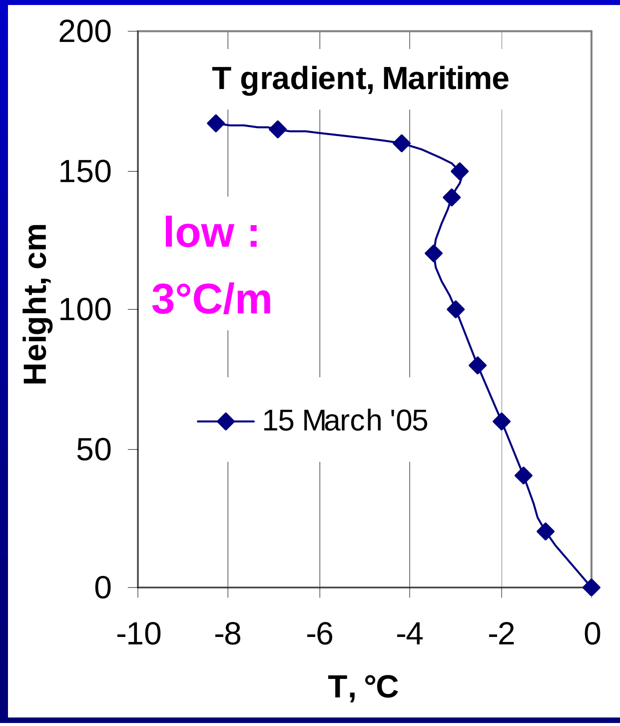


Clustered melt crystals



Ice layer

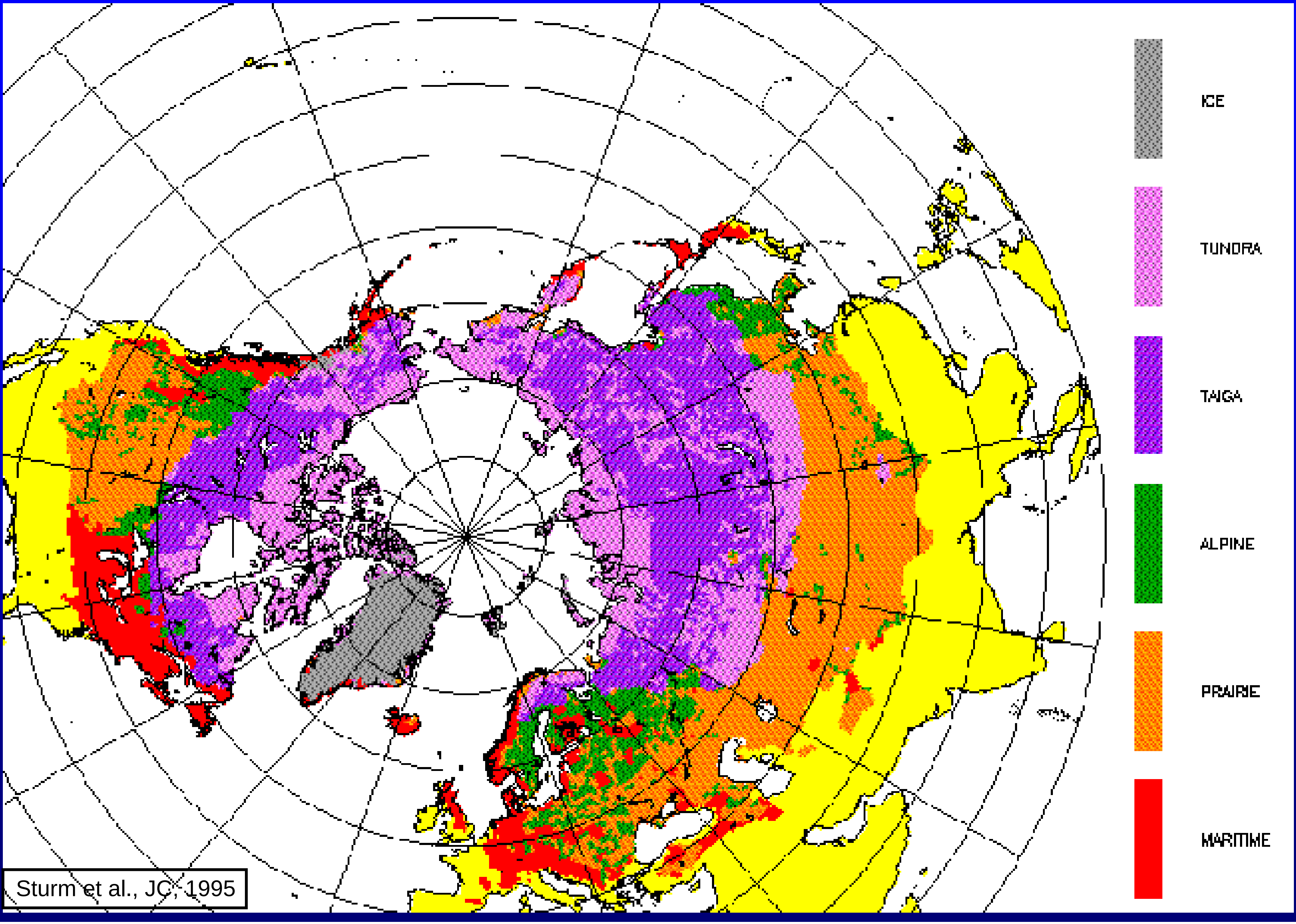




Visible properties and physical conditions of snowpacks

	Taiga	Tundra	Maritime	Alpine
Thickness	50 cm	40 cm	200 cm	150 cm
Mean density	0.18	0.35	0.32	0.3
Cohesiveness	Very low	Very high Very low	medium High	Medium low
T gradient	50°C/m	30°C/m	3°C/m	10°C/m
Wind speed	2 m/s	15 m/s	2 m/s	5 m/s

Geographical distribution of snowpacks



Sturm et al., JC, 1995

Snow metamorphism

→ Snow is not in thermodynamic equilibrium, its S/V ratio is too high

→ Snow crystals evolve over time

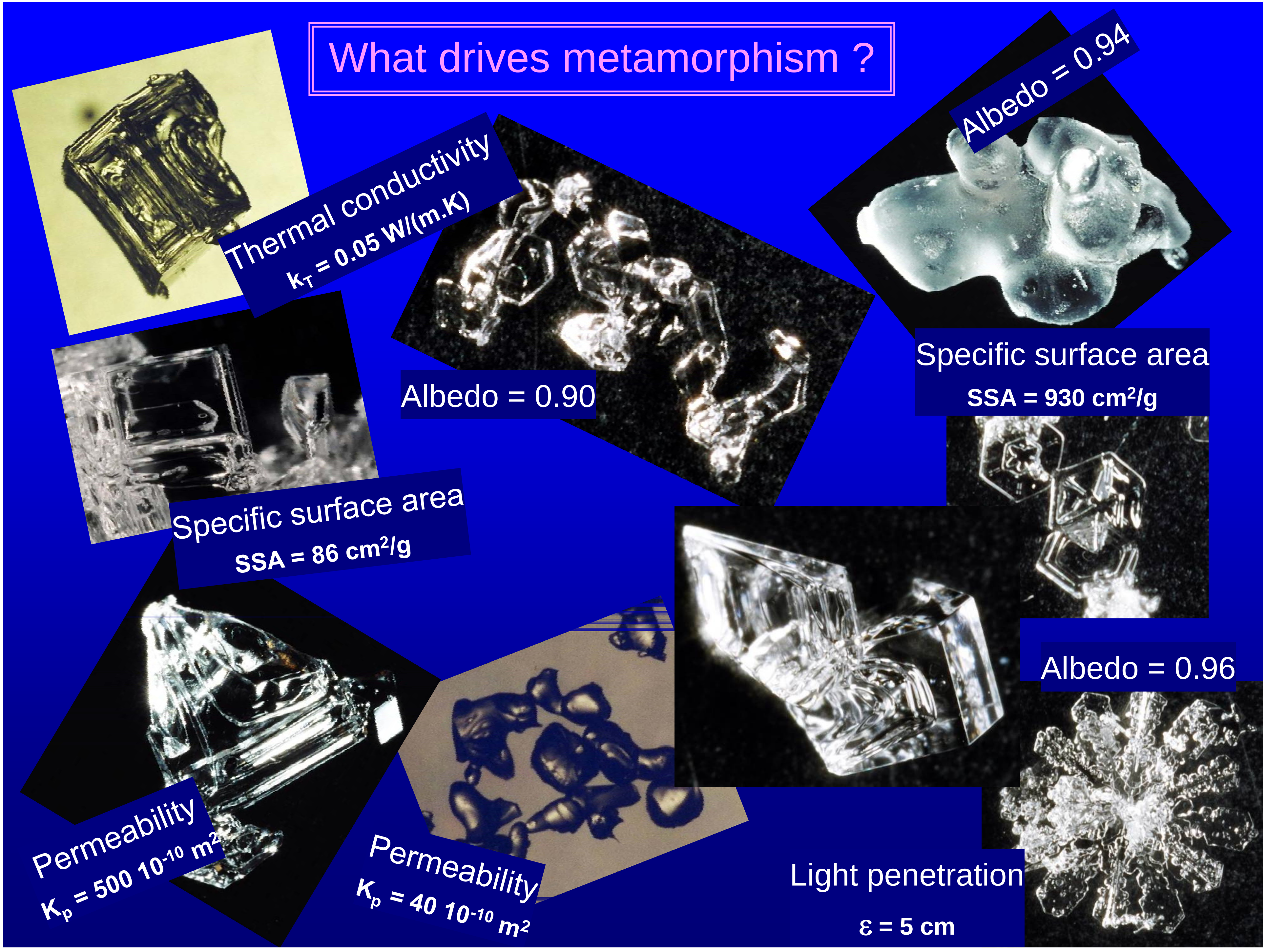
→ The changes are dictated by physical variables: temperature, temperature gradient, wind , etc.

Physical changes undergone by snow under environmental conditions

=

Snow metamorphism

What drives metamorphism ?

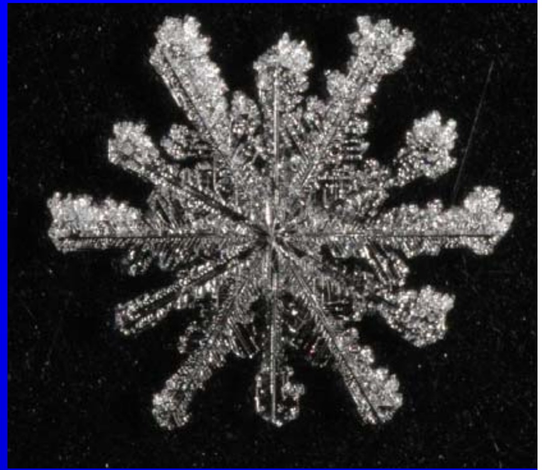


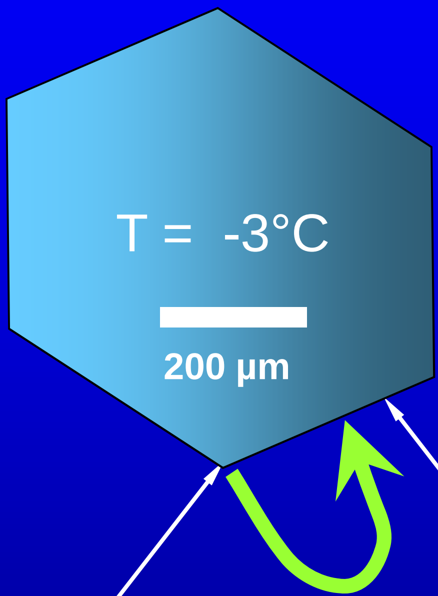
Under temperate climates

Snow : High surface area

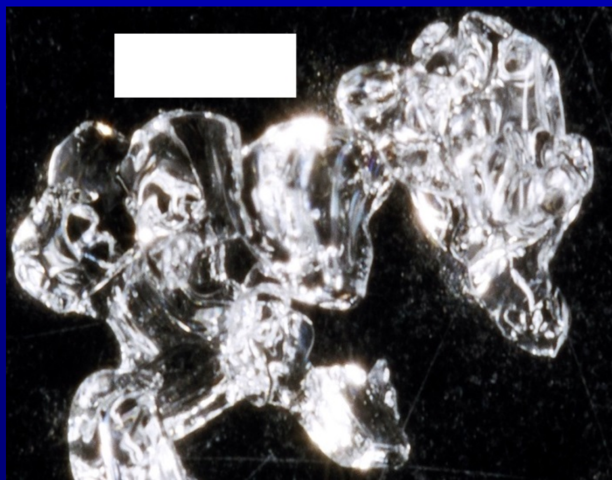
Surf. Energy : 109 mJ/m^2

Thermodynamically unstable





$$P_{H2O}(r_C) = P_0 \exp\left[-\frac{2\gamma V_m}{RT} \times \frac{1}{r_C}\right]$$

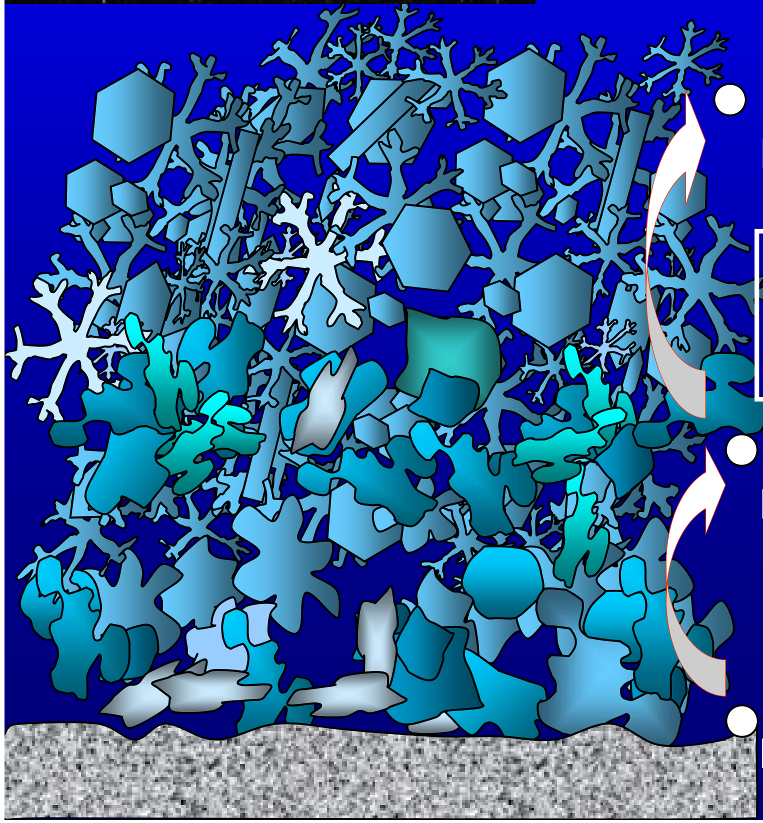


r_c = 1000 µm
P_{H2O}= 517.69 Pa

r_c = 10 µm
P_{H2O}= 517.72 Pa

P_{H2O} gradient= 0.15 Pa/cm

Under cold climates



T= -22°C

P_{H2O} = 84 Pa

High H_2O flux

T= -15°C

P_{H2O} = 163 Pa

T= -3°C

P_{H2O} = 470 Pa

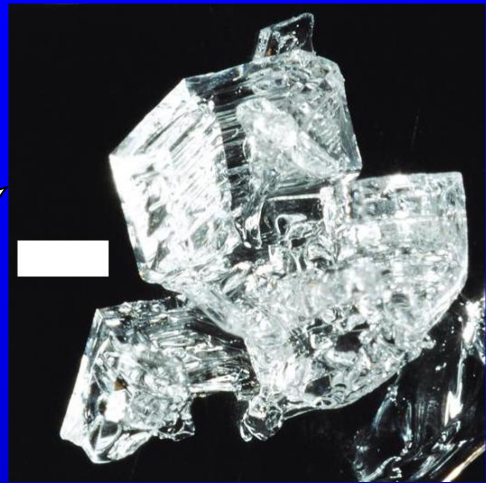
$$P\ (T_1)\ = P_0\ \exp\left[-\frac{L}{R}\times\left(\frac{1}{T_1}-\frac{1}{T_0}\right)\right]$$

Rapid grain growth

P_{H2O} gradient = 4 Pa/cm

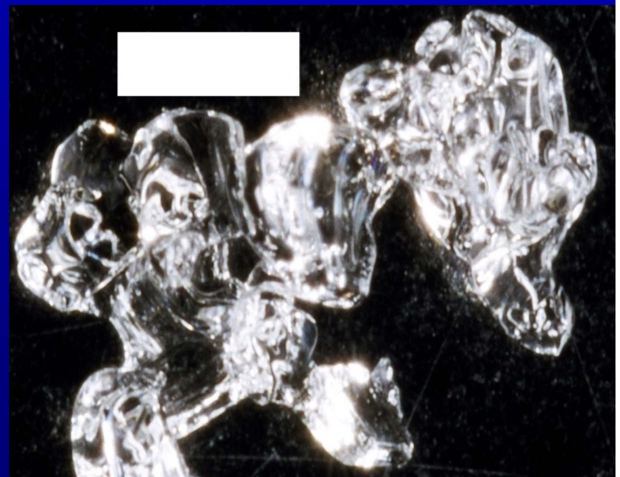
Effect of T and T gradient

T gradient (≈ cold) metamorphism

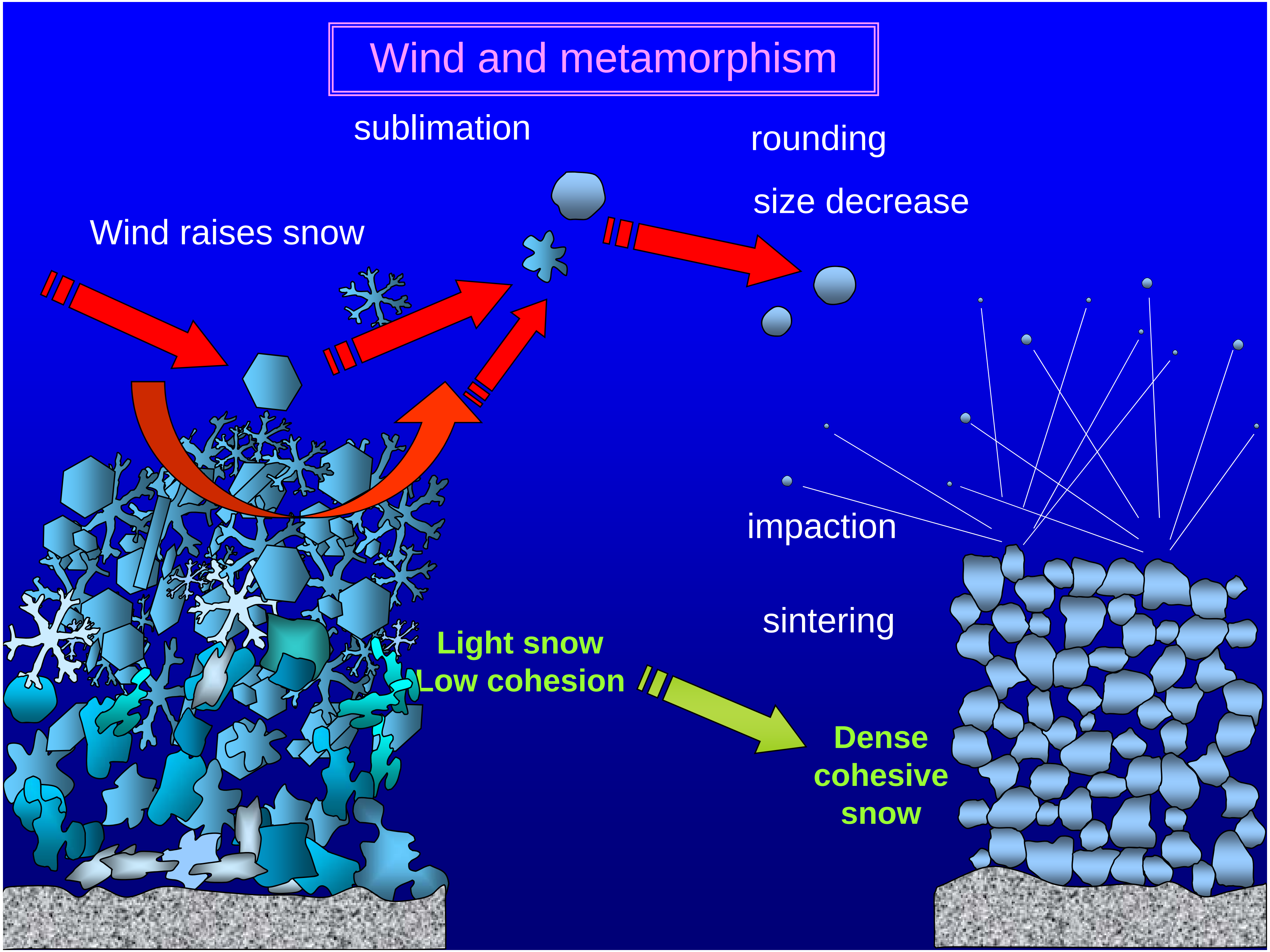


Large faceted uncohesive crystals, density ≈ 0.2

Small rounded cohesive crystals, density ≈ 0.3

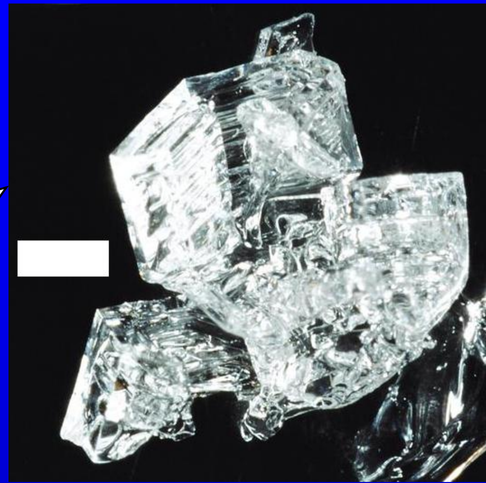


isothermal (≈ warm) metamorphism


Wind and metamorphism
sublimation
rounding
size decrease
Wind raises snow
impaction
sintering
Light snow
Low cohesion
Dense
cohesive
snow

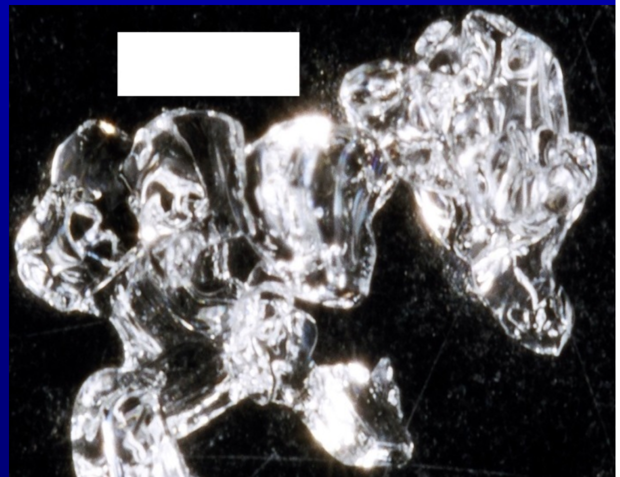
Effect of wind

Low wind (+ cold)



Large faceted uncohesive crystals, density ≈ 0.2

Small rounded cohesive crystals, density ≈ 0.4



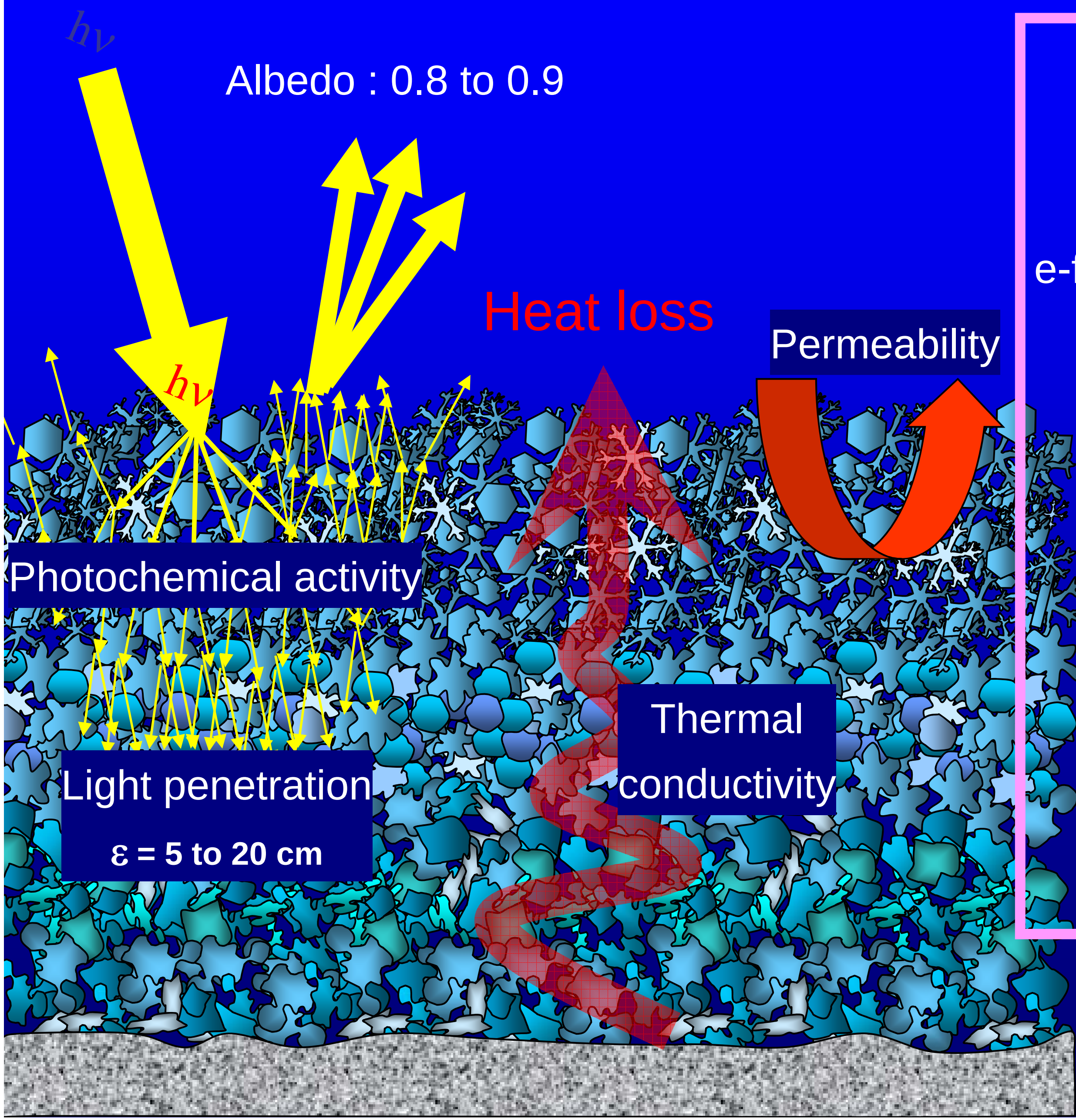
Low wind (+ warm)

or high wind

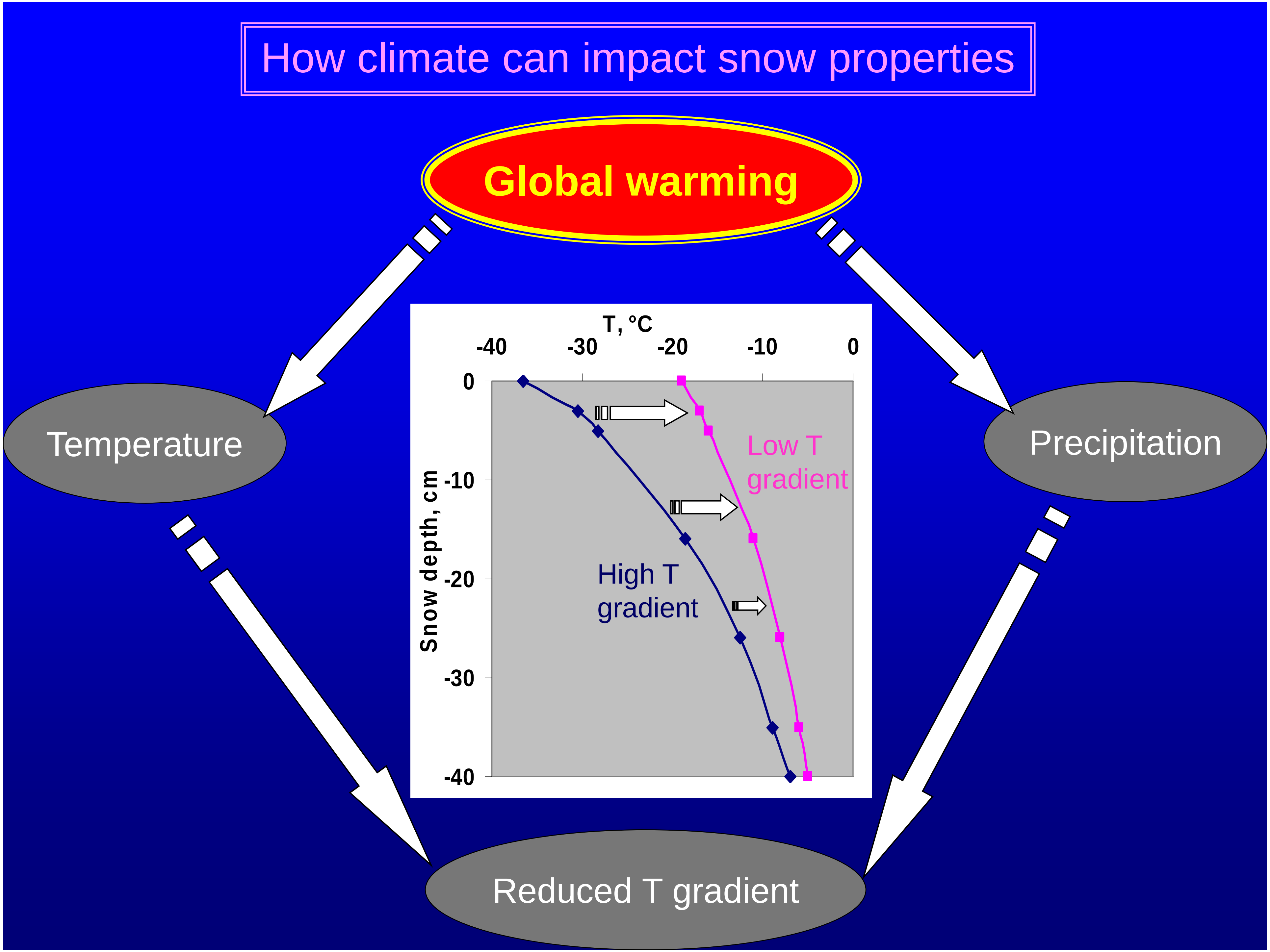
Climate and snowpack type

	Warm	cold
Low wind	Maritime/Alpine	Taiga
High wind	Prairie	Tundra

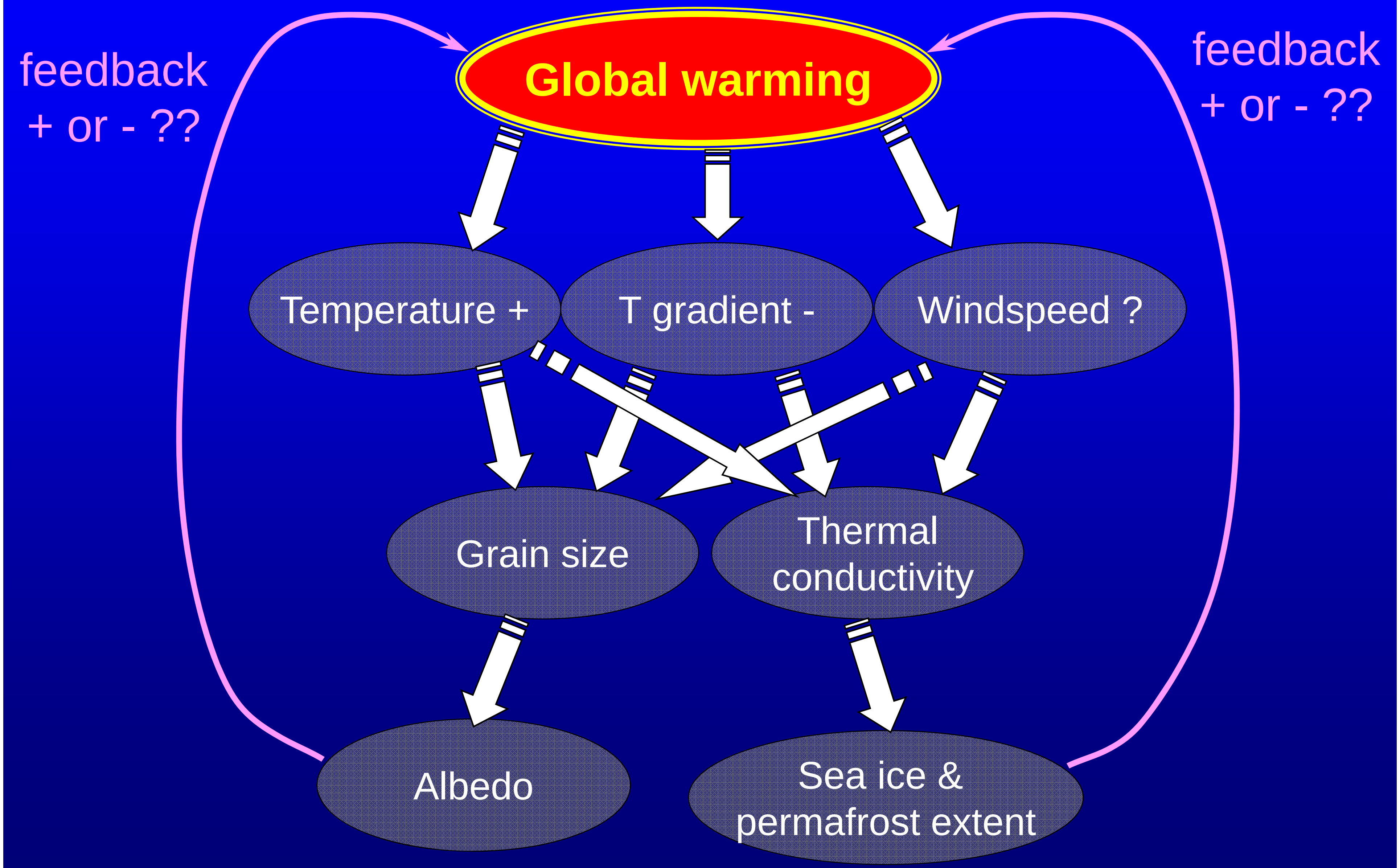
Metamorphism and physical properties of the snowpack



albedo :	energy budget of the surface
e-folding depth :	photochemical activity
thermal conductivity :	Energy budget of the soil, Sea ice growth
permeability :	Release of chemical species Sensible heat transfer

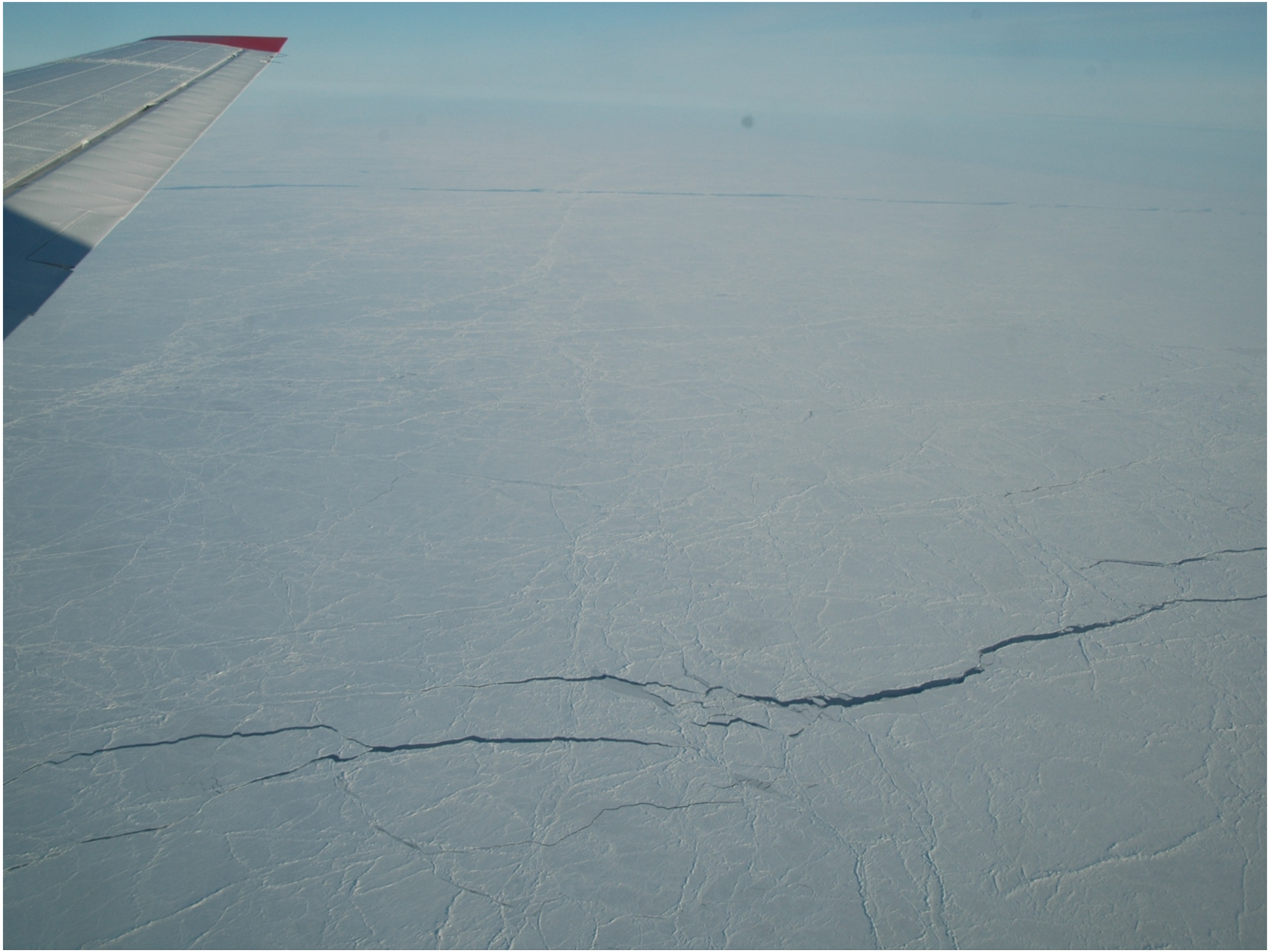

How climate can impact snow properties
Global warming
Temperature
Precipitation
Reduced T gradient
T, °C
-40
-30
-20
-10
0
Snow depth, cm
0
-10
-20
-30
-40
Low T
gradient
High T
gradient

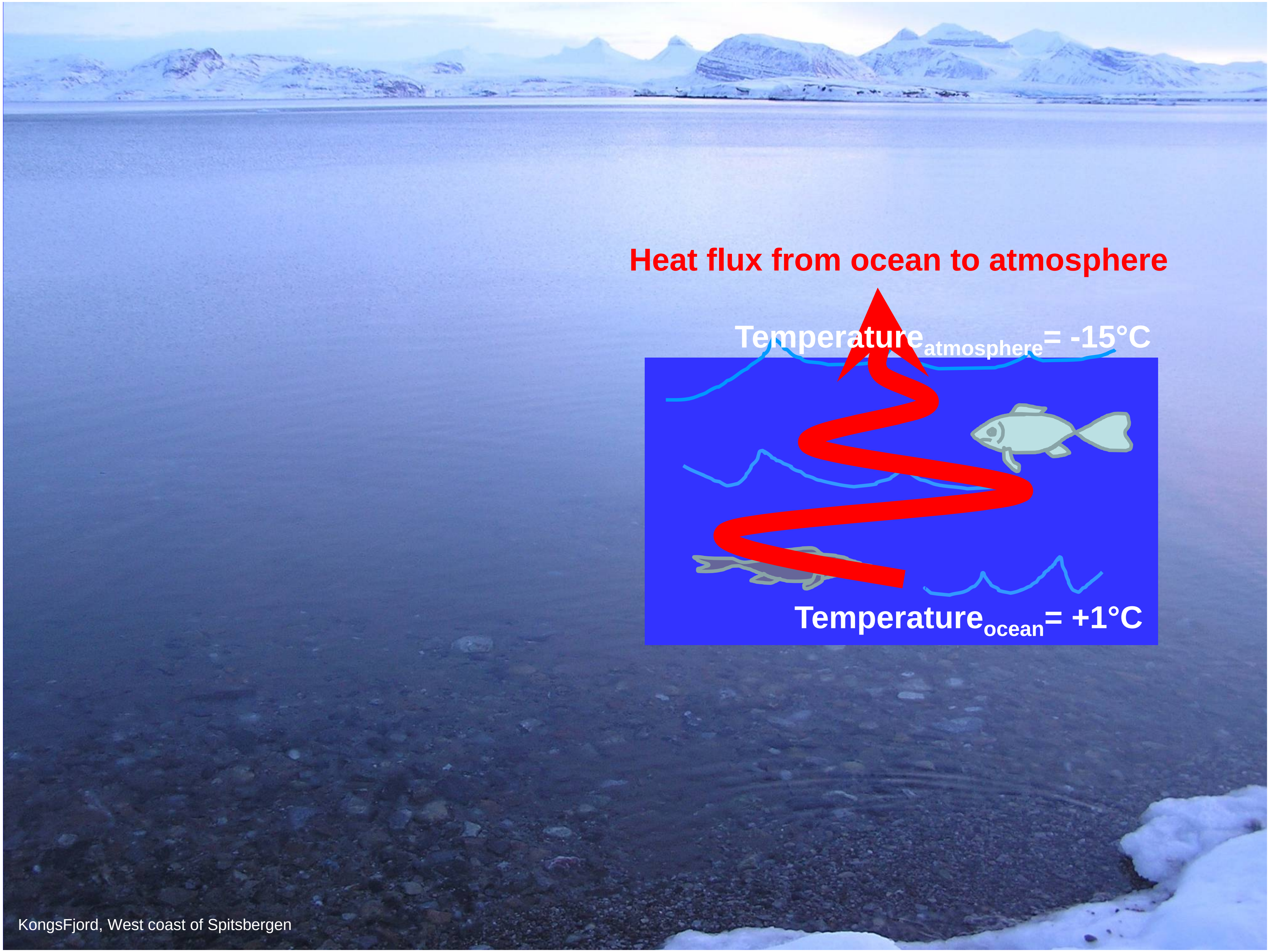
Climate, metamorphism and snow physics

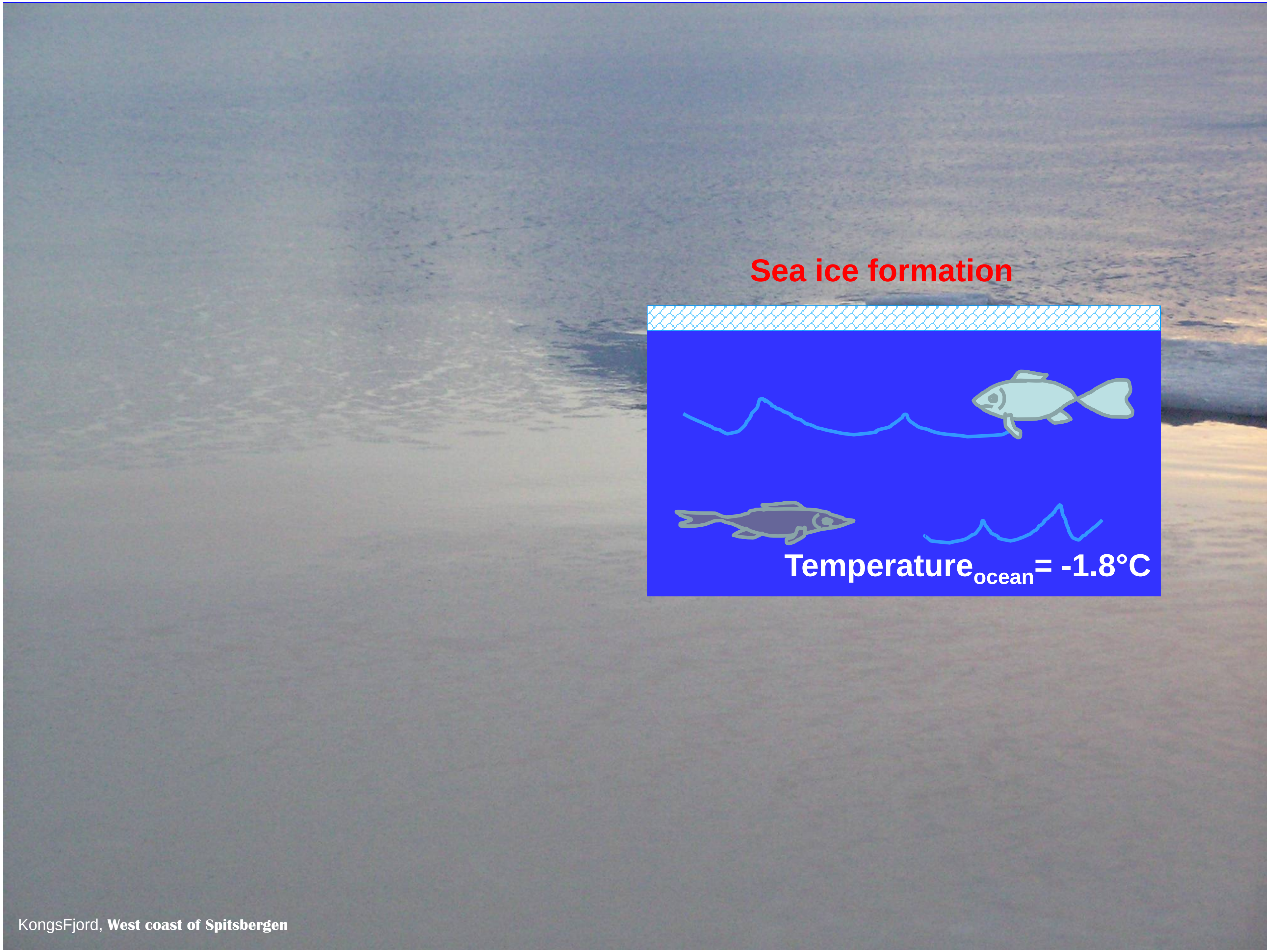


Snow climate feedback 1:

The growth of sea ice and the thermal conductivity of snow




Heat flux from ocean to atmosphere
Temperature$_{atmosphere}$= -15°C
Temperature$_{ocean}$= +1°C
KongsFjord, West coast of Spitsbergen


Sea ice formation
Temperature$_{ocean}$= -1.8°C
KongsFjord, West coast of Spitsbergen

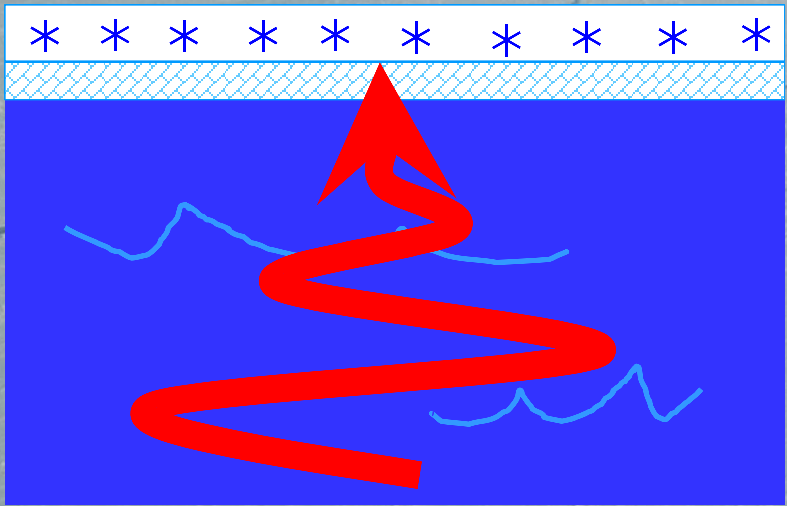
KongsFjord, **West coast of Spitsbergen**

KongsFjord, **West coast of Spitsbergen**


KongsFjord, **West coast of Spitsbergen**


StorFjord, East coast of Spitsbergen

Snow covers sea ice



and limits the growth of the ice pack

20 cm of snow

= 5 cm of styrofoam

Insulating power of snow

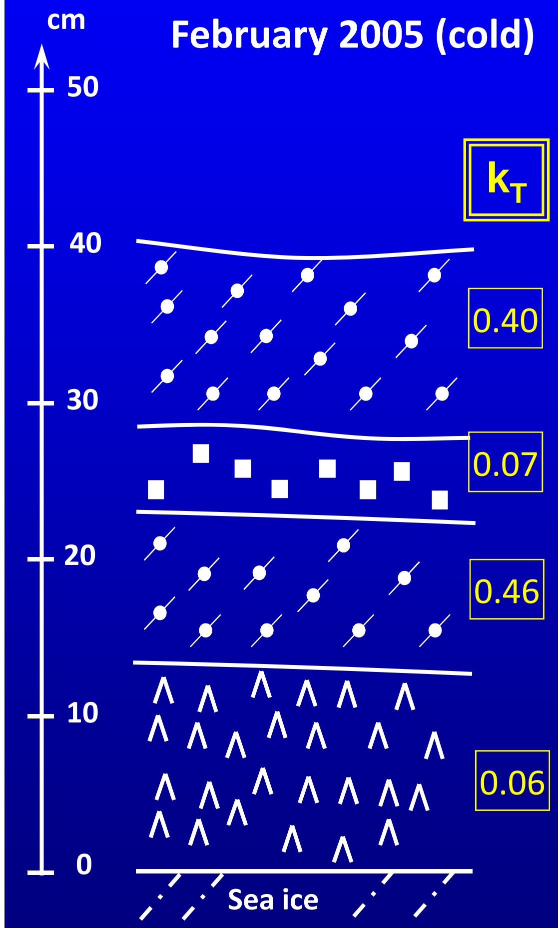
But during the night, enormous amounts of snow fell, so that arms and men lying down were covered. Pack animals were hobbled by the snow. There was great hesitation in getting up, because the snow was keeping the men lying down warm, except when it had slipped off their shoulders.

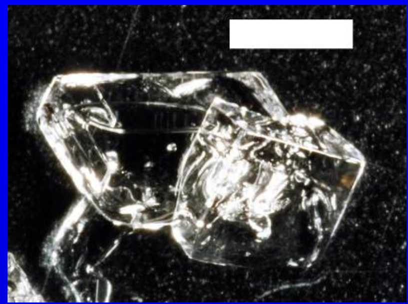
Xenophon of Athens, Anabasis, Book IV, Chapter IV, Sentence 11 (400 BP)

StorFjord, East cosat of Spitsbergen

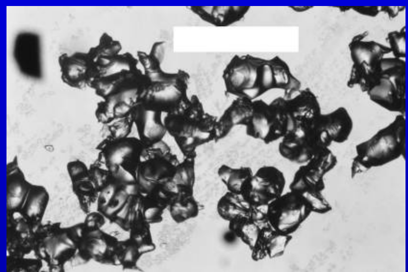
Insulating power of snow and climate

February 2005 (cold)





■ Facted crystals

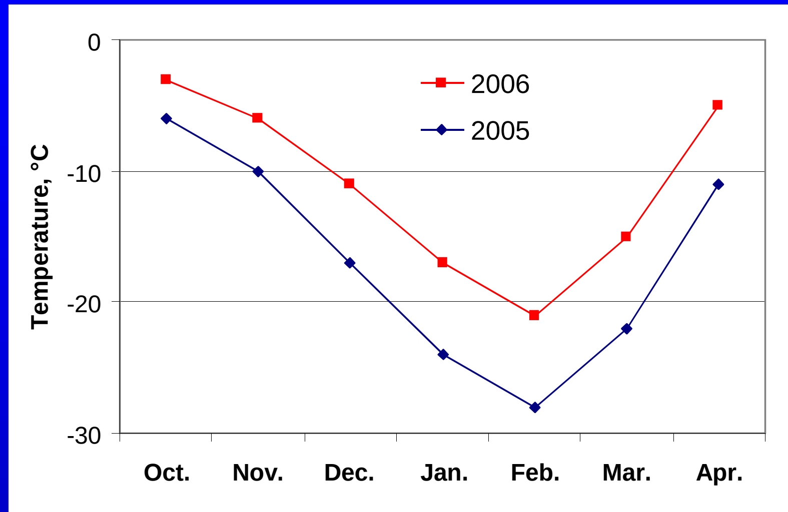


Wind slab

Λ Depth hoar

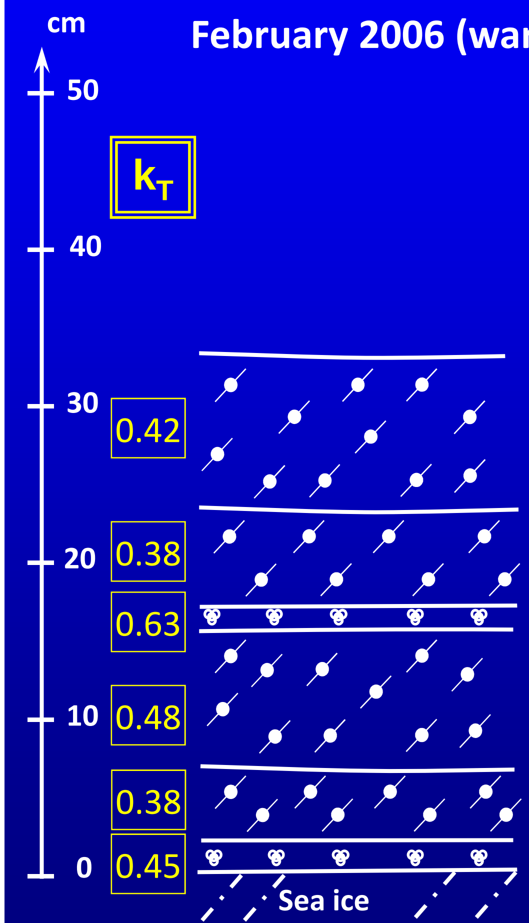
snow of 2005 = 2 boards of styrofoam

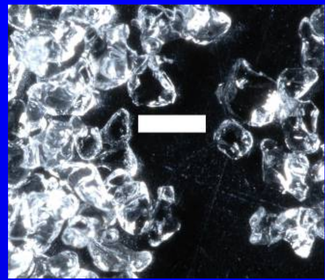
k_T (styrofoam) = 0,034



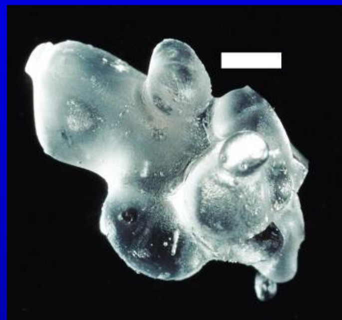
Insulating power of snow and climate

February 2006 (warm)

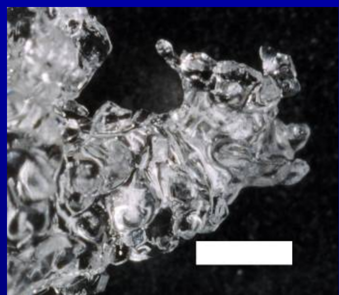




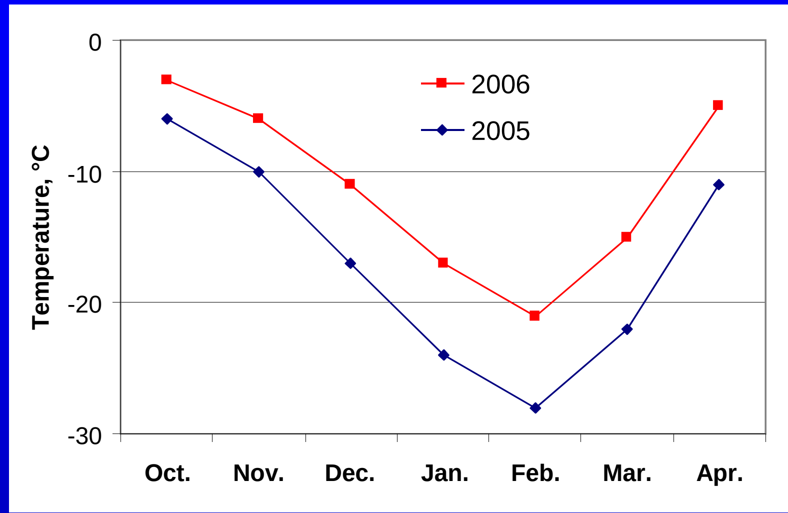
• Small rounded grains



Melt-freeze polycrystals



Ice layer



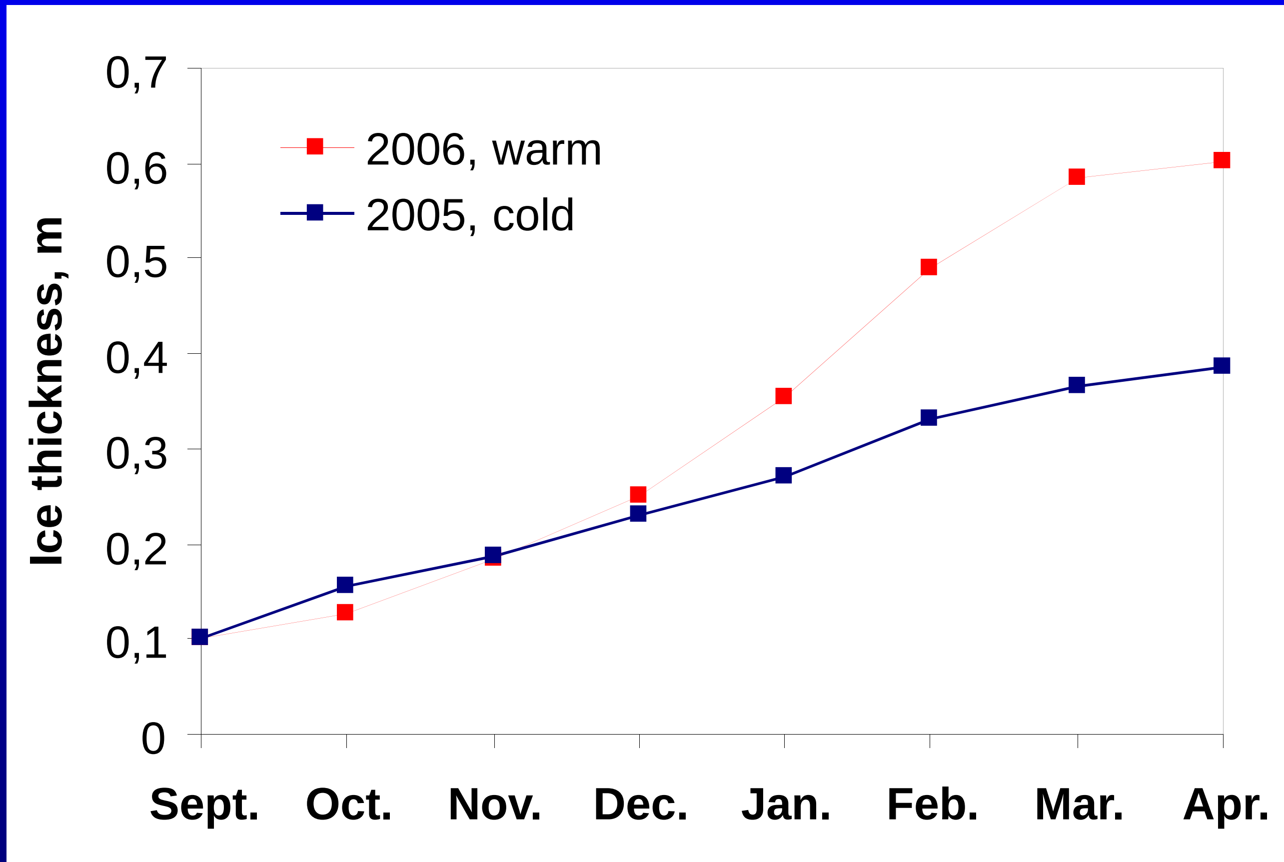
Snow of 2006 = 1/2 board of styrofoam

k_T (styrofoam) = 0,034

Insulating power of snow and climate

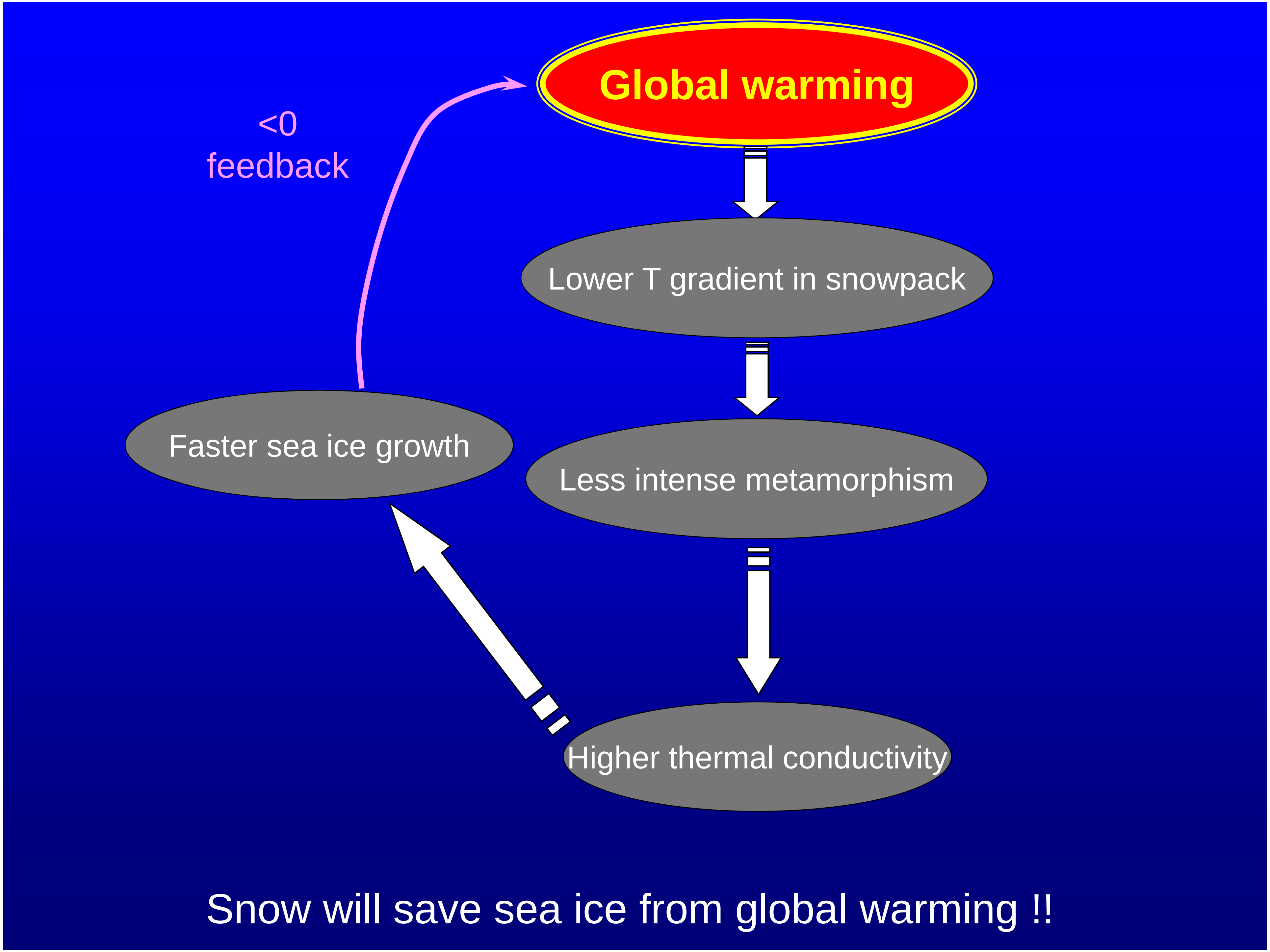
Snow of 2006 = 1/2 board of styrofoam

snow of 2005 = 2 boards of styrofoam

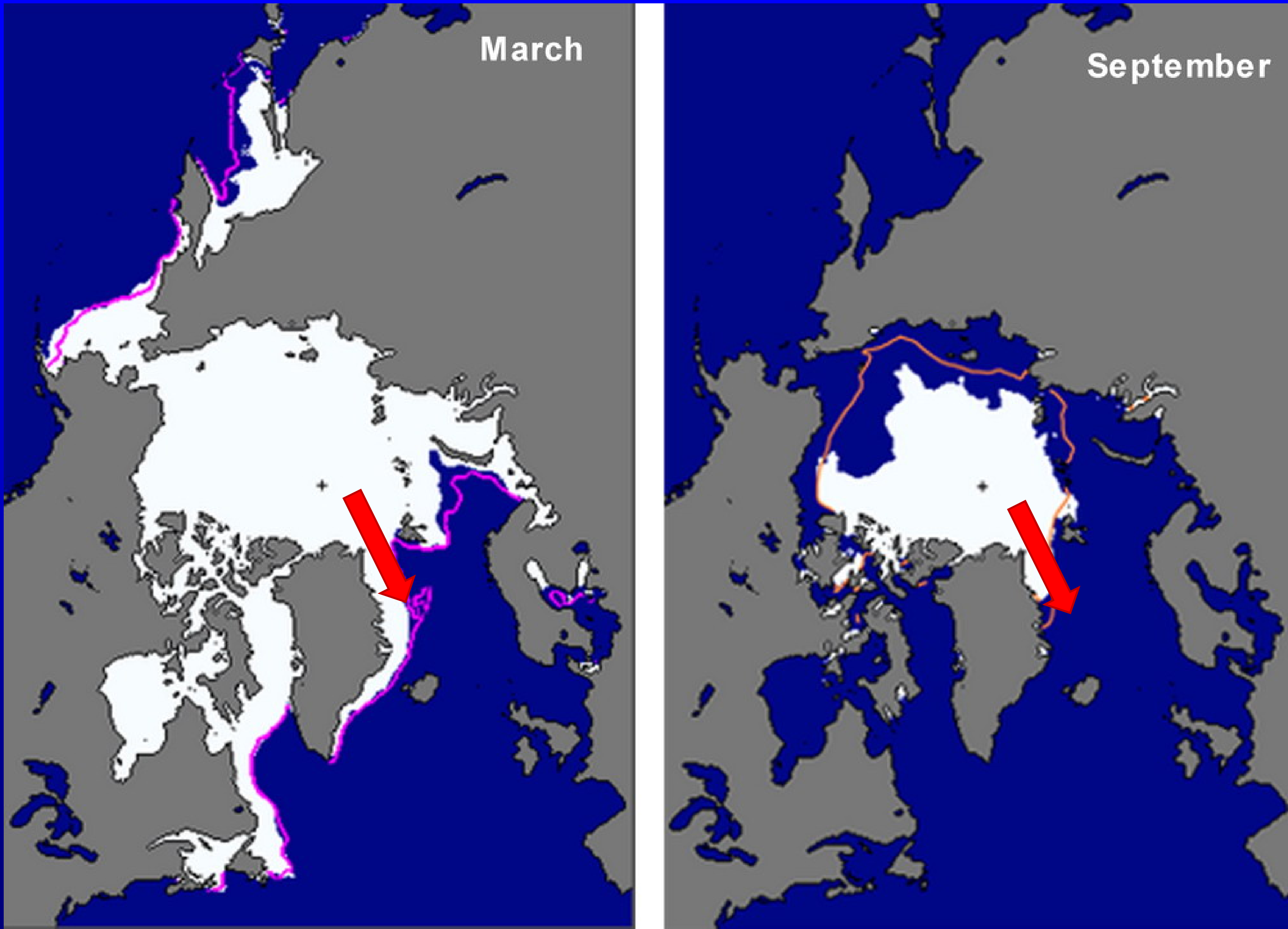


60 cm

38 cm

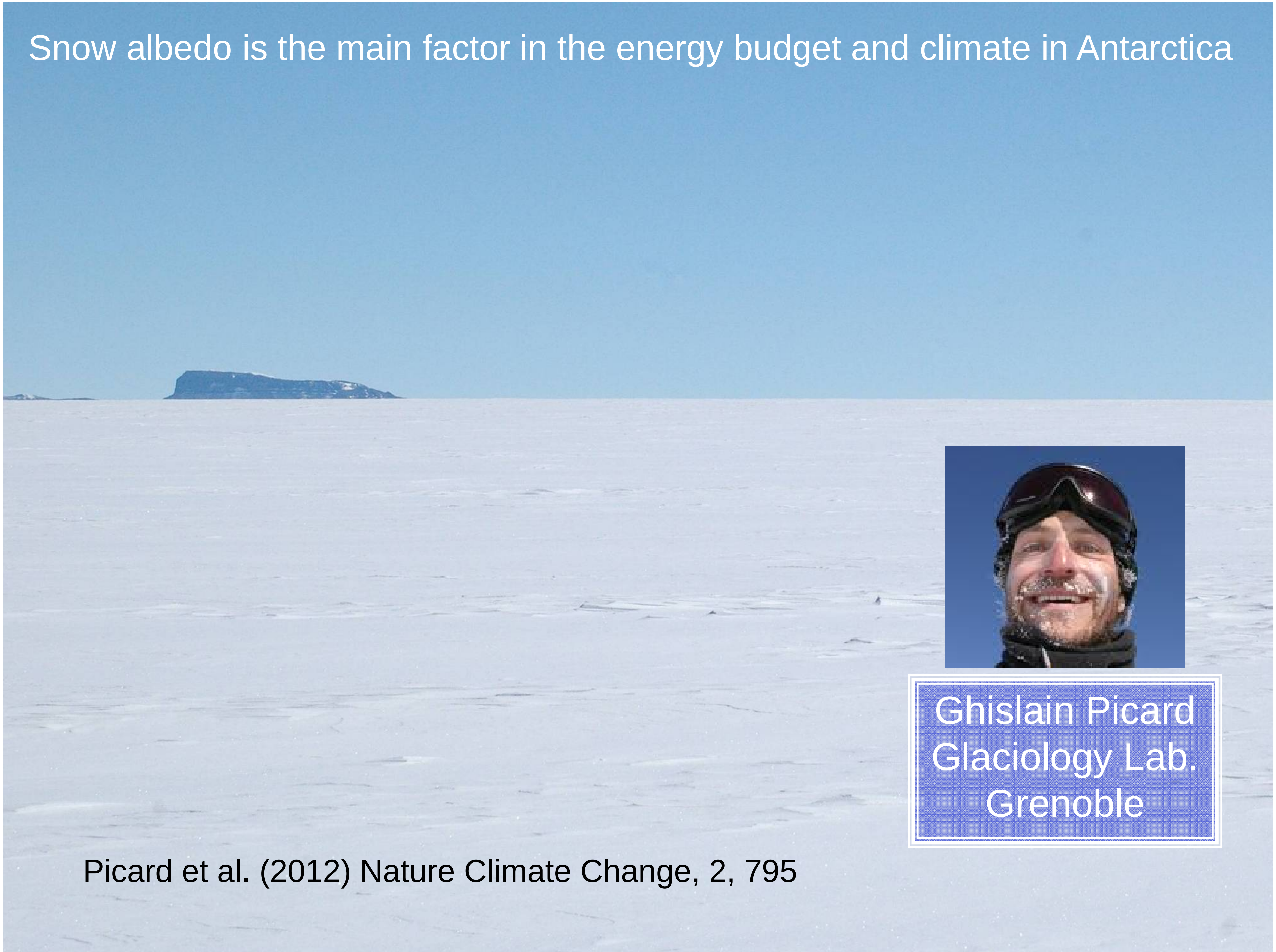


Global warming
Lower T gradient in snowpack
Less intense metamorphism
Higher thermal conductivity
Faster sea ice growth
<0
feedback
Snow will save sea ice from global warming !!


March
September

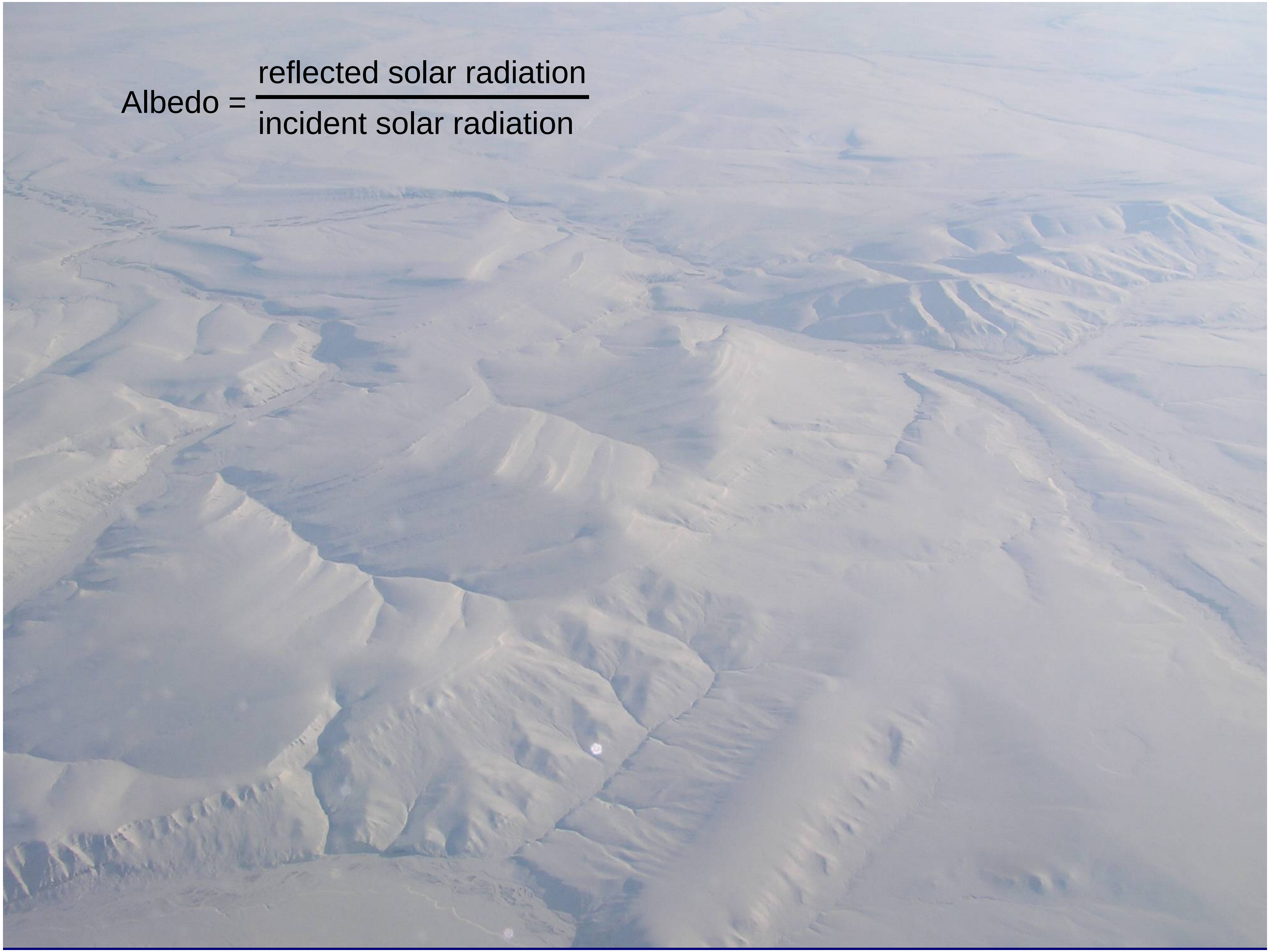
Snow climate feedback 2:

Precipitation and the albedo of Antarctica

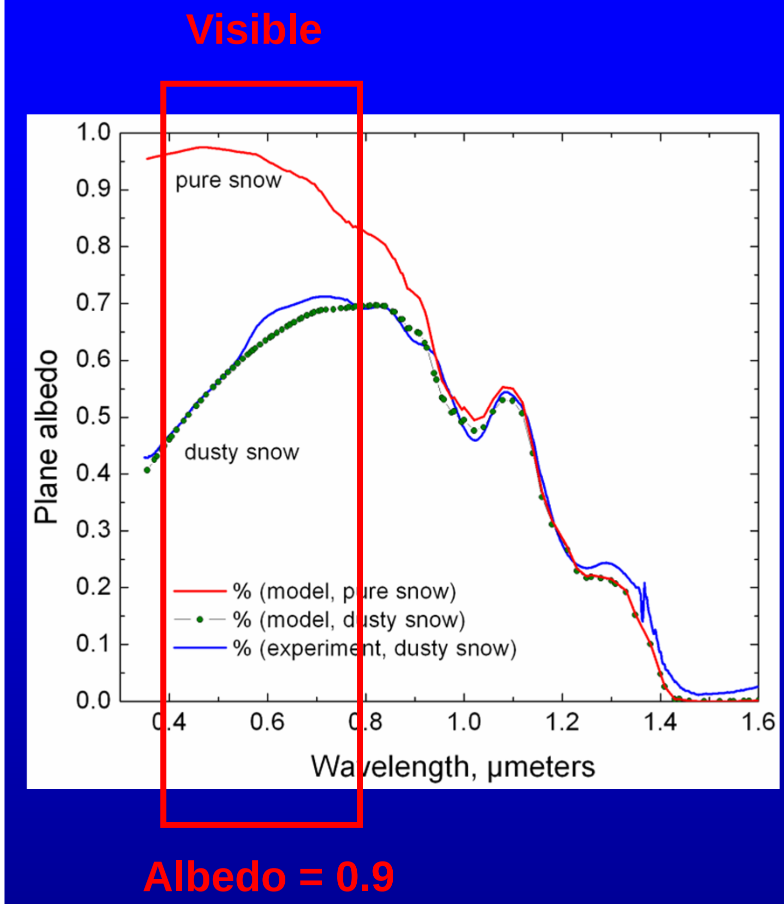


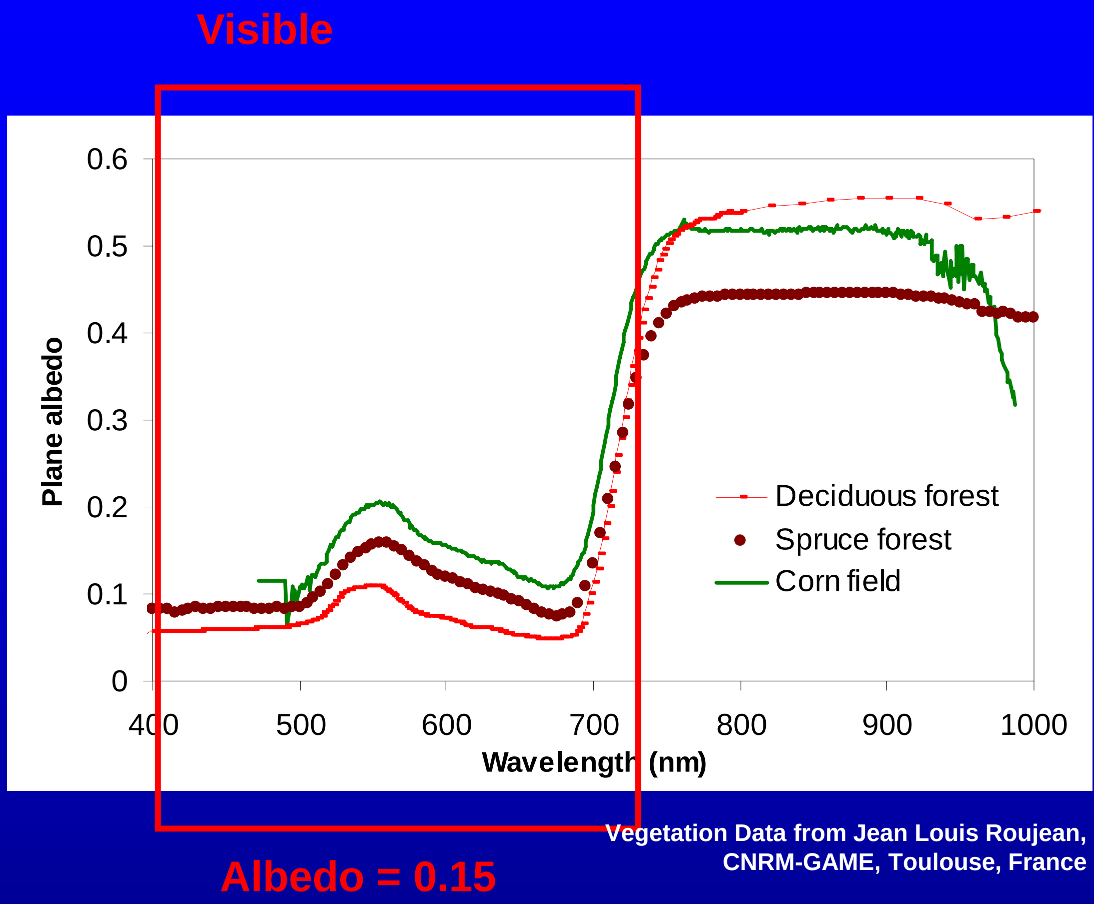
Snow albedo is the main factor in the energy budget and climate in Antarctica
Ghislain Picard
Glaciology Lab.
Grenoble
Picard et al. (2012) Nature Climate Change, 2, 795

$$\text{Albedo} = \frac{\text{reflected solar radiation}}{\text{incident solar radiation}}$$



Snow and albedo



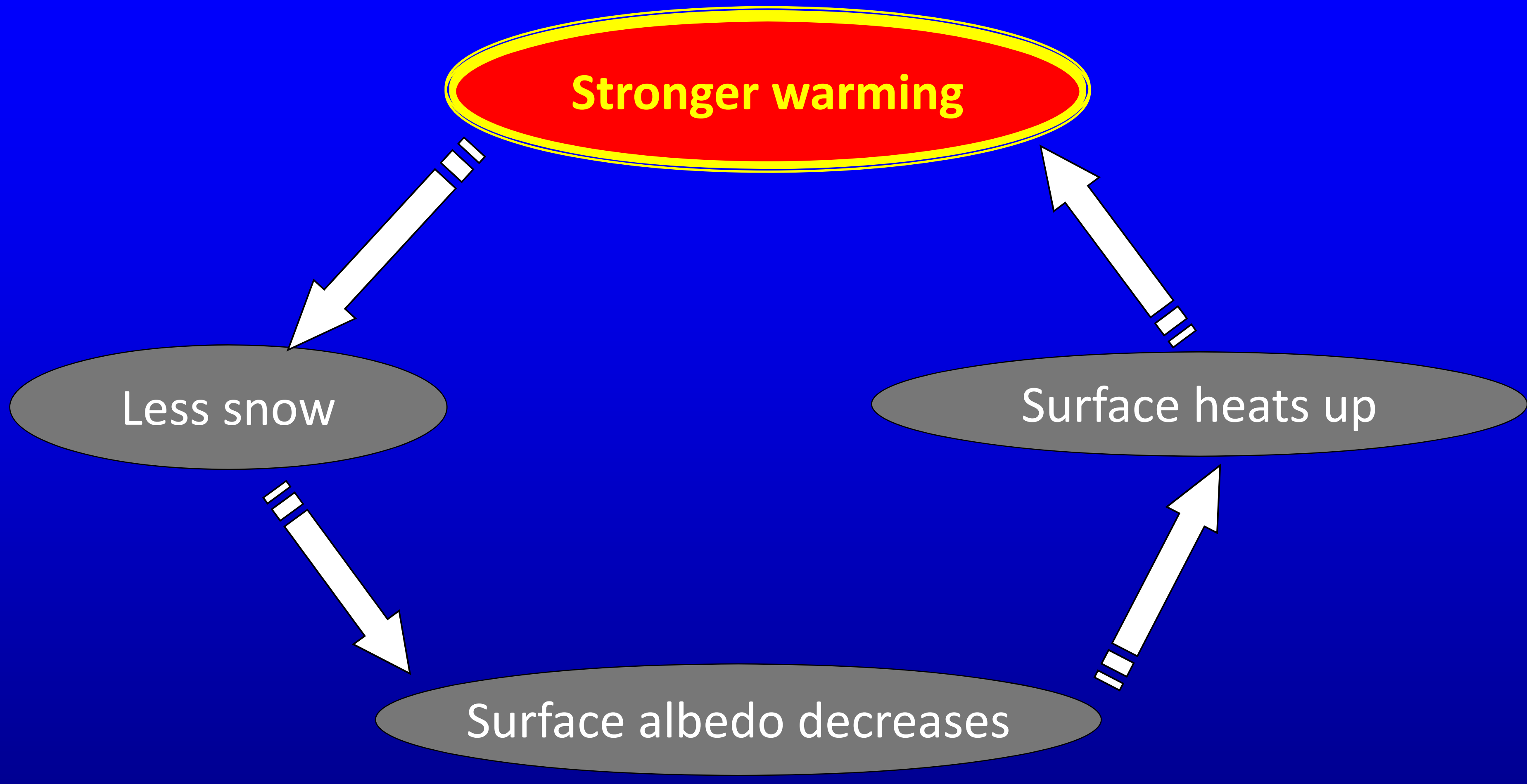


Vegetation Data from Jean Louis Roujean, CNRM-GAME, Toulouse, France

Consequence of snow cover decrease: more absorbed radiation

- **Snow-climate positive feedback**

The main snow-albedo feedback



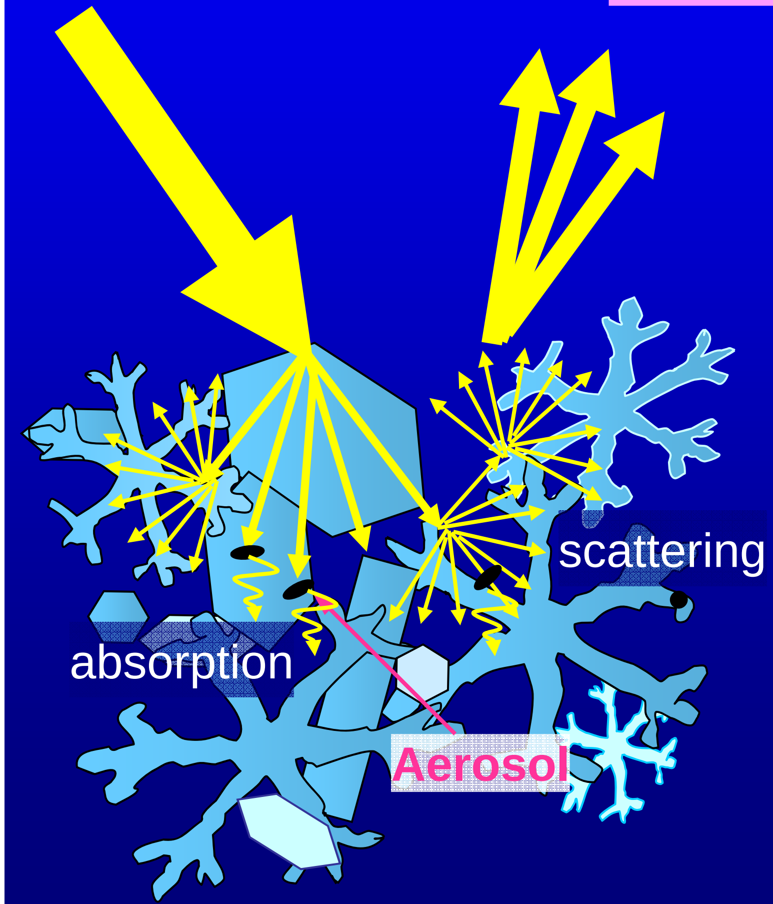
Positive feedback

Are there negative feedbacks ?

Snow albedo

Albedo determined by

- Scattering : increases with decreasing grain size
- Absorption : increases with increasing impurity content



In Antarctica, snow is clean

Albedo is determined by grain size only*

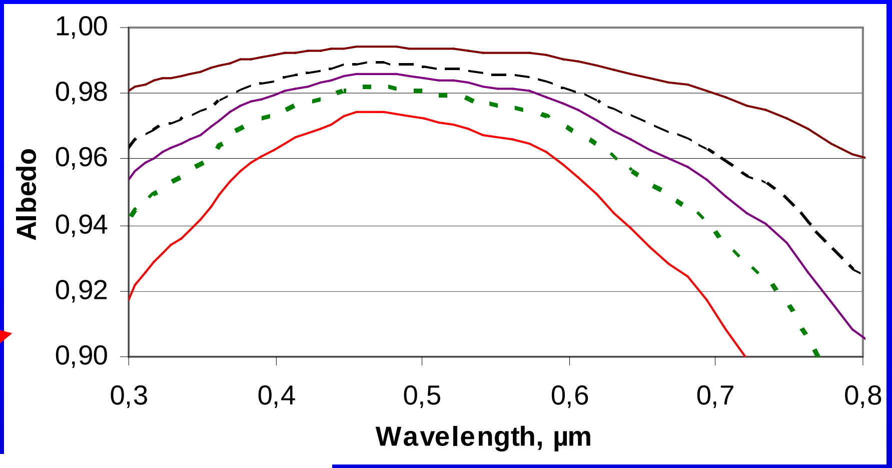
*almost

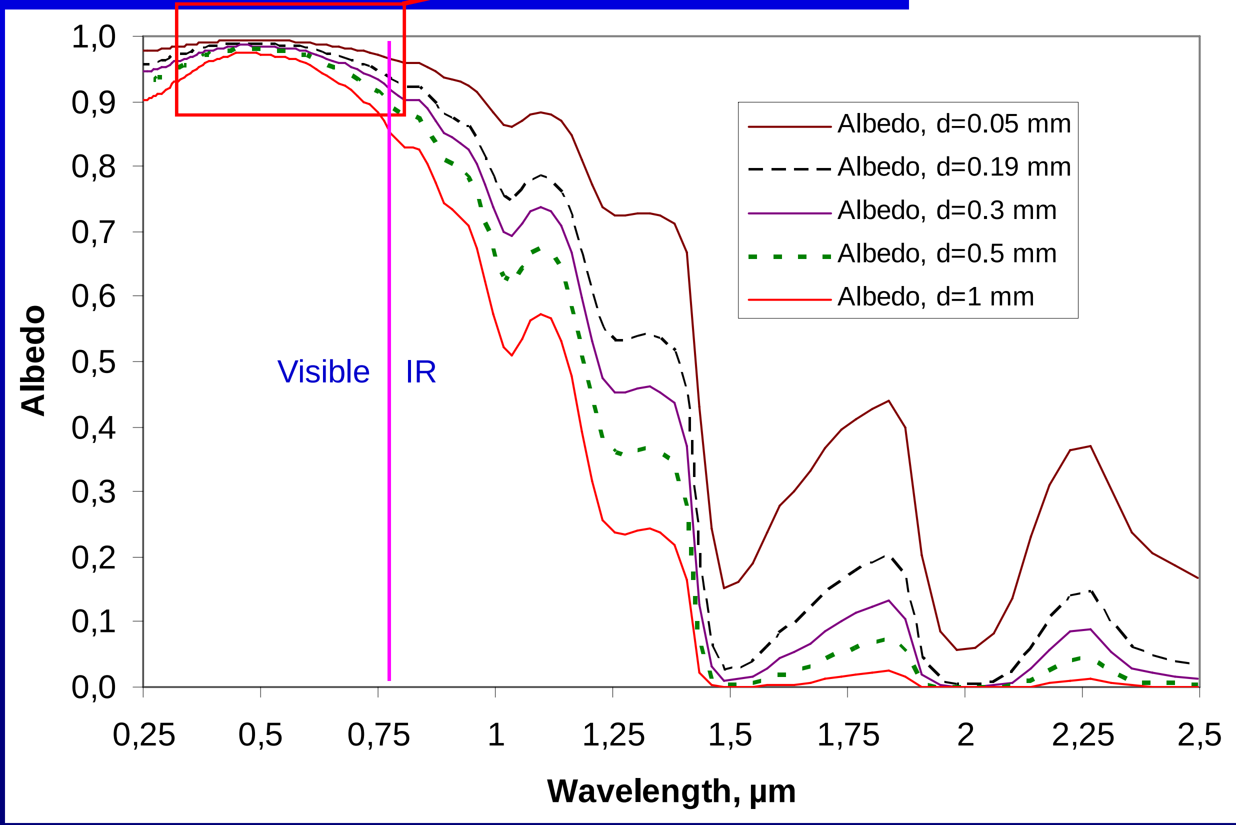
Snow albedo

Snow with small grains has the highest albedo

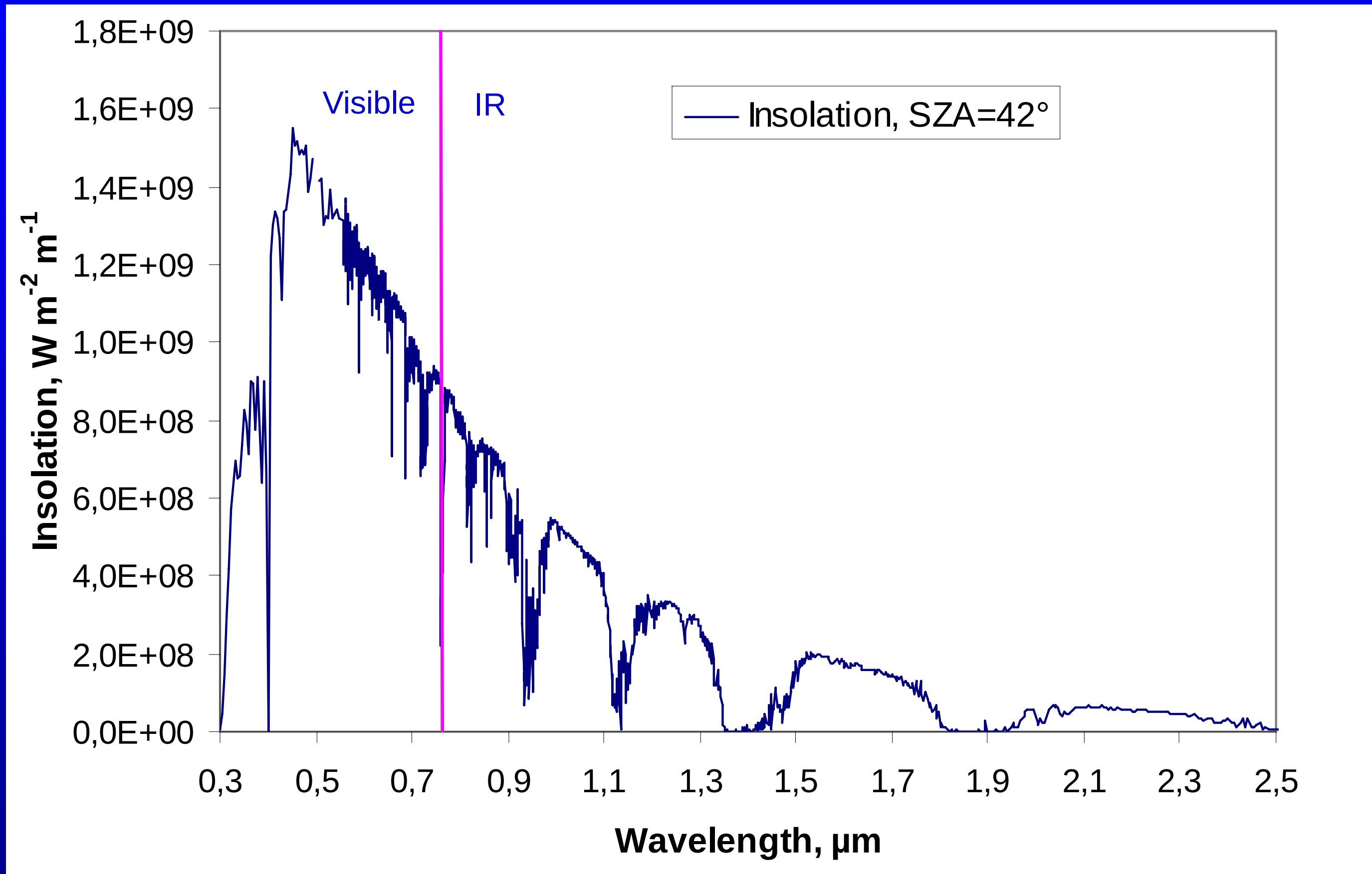
Snow with large grains has a lower albedo

Albedo of pure snow

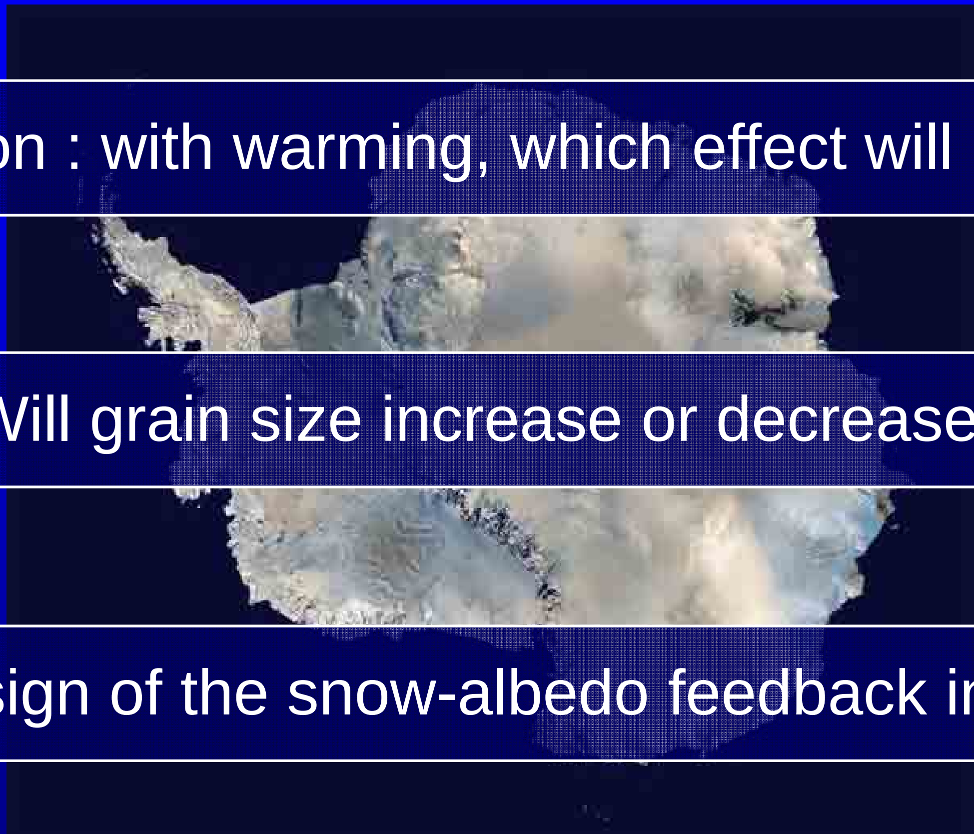




d= diameter of snow grains, approximated as spheres


1,8E+09
1,6E+09
1,4E+09
1,2E+09
1,0E+09
8,0E+08
6,0E+08
4,0E+08
2,0E+08
0,0E+00
Insolation, W m-2 m-1
Visible
IR
Insolation, SZA=42°
0,3
0,5
0,7
0,9
1,1
1,3
1,5
1,7
1,9
2,1
2,3
2,5
Wavelength, µm

Climate warming ⇘ More precipitation ⇗ More small grains ⇘ Albedo increases ⇗ Surface cools down



Our question : with warming, which effect will predominate ?

Will grain size increase or decrease ?

What is the sign of the snow-albedo feedback in Antarctica ?

Climate warming ⇘ Metamorphism is faster ⇗ Grains grow faster ⇘ Larger grains ⇗ Surface heats up

Monitor snow physical properties using passive microwave sensing at 89 and 150 GHz

$$T_B^{150}(\nu) = \varepsilon_{150}(\nu)\ T_{Snow\ 0-7cm}$$

$\Longrightarrow$ T_B of top 7 cm

$$T_B^{89}(\nu) = \varepsilon_{89}(\nu)\ T_{Snow\ 0-20cm}$$

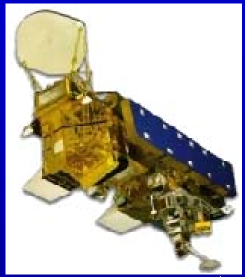
$\Longrightarrow$ T_B of top 20 cm

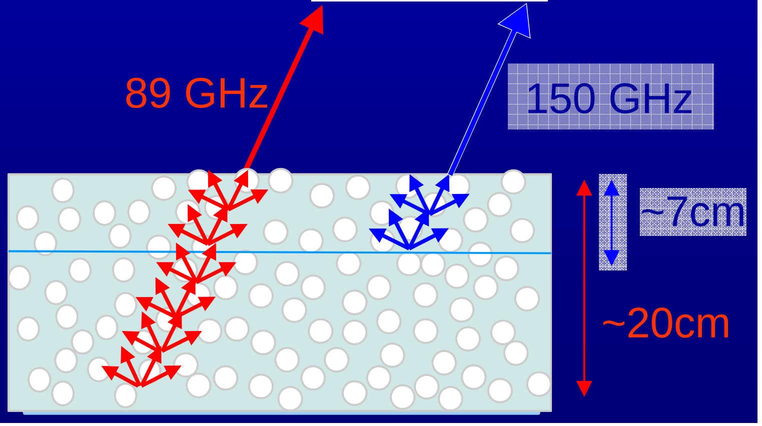
Brightness Temperature
= f(frequency)

Snow Temperature

Emissivity=
Dielectric properties of the medium
=f(frequency, grain size)

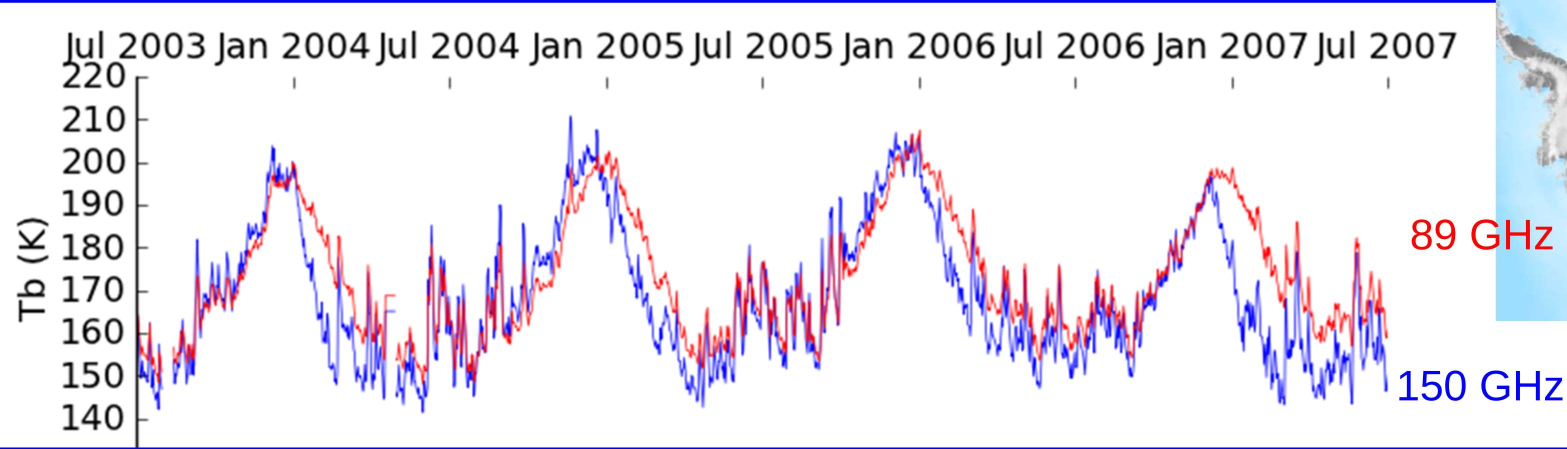
AMSU*

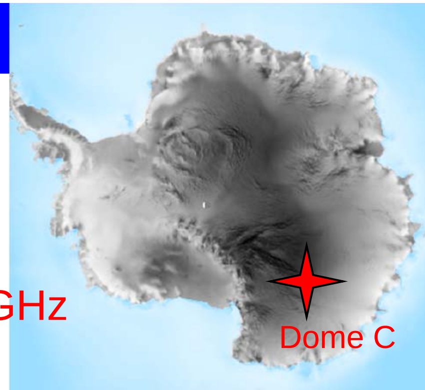


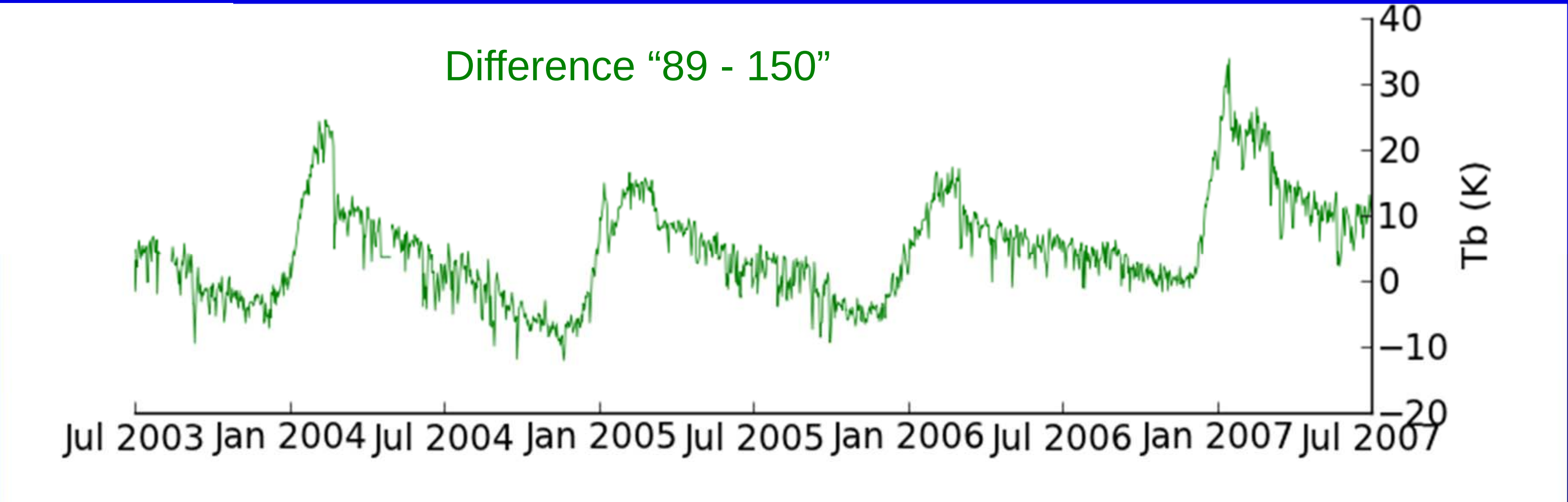


*Advanced Microwave Sounding Unit (AMSU)

AMSU data at Dome C







$$T_B = \varepsilon T_{Snow}$$

30 K differences in T_B cannot be explained by changes in T_{snow} only

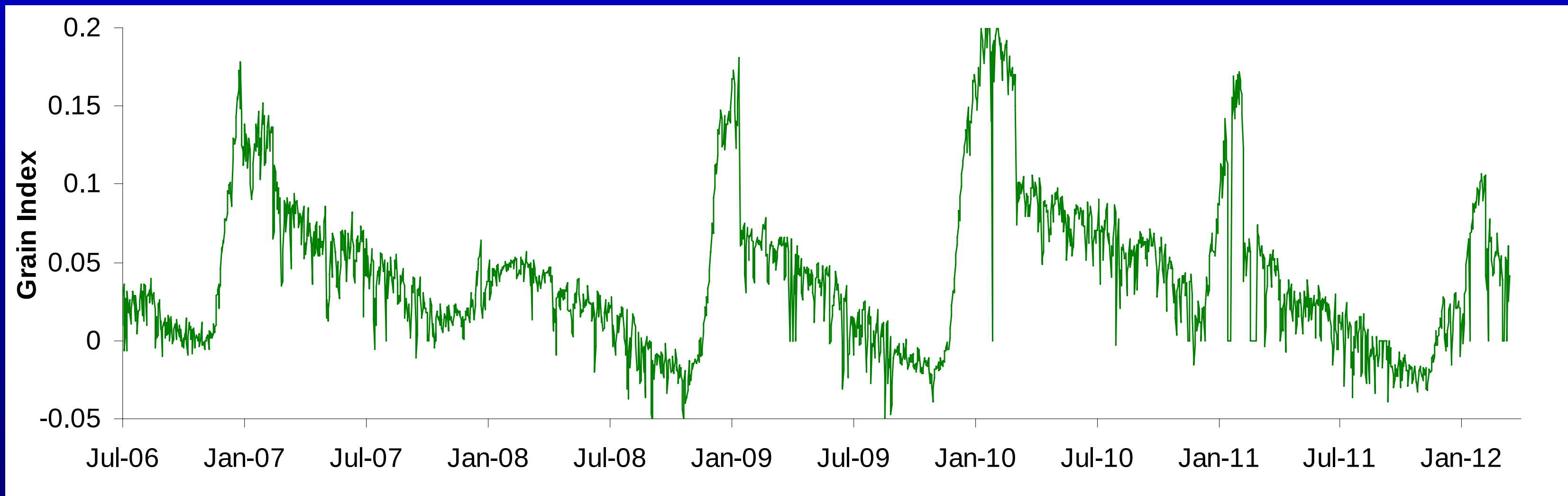
Changes in ε must be invoked, and ε changes over time

To reduce temperature effects, we define the Grain Index

$$GI = \frac{T_B^{89} - T_B^{150}}{T_B^{89}}$$

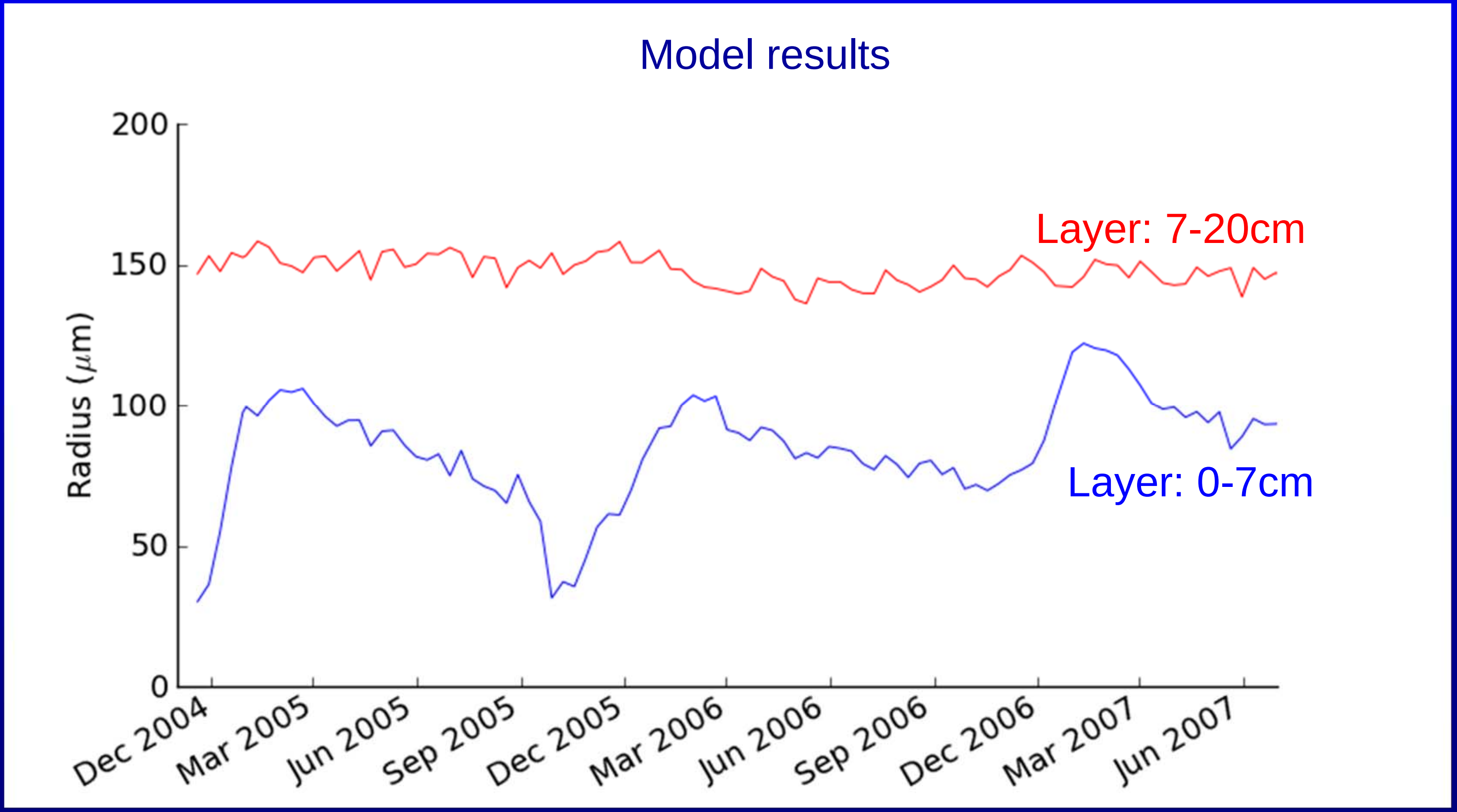
$$GI \approx 1 - A\langle \varepsilon \rangle_{0-7\,cm}$$

We test that GI in fact reflects grain size in the range 0-7 cm

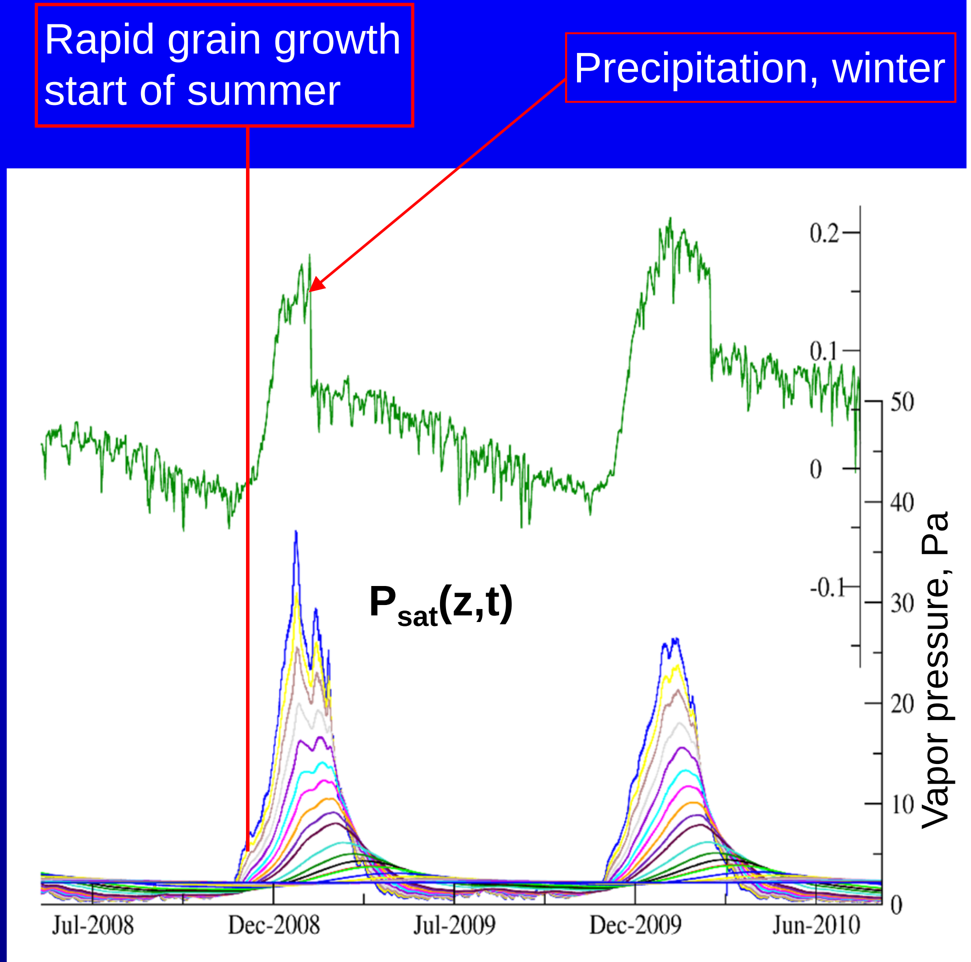


Test of hypothesis: microwave emission model

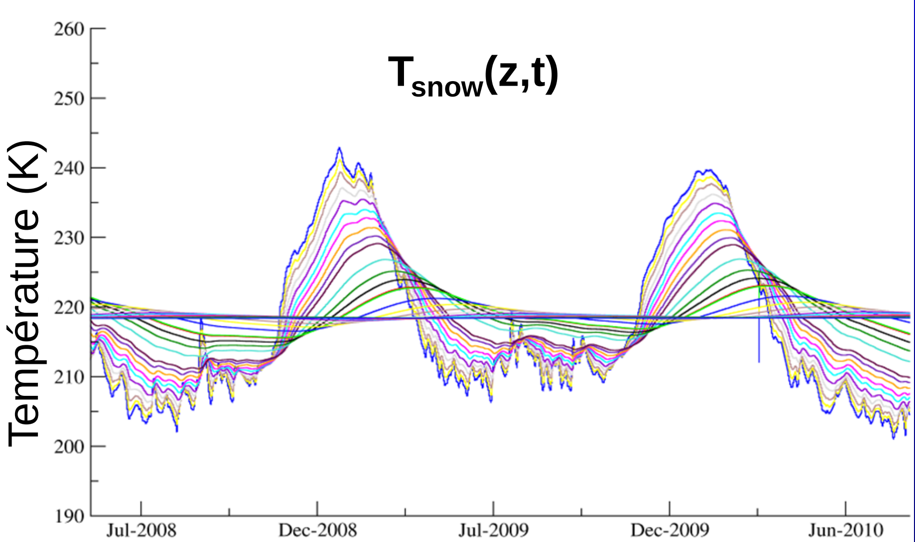
Inverse model of microwave signal to determine mean grain sizes at 0-7 cm and 7-20 cm



Test of hypothesis: thermodynamic snow model



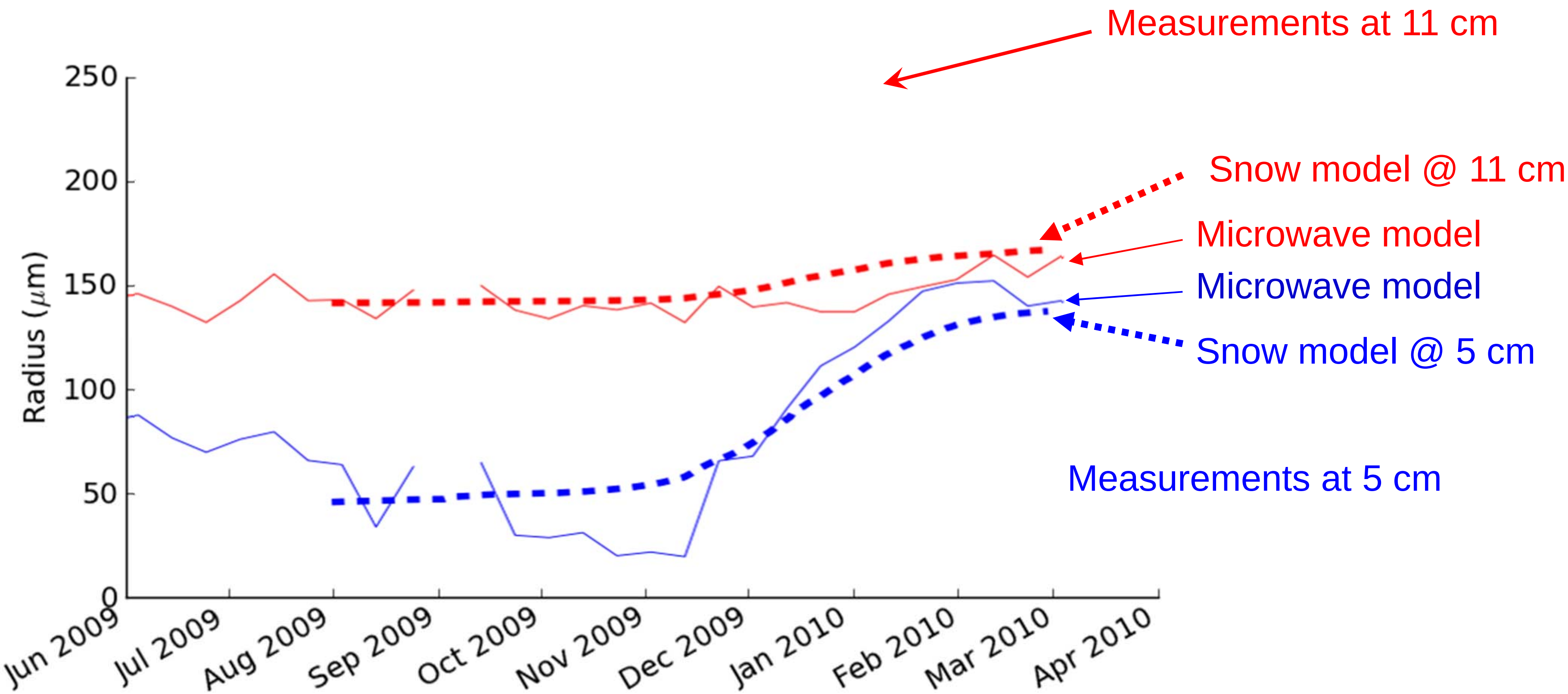
After JM Barnola

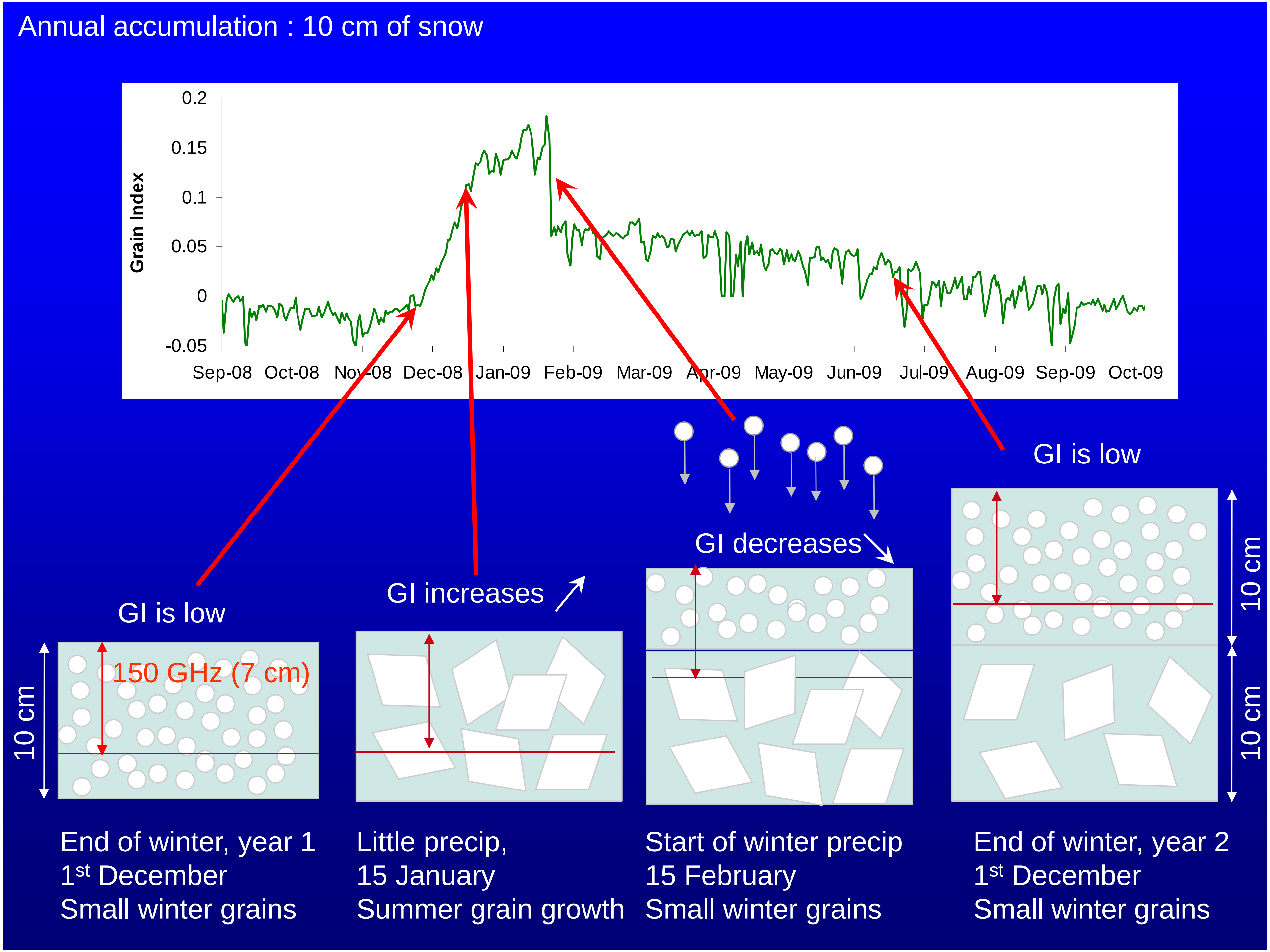


T strings measurements at 40 levels

Test of hypothesis: snow model + measurements

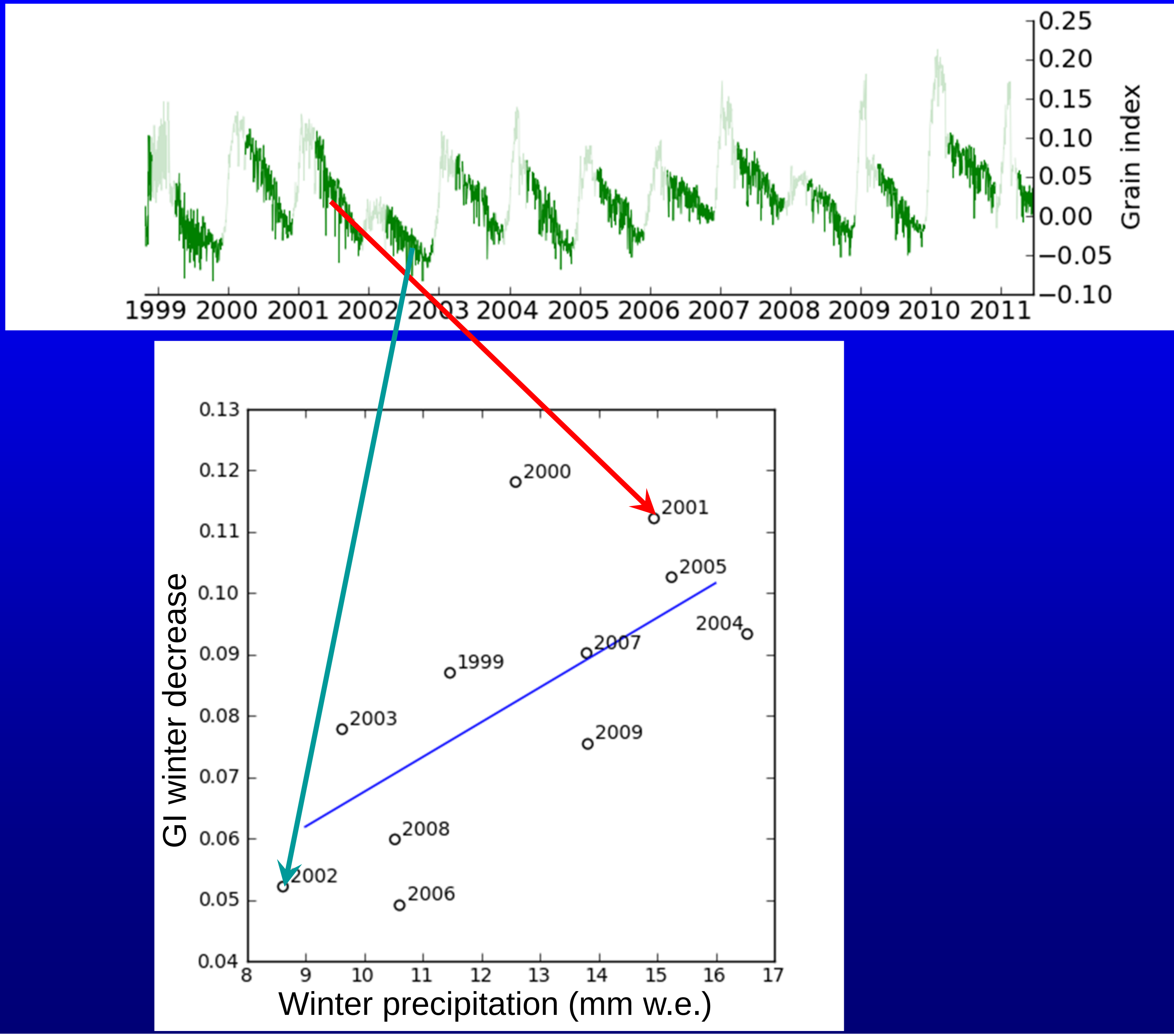
Run snow model to simulate grain growth



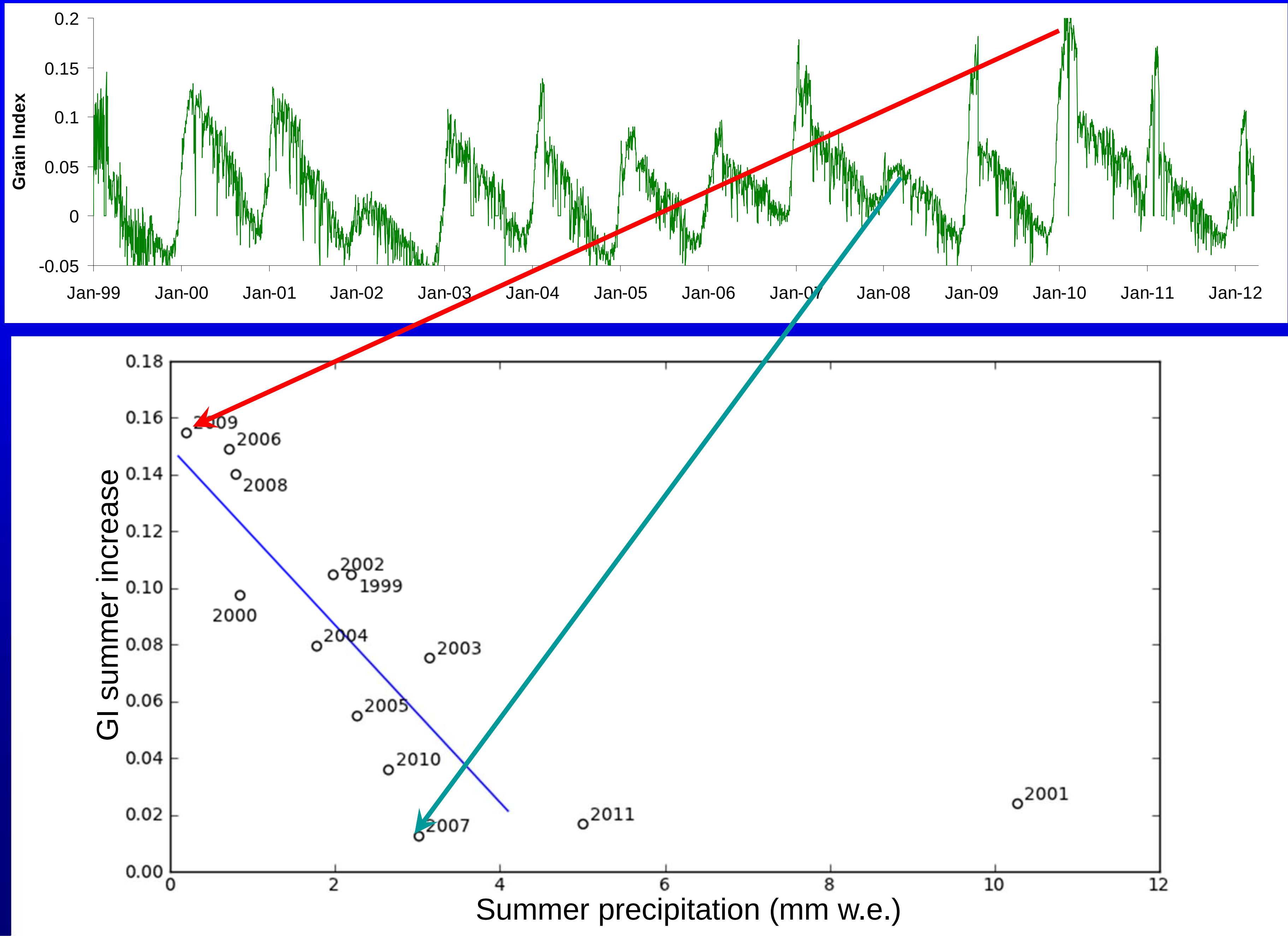


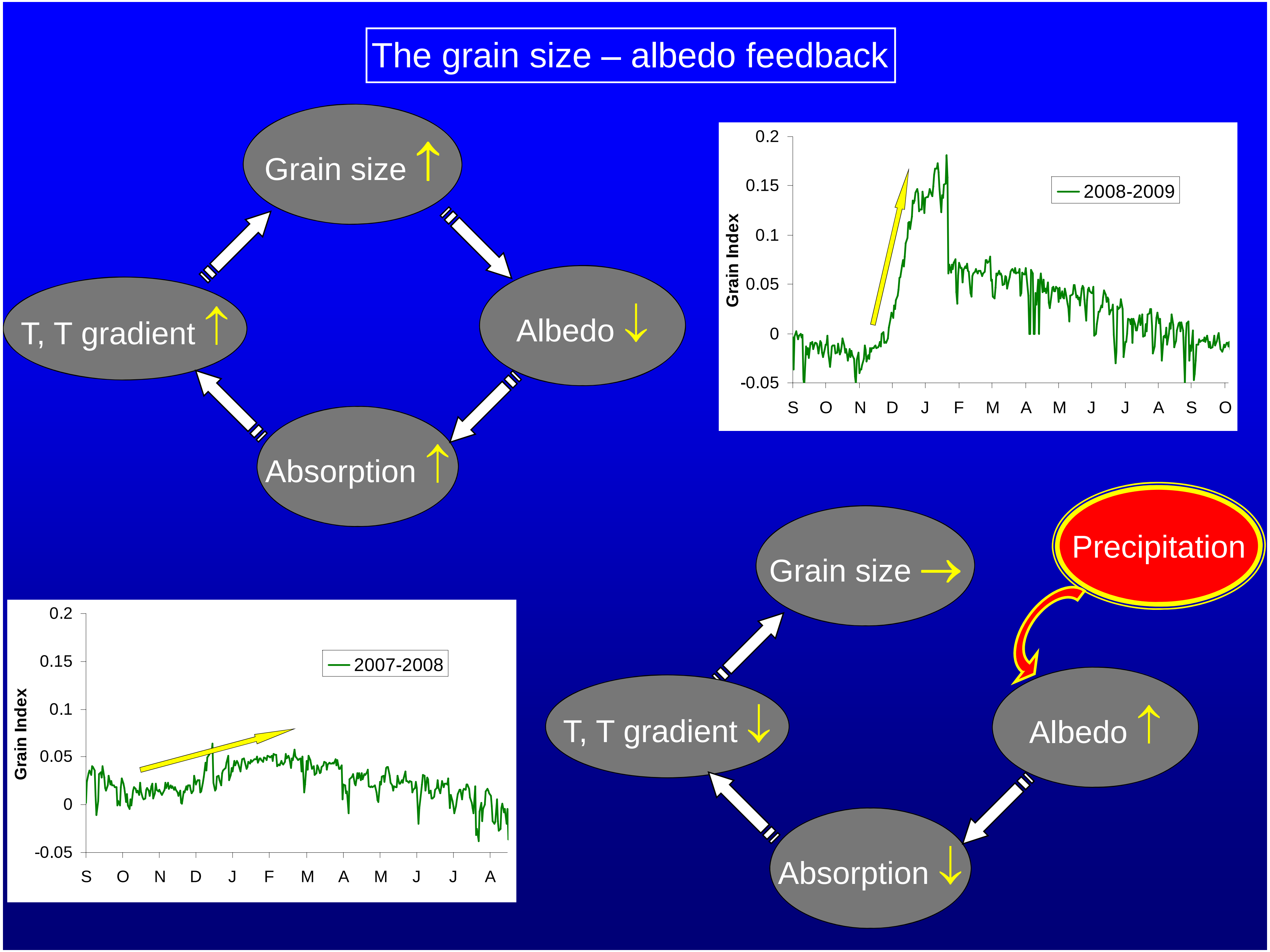
Annual accumulation : 10 cm of snow
Grain Index
0.2
0.15
0.1
0.05
0
-0.05
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
GI is low
150 GHz (7 cm)
10 cm
GI increases
GI decreases
GI is low
10 cm
10 cm
End of winter, year 1
1st December
Small winter grains
Little precip,
15 January
Summer grain growth
Start of winter precip
15 February
Small winter grains
End of winter, year 2
1st December
Small winter grains

Confirmation with interannual variability: winter



Confirmation with interannual variability: summer



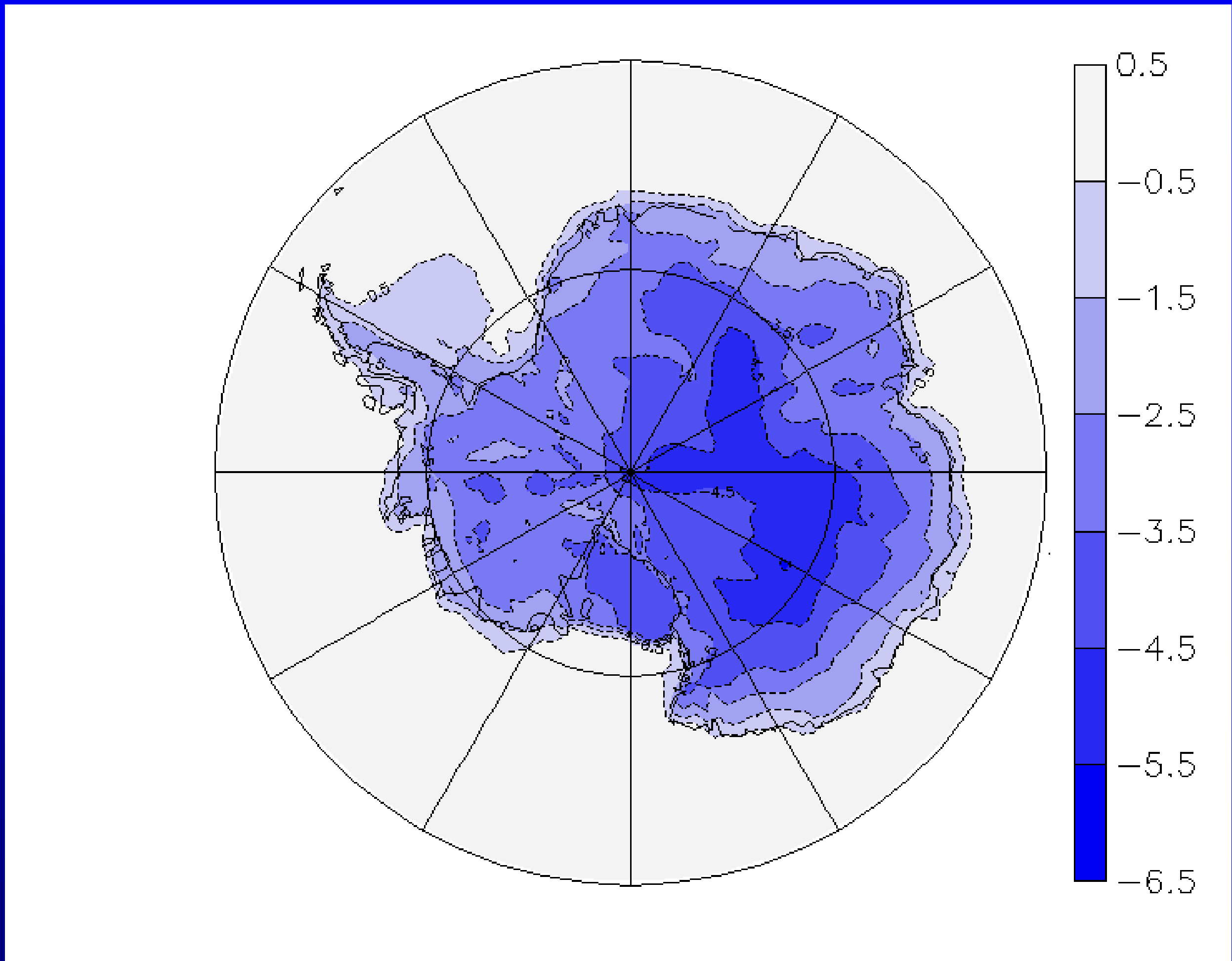


The grain size – albedo feedback
Grain size ↑
Albedo ↓
Absorption ↑
T, T gradient ↑
Grain Index
0.2
0.15
0.1
0.05
0
-0.05
S O N D J F M A M J J A S O
2008-2009
Precipitation
Grain size →
Albedo ↑
Absorption ↓
T, T gradient ↓
Grain Index
0.2
0.15
0.1
0.05
0
-0.05
S O N D J F M A M J J A
2007-2008

Impact of albedo increase on surface temperature

High summer precipitation ⇒ albedo increase of 0.03

Use LMDz GCM to calculate effect of albedo increase of 0.03



Summer mean

Future impact of this snow – albedo feedback

By 2100:

20 % increase in precipitation

3 K temperature rise

(SRES A1B GHG emission scenario)

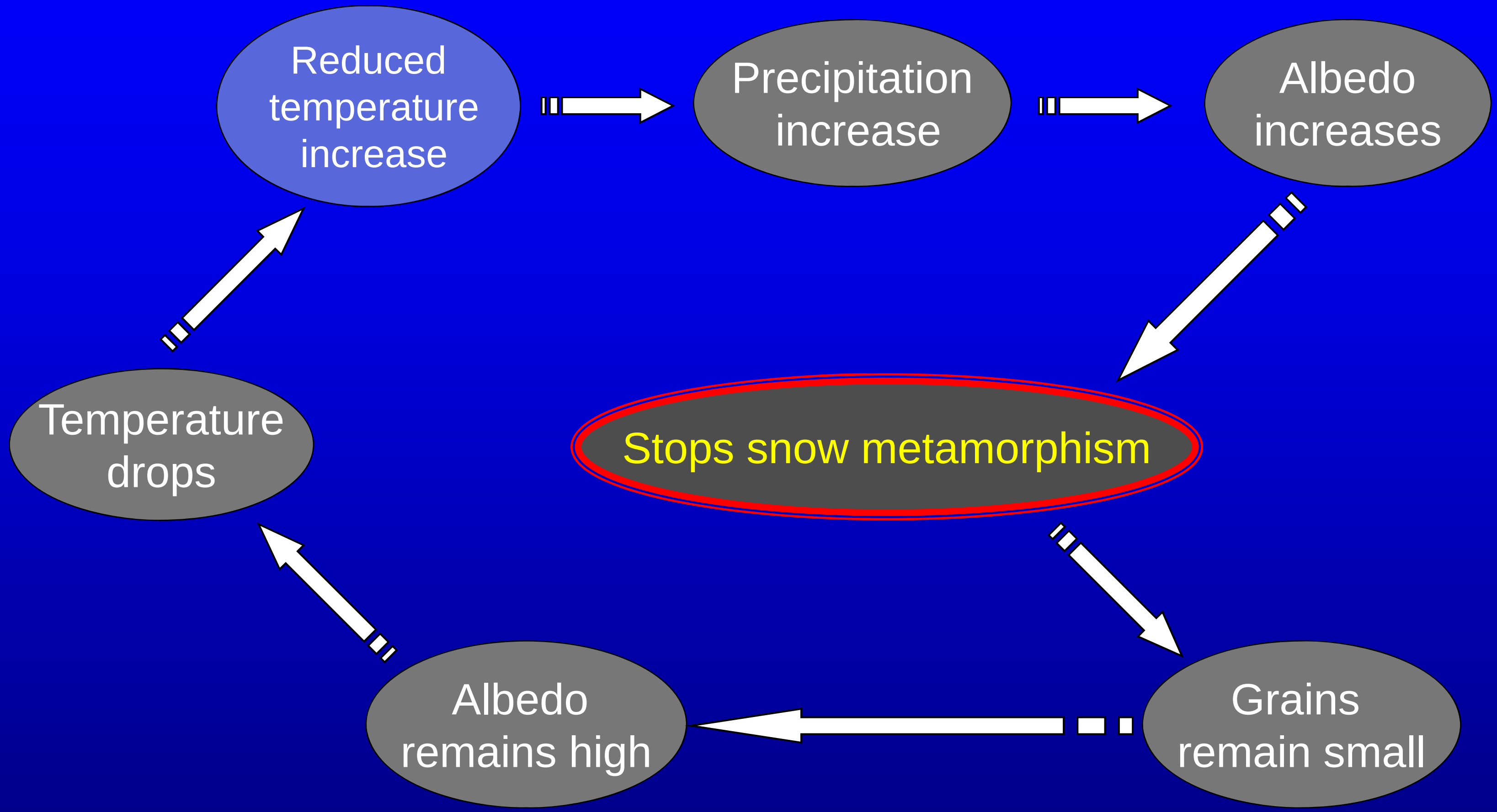
mean albedo increase of 0.004 ⇒ -1.5 W m^{-2} forcing

⇒ -0.5 °C in summer

⇒ -0.3 °C in annual mean

⇒ 10% negative feedback

Conclusion



Snow will save Antarctica from global warming !

Snow climate feedback 3:

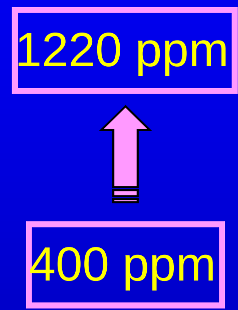
Permafrost, vegetation and snow

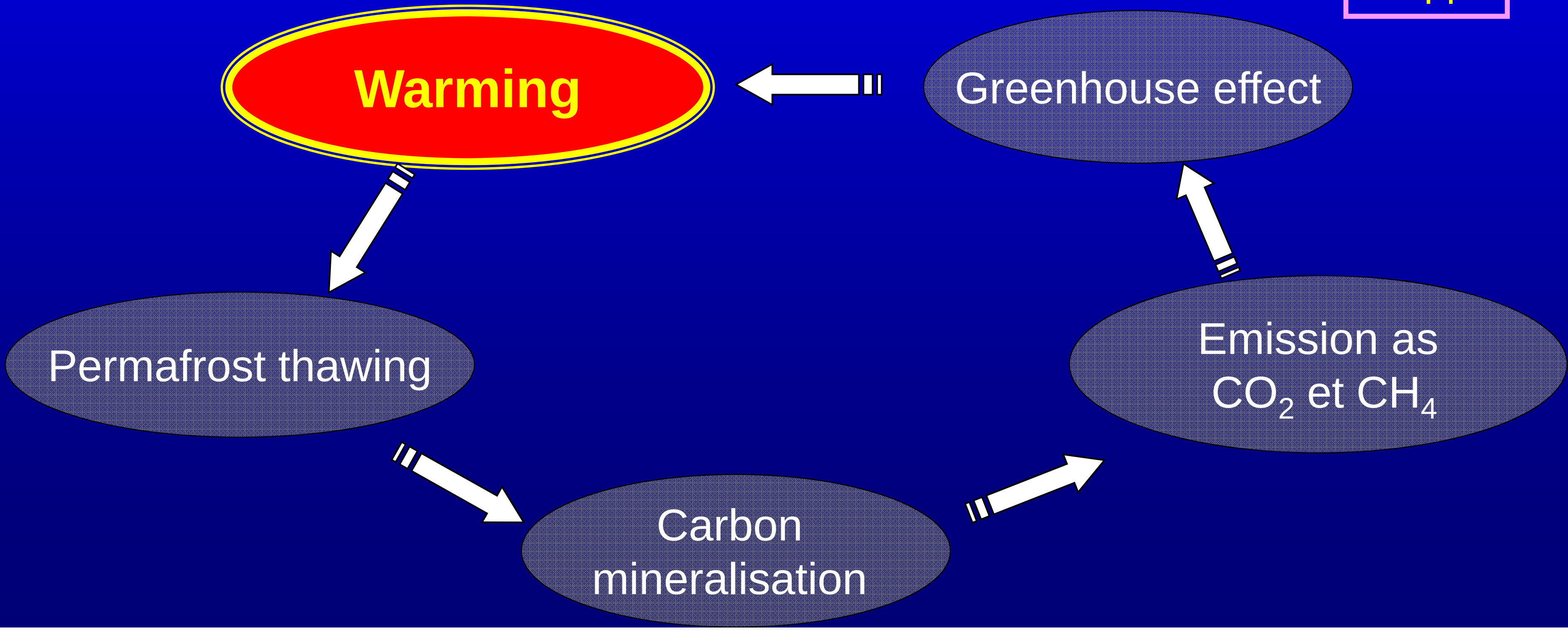
Permafrost

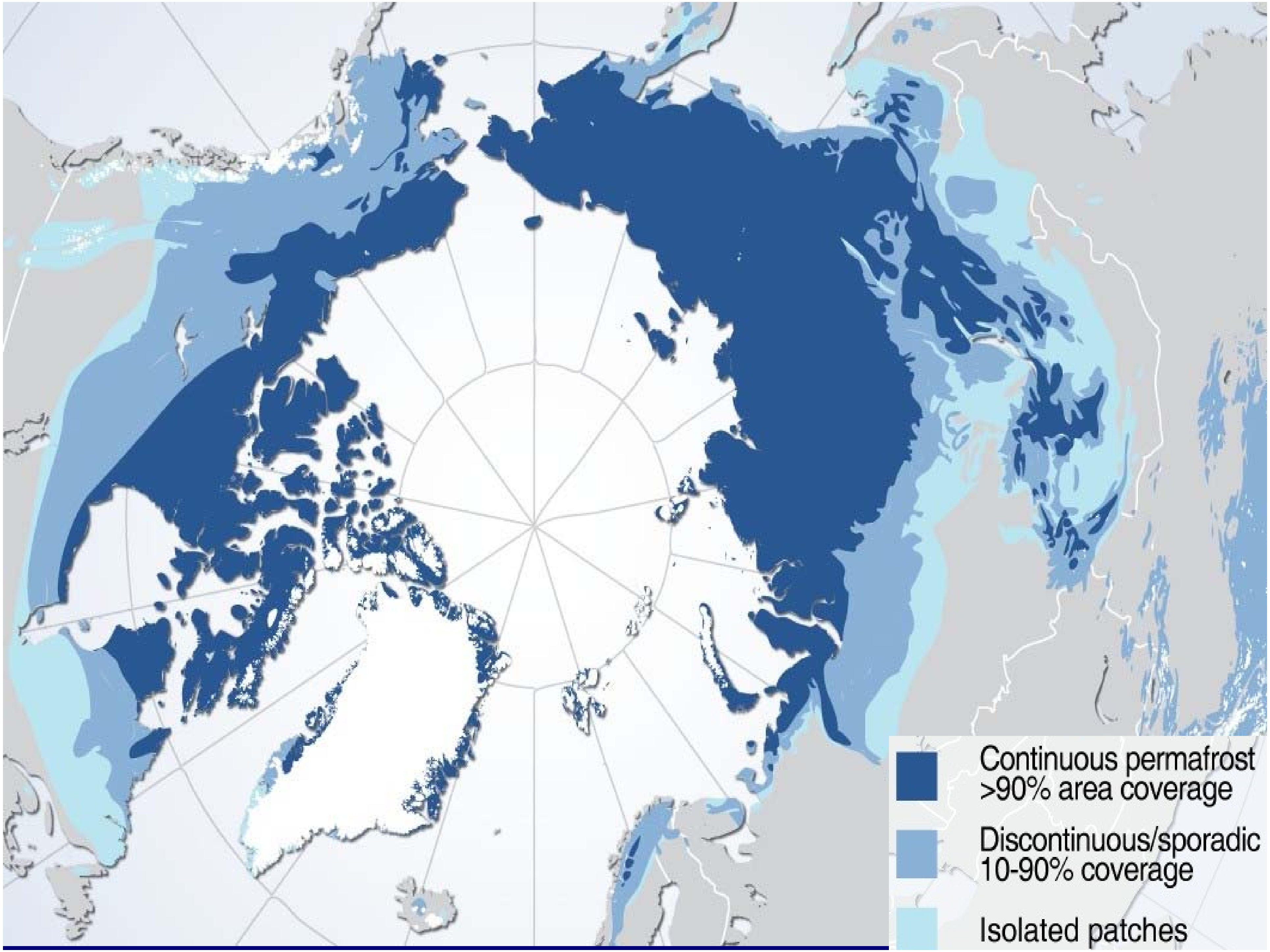
= ground that remains frozen for at least 2 consecutive years

→ Organic carbon reservoir : 1600 Pg C

Atmosphere :   730 Pg C






Continuous permafrost
>90% area coverage
Discontinuous/sporadic
10-90% coverage
Isolated patches

Questions

With climate warming :

→ How will the thermal regime of permafrost evolve ?

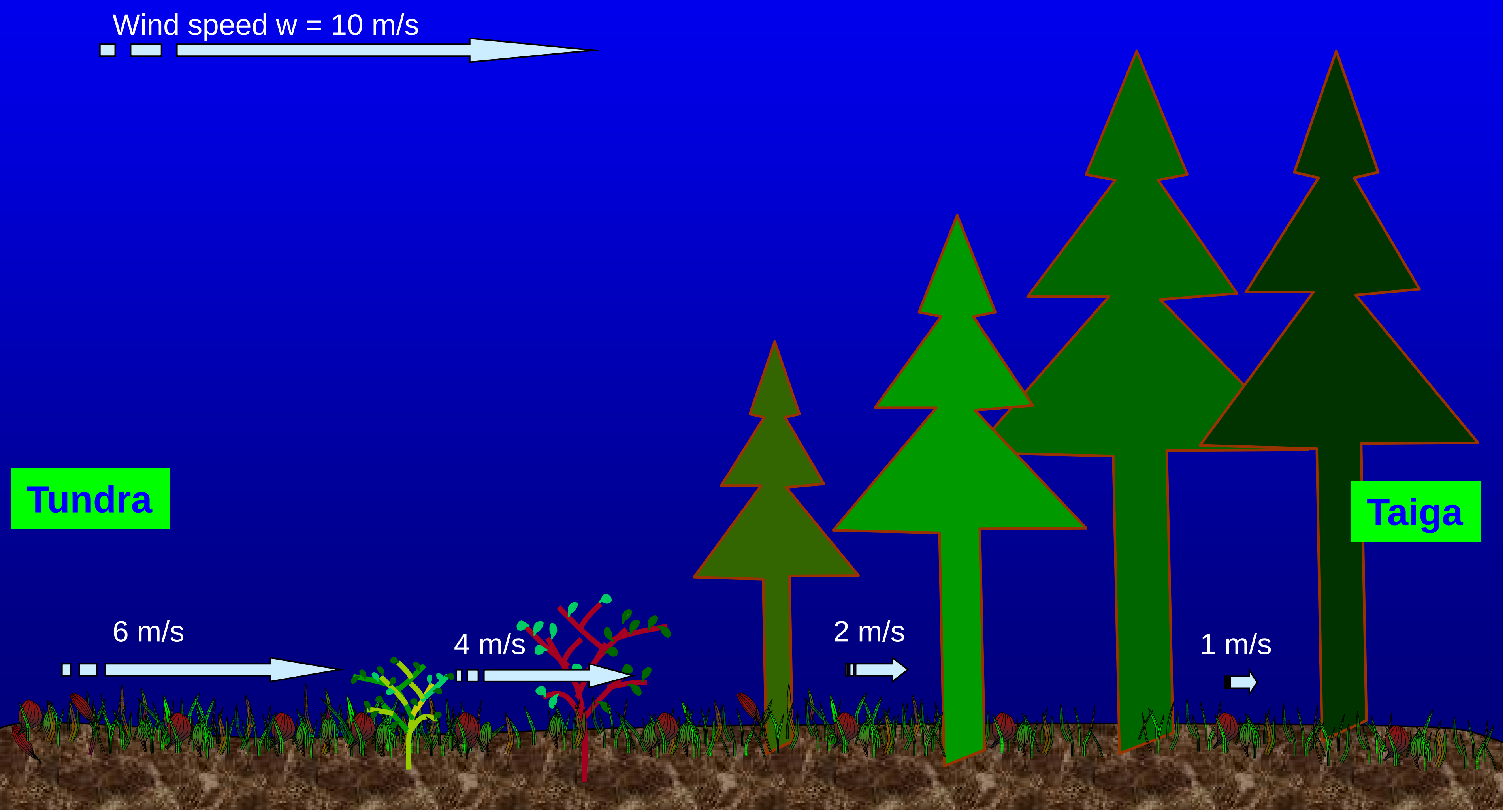
→ What is the fate of carbon in thawing permafrost ?

Factors affecting the energy budget of permafrost

Vegetation, wind speed and turbulent fluxes

Sensible heat flux : $H \propto w$

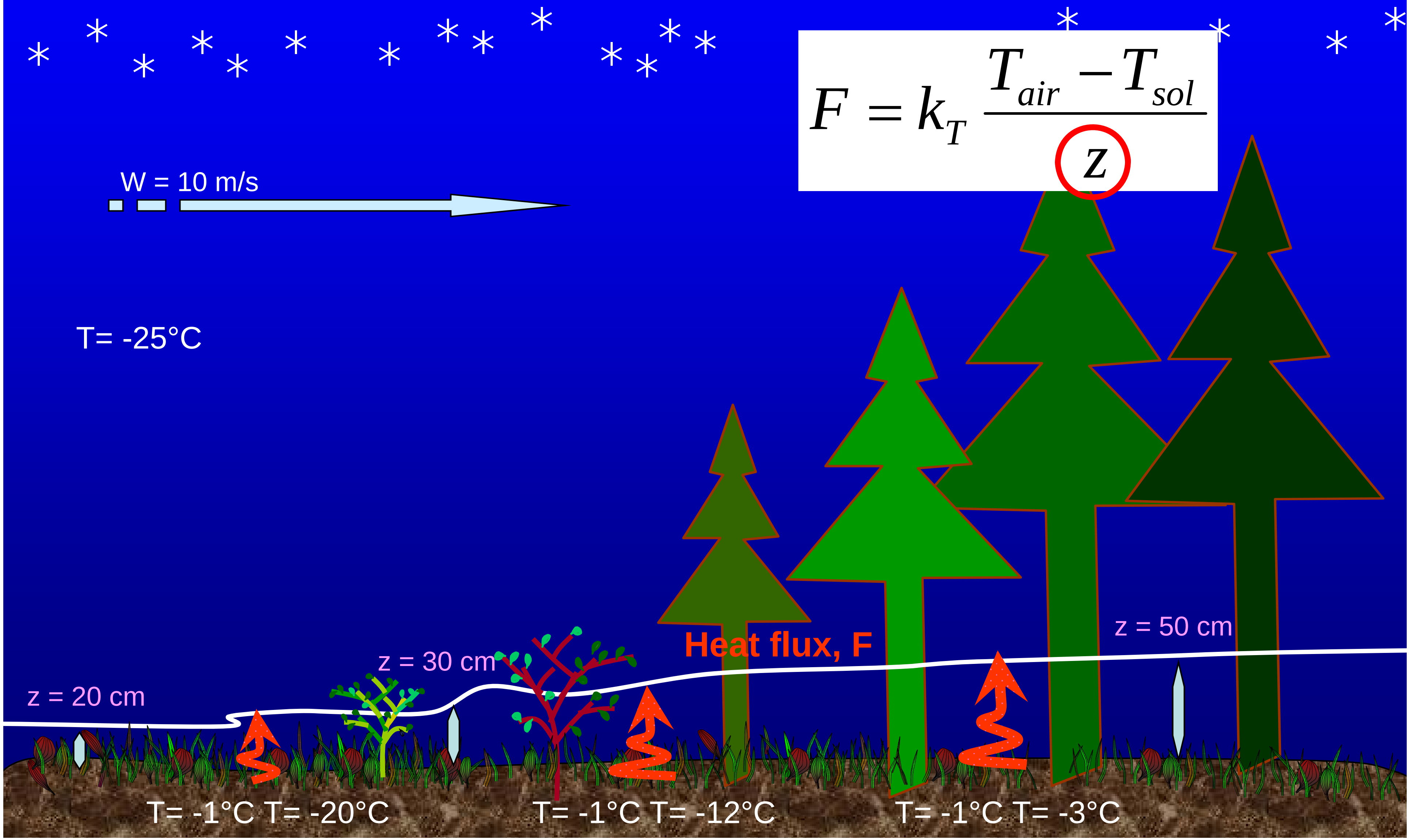
Latent heat flux : $L \propto w$



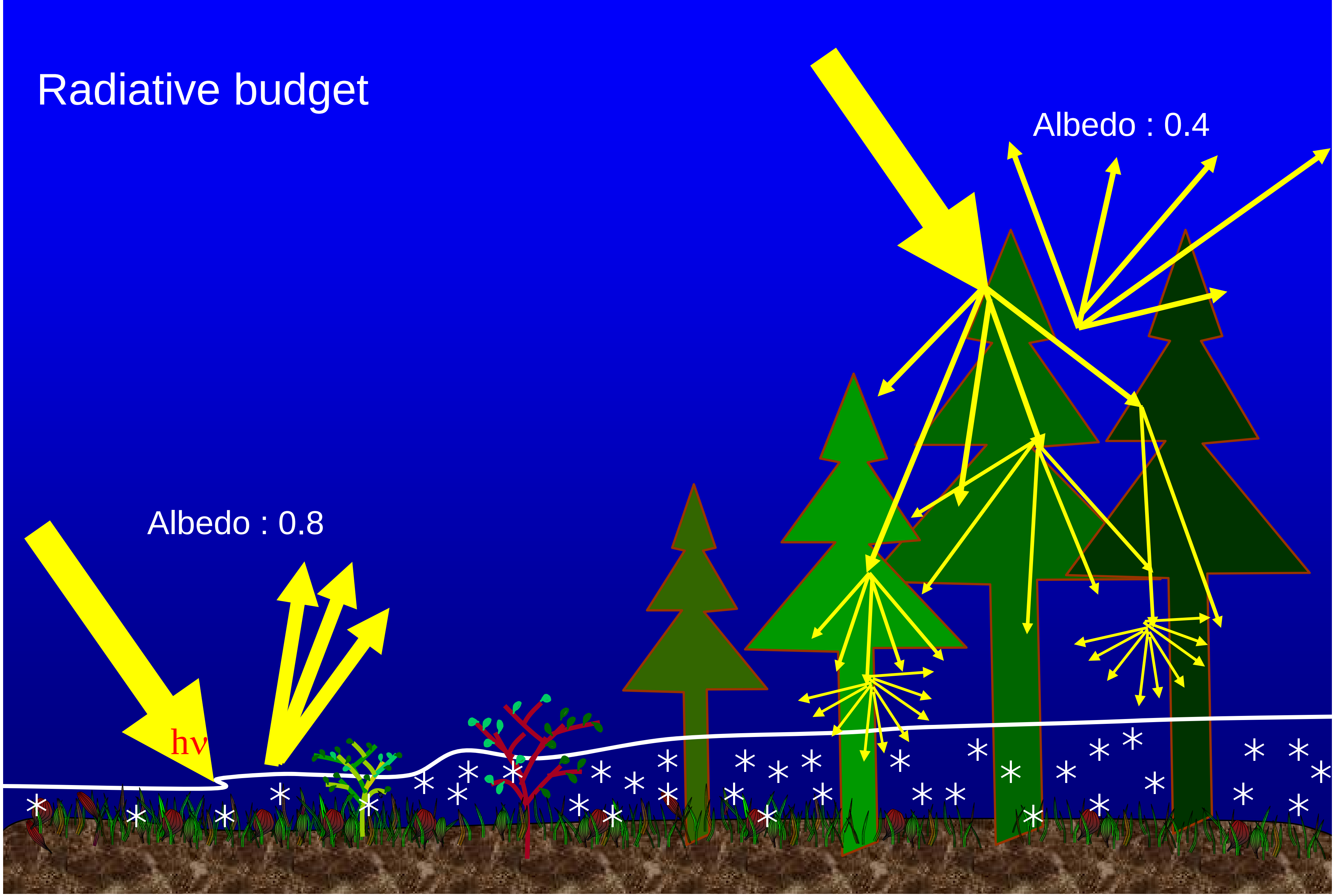
Factors affecting the energy budget of permafrost

Vegetation and snowpack height

$$F = k_T \frac{T_{air} - T_{sol}}{z}$$



Factors affecting the energy budget of permafrost



Result: impact of vegetation on the energy budget of permafrost

	Tundra	Taiga
Turbulent fluxes	High	Low
Conductive fluxes	High	Low
Albedo	High	Low
	3 -	0

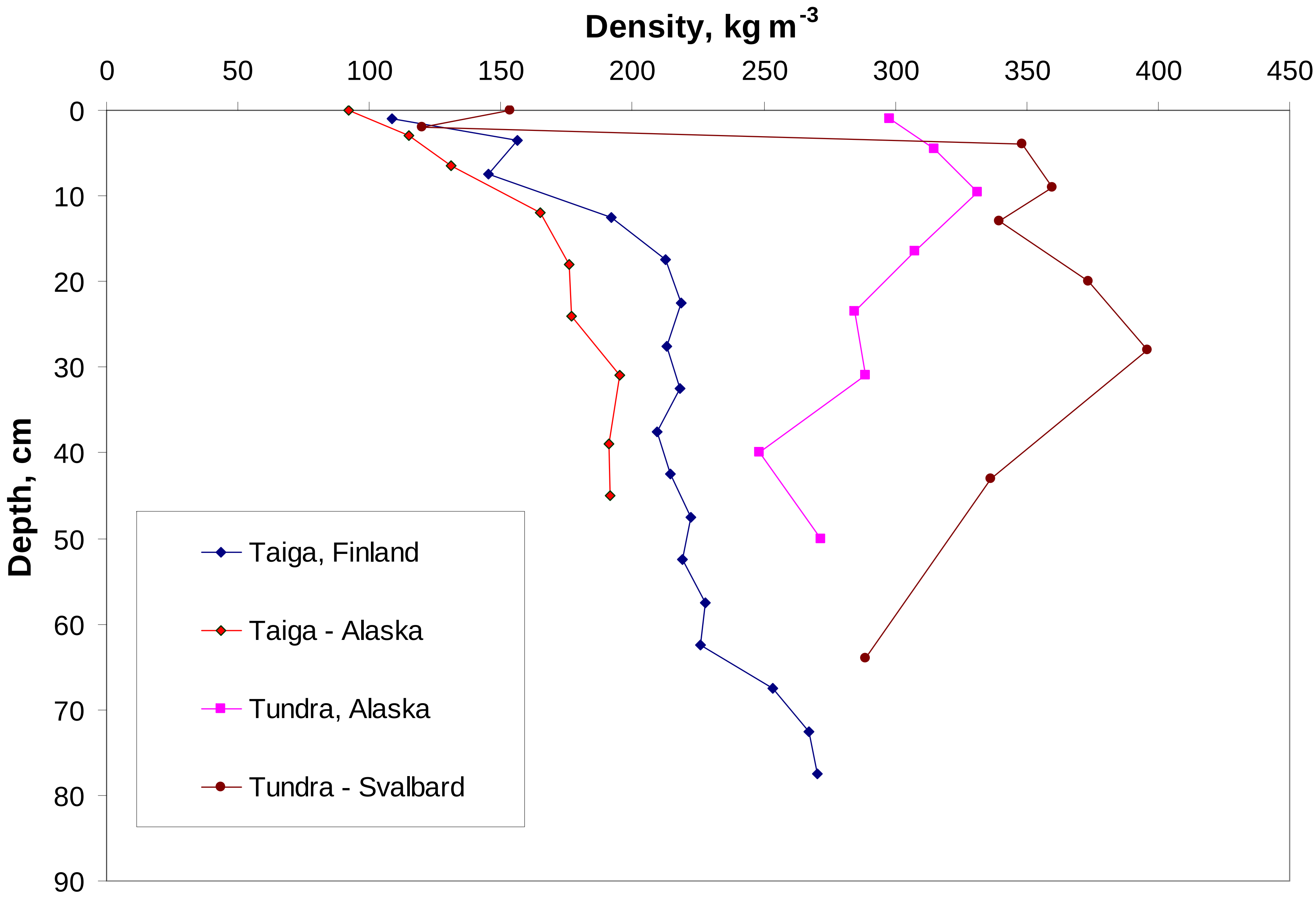
⇒ **Vegetation destabilizes permafrost**

Tundra snow

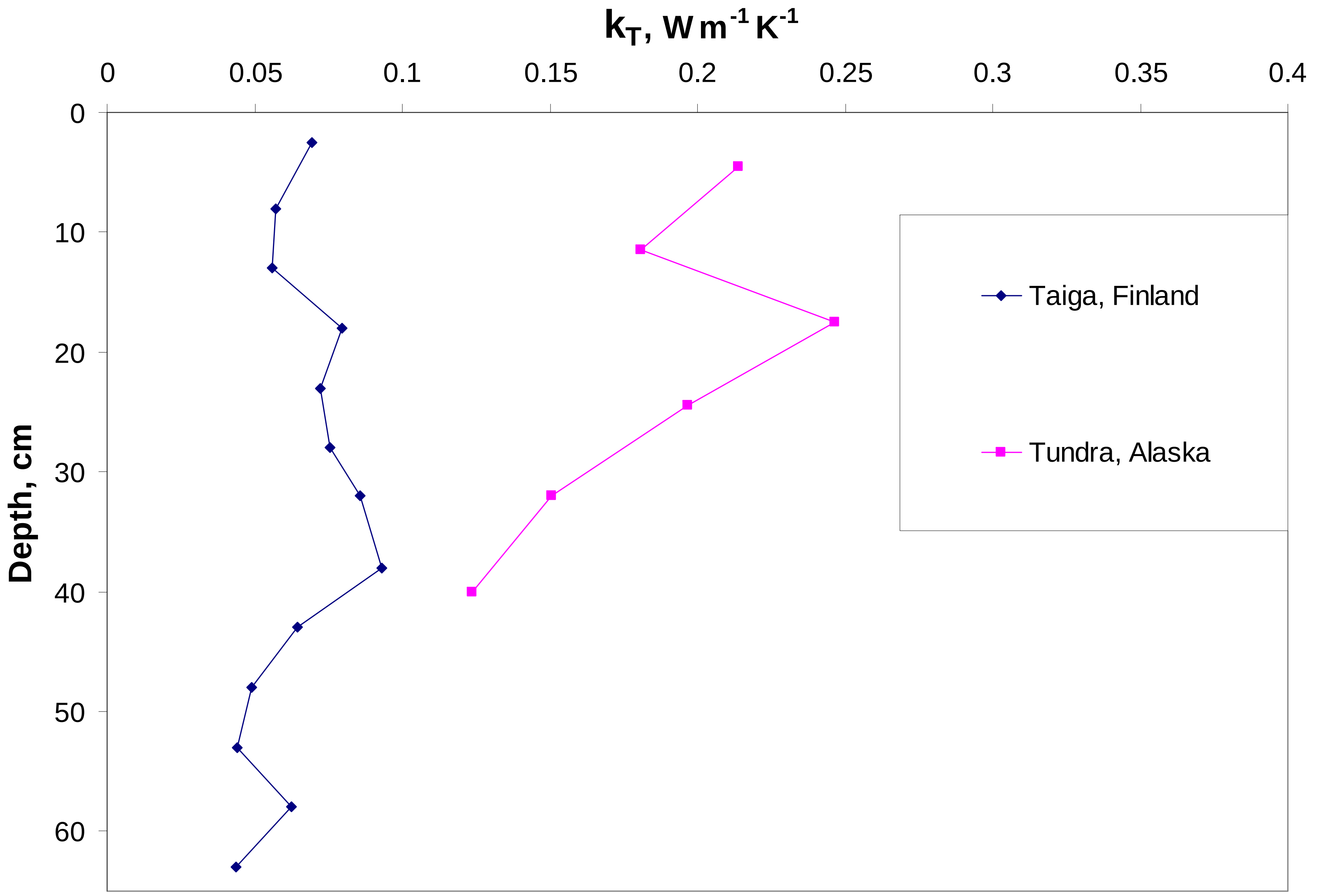
Barrow, Alaska

Wind crust

Density profiles



Thermal conductivity profiles

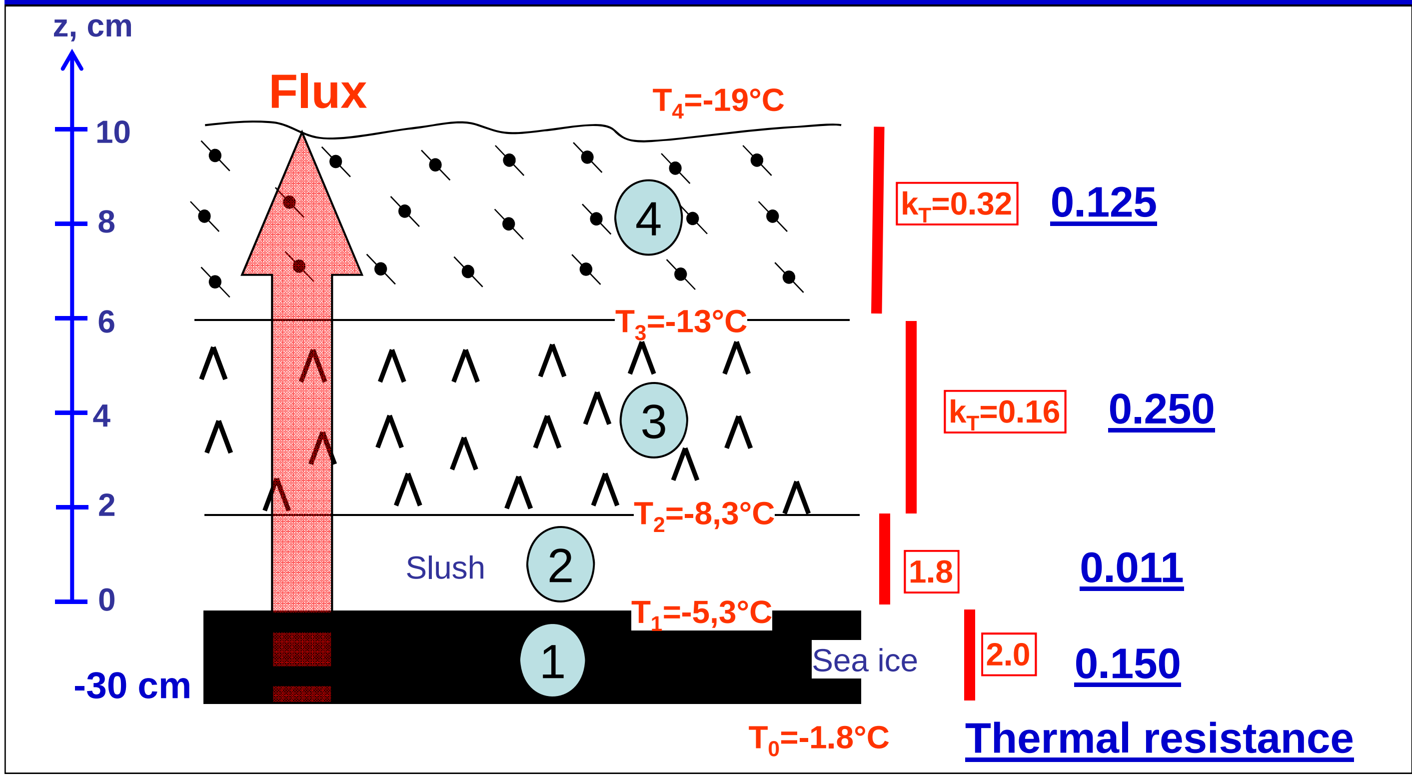


Thermal budget of snow

$$F = k_T \frac{T_{air} - T_{sol}}{z}$$

$$R_T = \sum_{\text{all layers}} \frac{h_i}{k_i}$$

$$F = \frac{T_{ground} - T_{snowsurface}}{R_T}$$



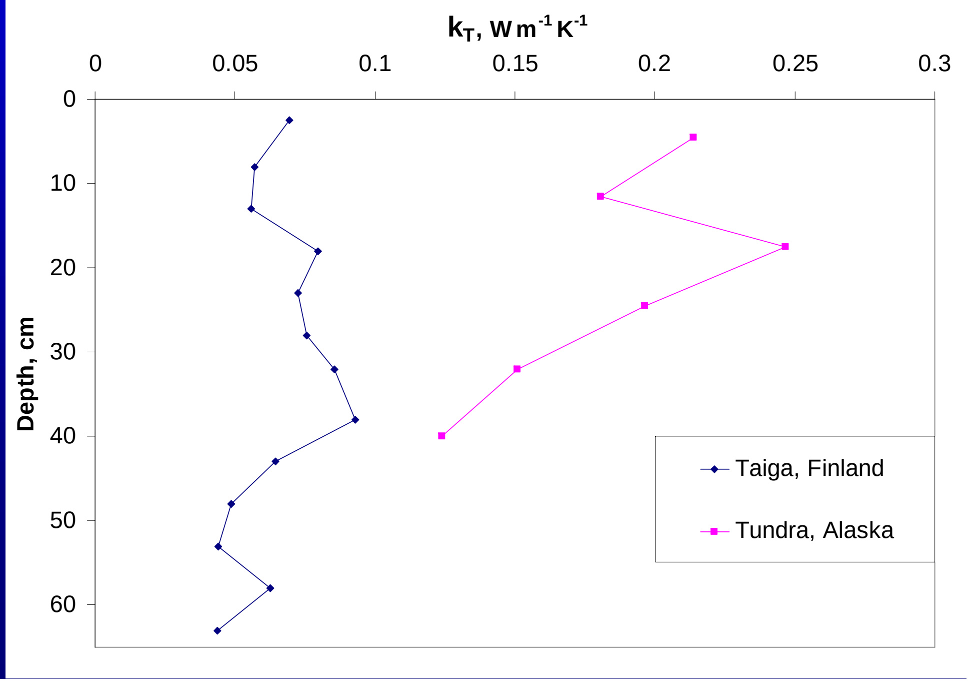
Thermal budget of snow

$$F = \frac{T_{ground} - T_{snowsurface}}{R_T}$$

R_{Tundra} = (3.7 ± 1.8) m^2 K W^{-1}

x 5

R_{Taiga} = (17.3 ± 4.0) m^2 K W^{-1}



Result: impact of vegetation on the energy budget of permafrost

	Tundra	Taiga
Turbulent fluxes	High	Low
Conductive fluxes	High	Low
Albedo	High	Low
Thermal conductivity	High	Low
	4	0

4 - 0

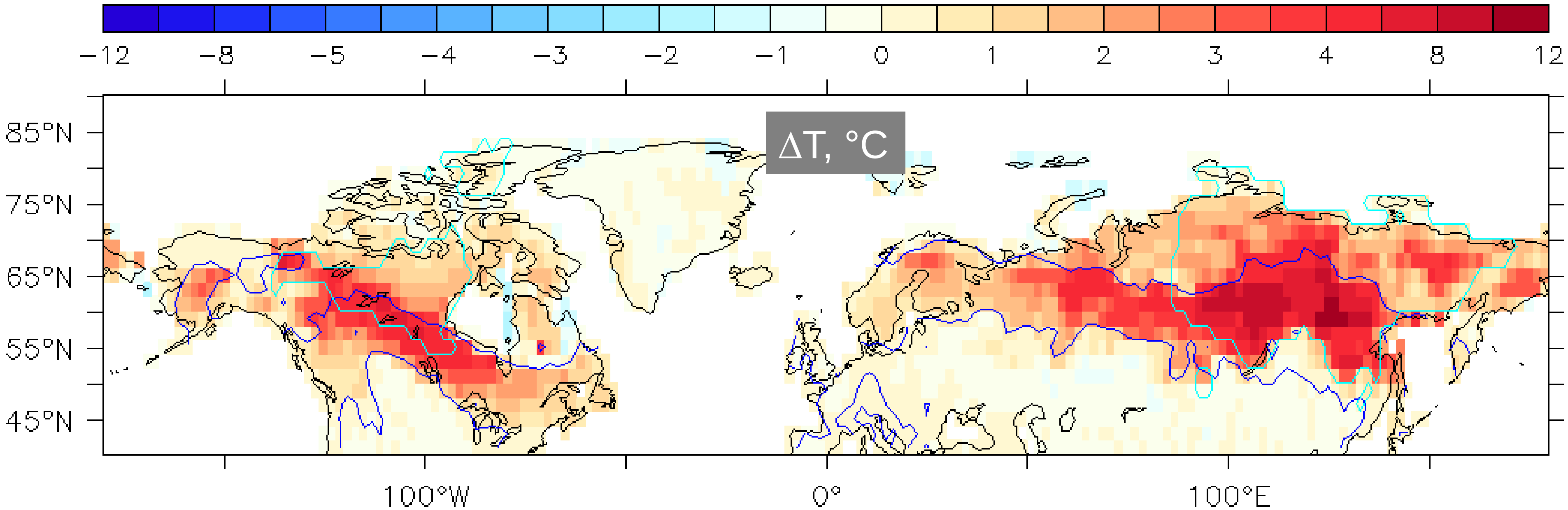
Partial quantification of the impact of vegetation

Land surface model (ORCHIDEE) to simulate the thermal regime of the ground and the dynamics of carbon stored in soils. ORCHIDEE forced by 20th century climate.

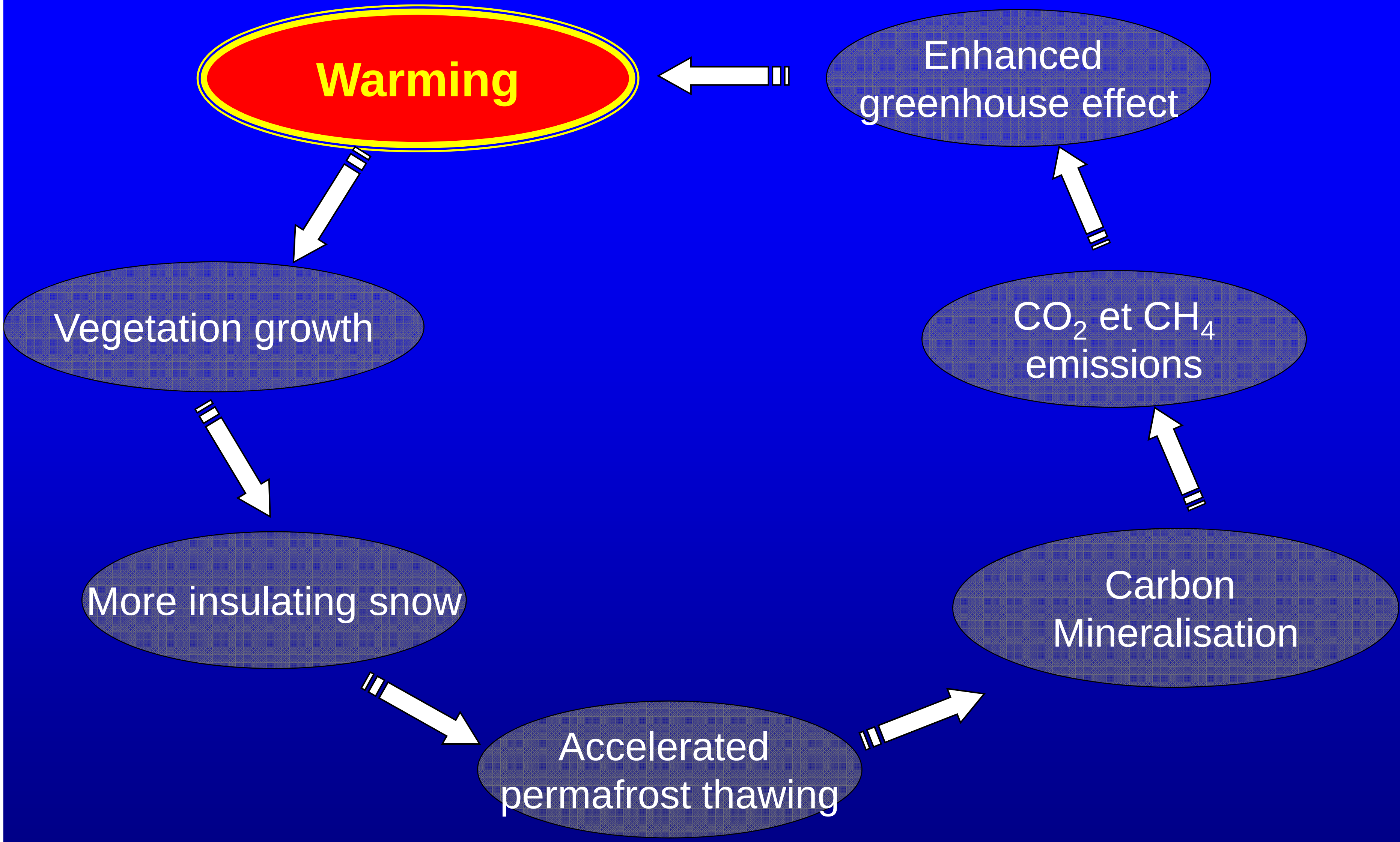
Testing the impact of snow physical properties : VARIED - CONTROL

VARIED	Tundra	Taiga
Density	330	200
Conducti.	0.25	0.07

CONTROL	Tundra	Taiga
Density	330	330
Conducti.	0.20	0.20



Gouttevin et al. (2012) JGR, 117, D02020



Snow will accelerate permafrost thawing !

Oil sands mining will save permafrost from global warming !!

Conclusion

→ Snow is the most reflective surface on Earth and affects the radiation budget

→ Snow forms an insulating layer on the ground

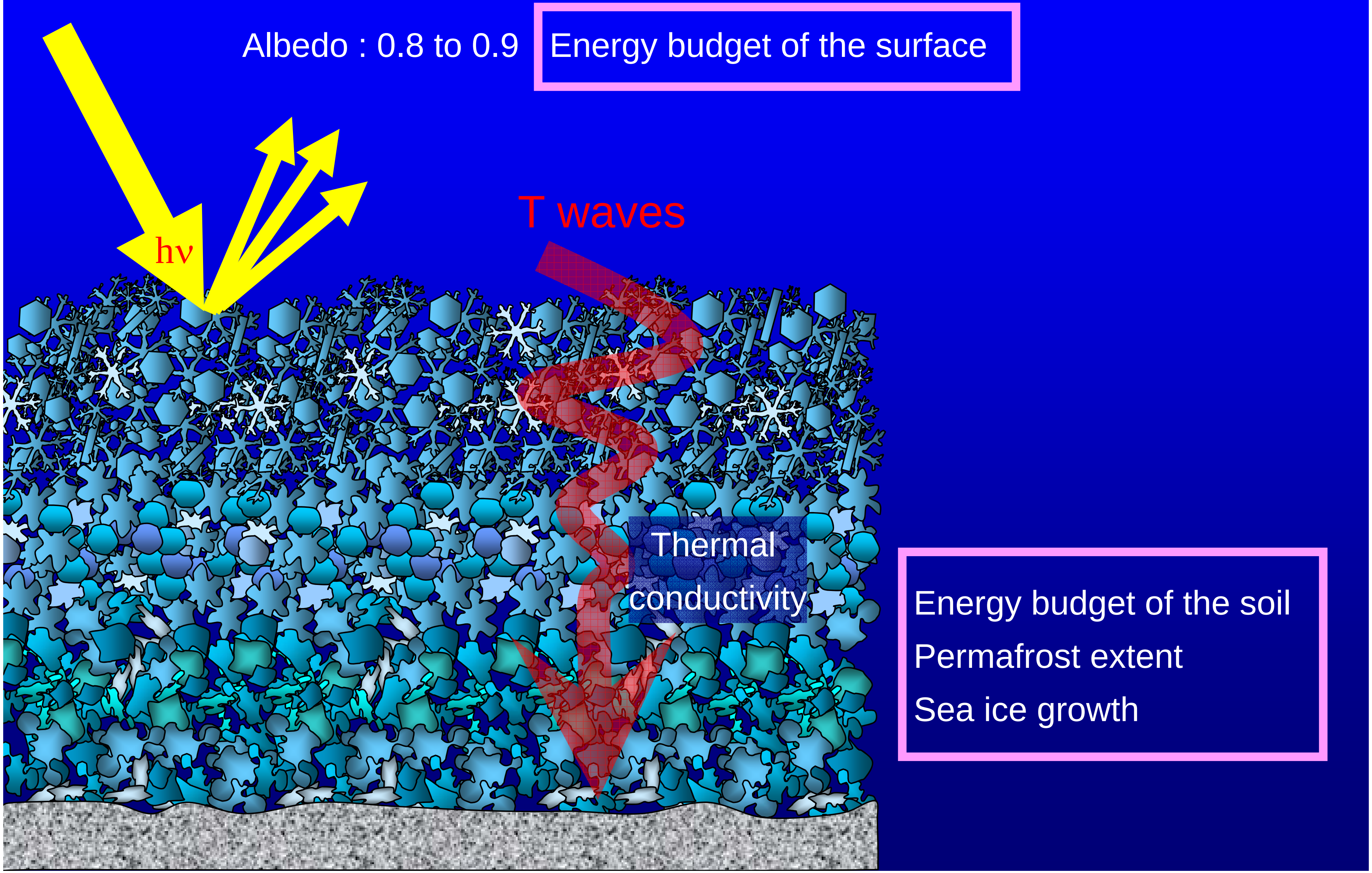
→ Snow physical properties are highly dependent on climate and ecosystems

→ There are many snow-climate feedbacks, some positive, some negative

→ Predicting climate change, especially in polar regions, requires a more detailed understanding of the many complex snow feedbacks.


Thank you !!
Polar research can be dangerous to your health

Physical properties of the snowpack



Rôles de la neige sur la banquise

Isolation thermique: limite le refroidissement de l'océan et la croissance de la glace de mer

Refroidit la surface: réfléchit la lumière solaire

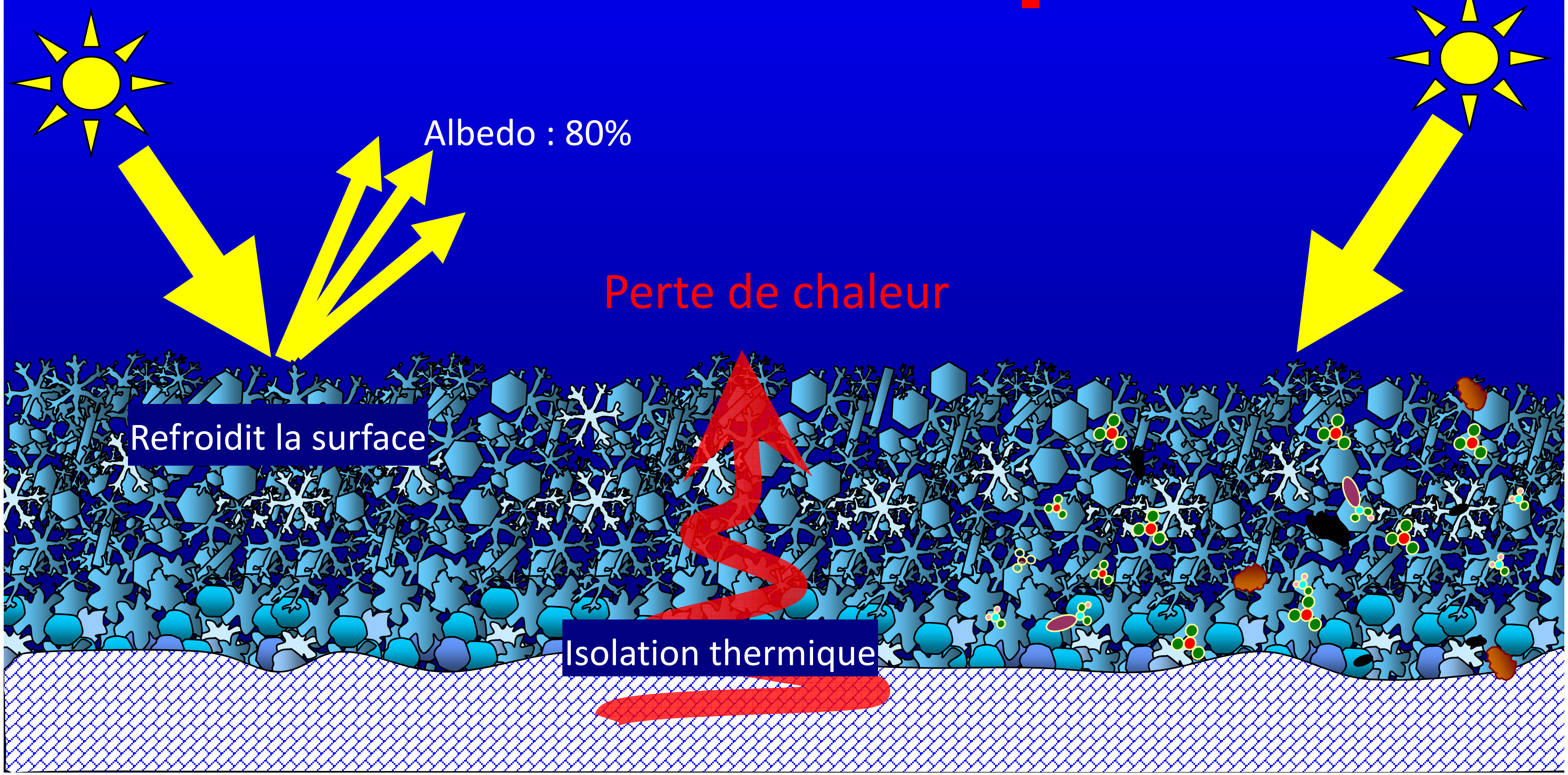
Rôle physique

Contient des impuretés: favorise des réactions chimiques, destruction de l'ozone

Rôle chimique

Contient des bactéries: modifie la composition de l'atmosphère

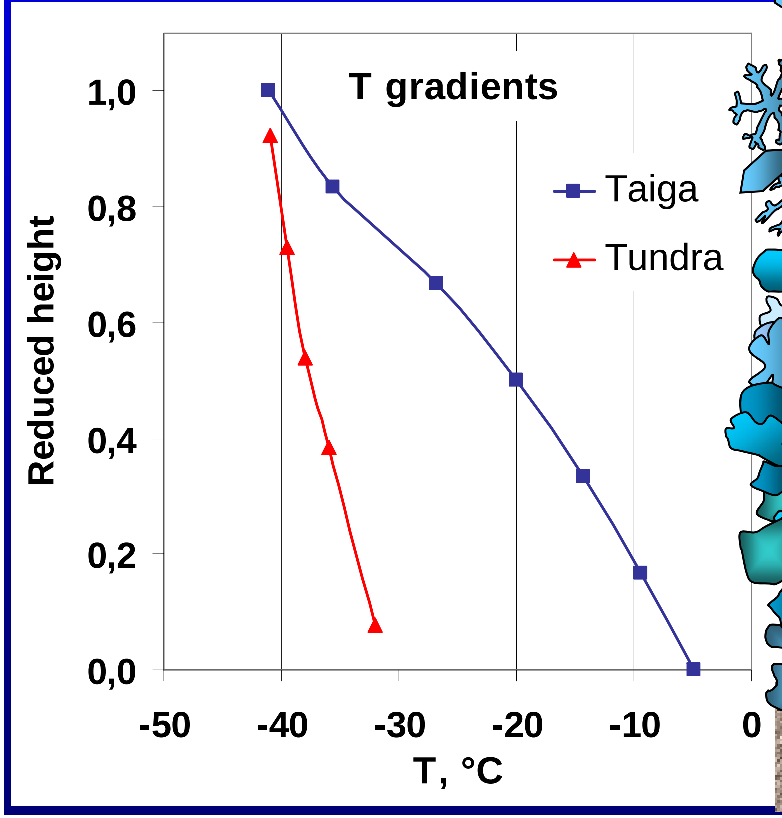
Rôle biologique

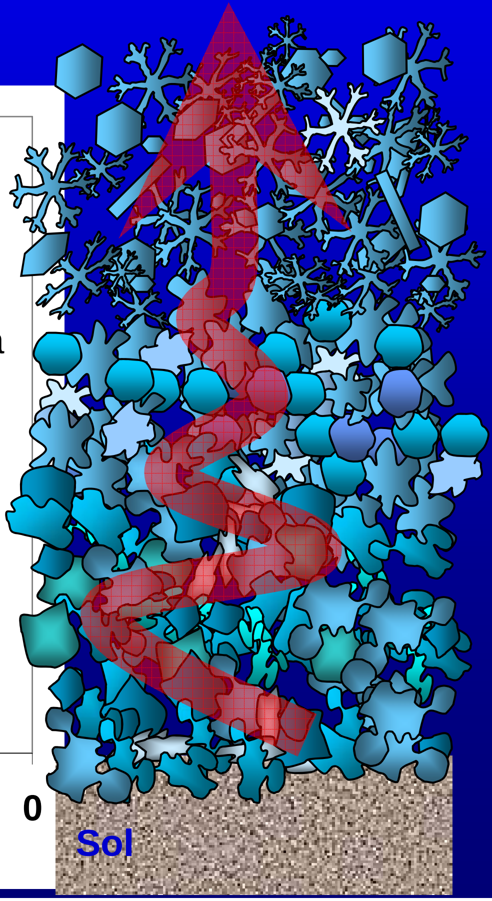


Thermal conductivity, k_T

$$F = -k_T \frac{\partial T}{\partial z}$$

Flux

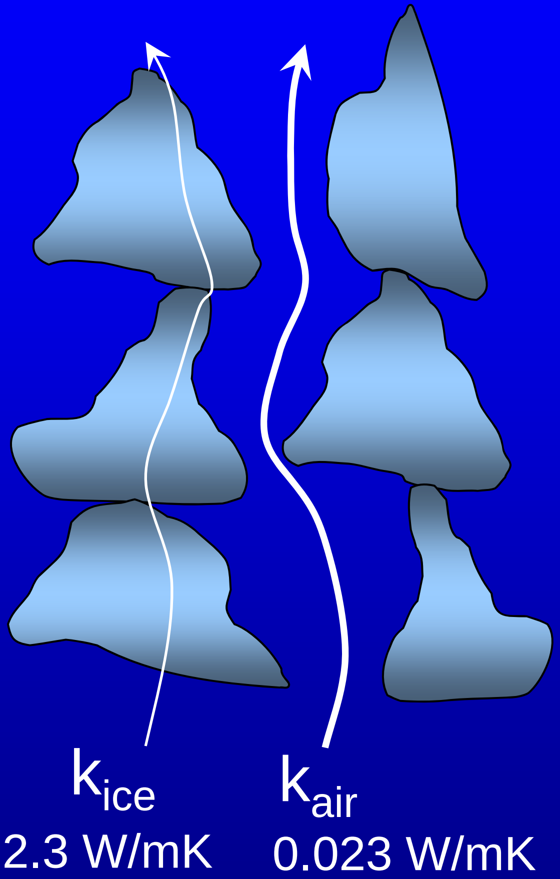




Material	k_T $Wm^{-1}K^{-1}$
Air	0.023
Wood	0.04 – 0.4
Water	0.6
Glass	1.1
Limestone	0.5
Ice	2.3
Stainless steel	15
Aluminium	237
Copper	401
Diamond	1000

High T gradient (cold)

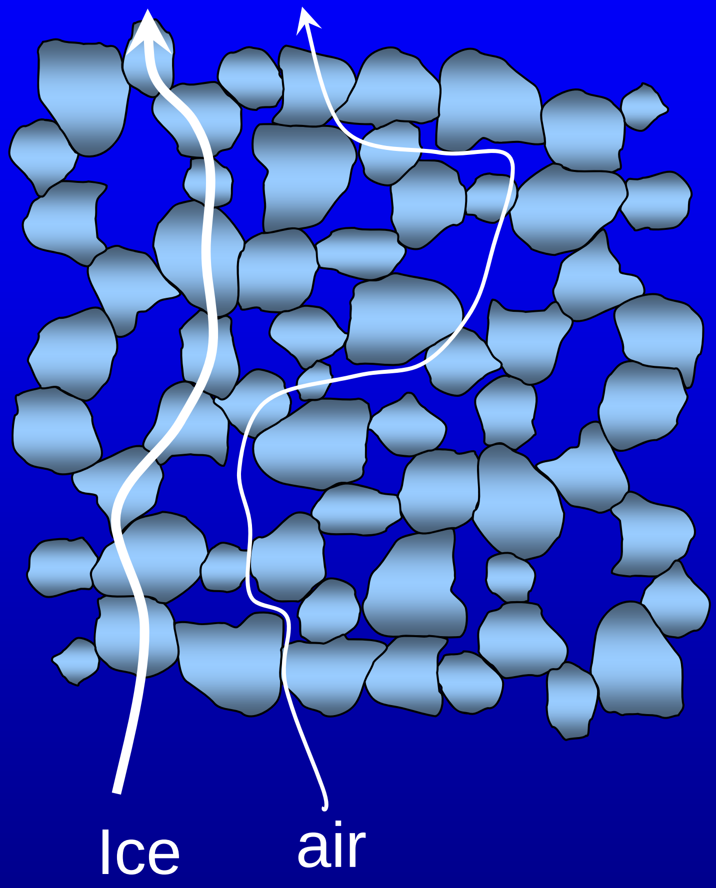
Depth hoar



$$k_T = 0.10 \text{ W m}^{-1} \text{ K}^{-1}$$

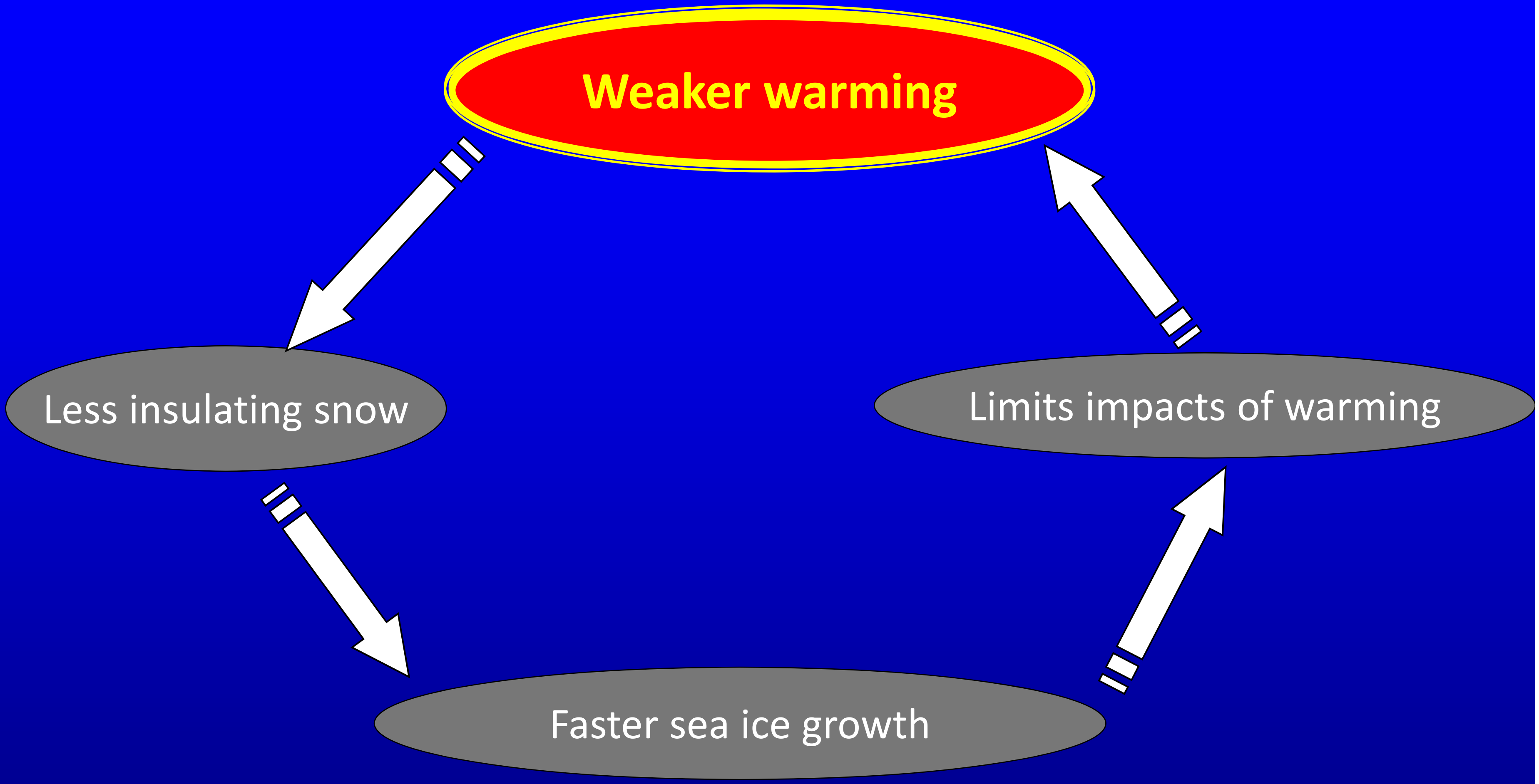
Low T gradient (warm)

Fine grained snow



$$k_T = 0.40 \text{ W m}^{-1} \text{ K}^{-1}$$

Insulating power of snow and climate



Negative feedback

Are there positive feedbacks ?