Snow on sea ice (**SOSI**): The real world and ESMs

Martin V, 10 janvier 2024; for the IPSL snow-group

SOSI science

- Fairly small community
  - **Sea ice** people do not care much about snow.
  - **Snow** people rarely go on sea ice.
- Snow on **sea ice** unlike that on **land** and **ice sheets**
- ESM representation: fairly simple

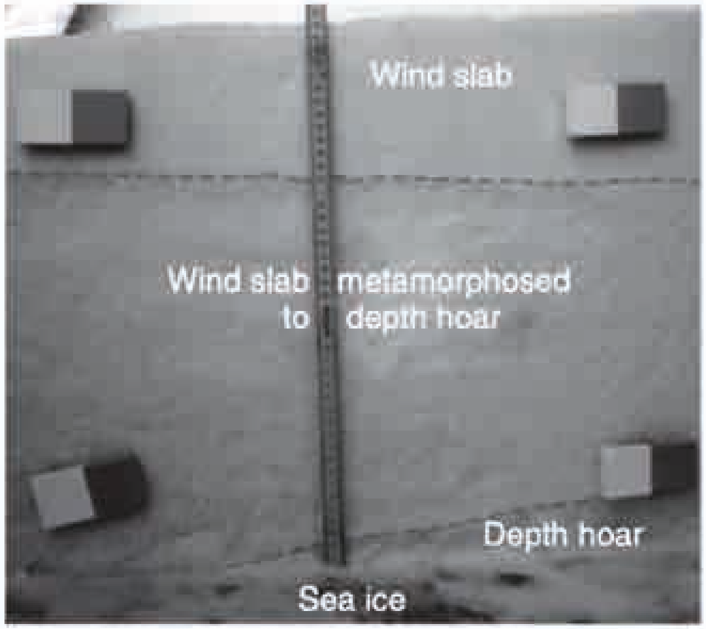
The real world

Snow falls, also on sea ice

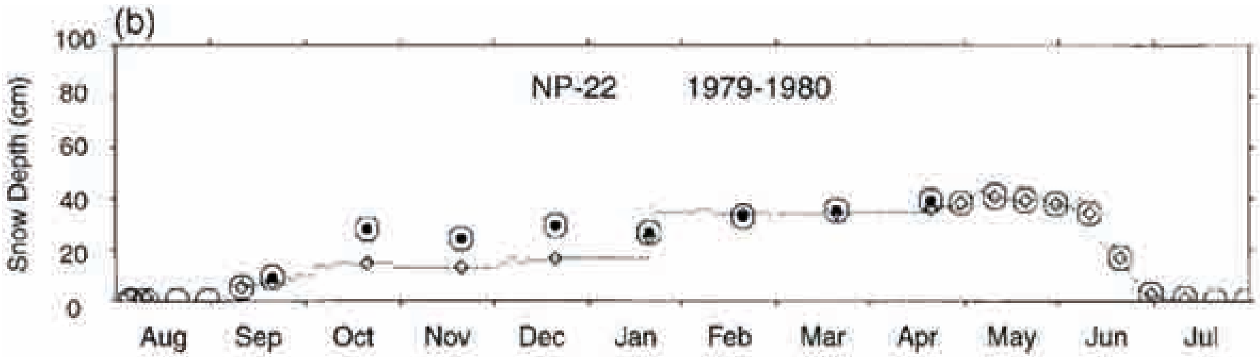
- 2 sea ice regions
- Arctic is a desert (30 cm snow/yr)
  Antarctic is more wet (>1m snow/yr)
- Arctic snow depth ~ 30 cm
  Antarctic snow depth ~ 20-100 cm

Snow on Arctic sea ice

- A few snow fall episodes in **fall** and **spring**
- Complete loss in summer
- 2 layer system: wind slab and depth hoar



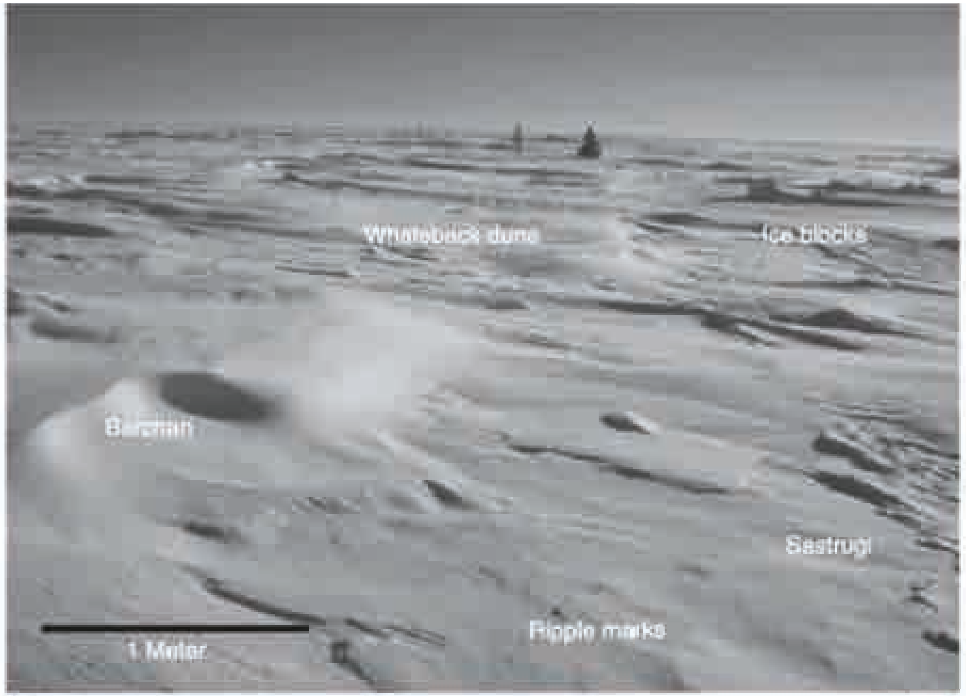
Sturm and Massom (2017)

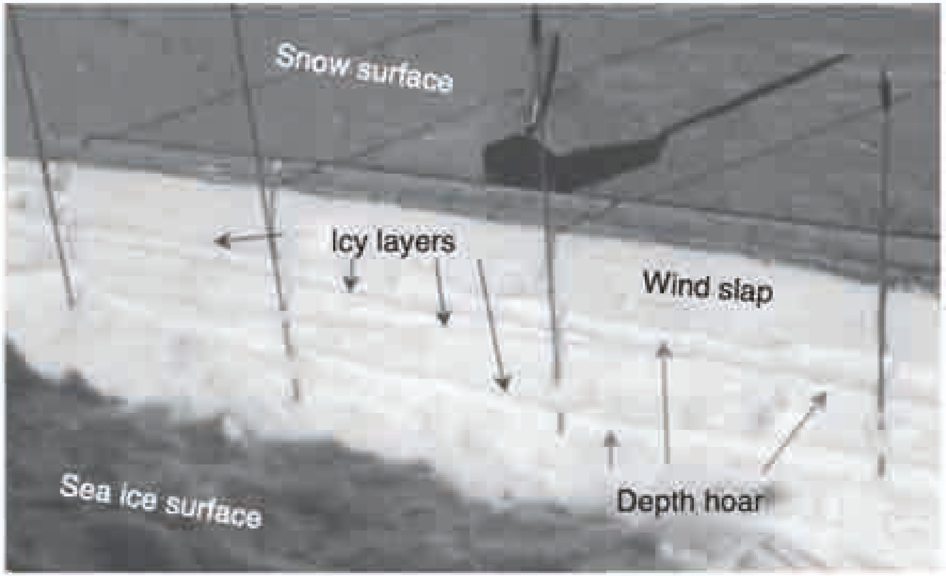


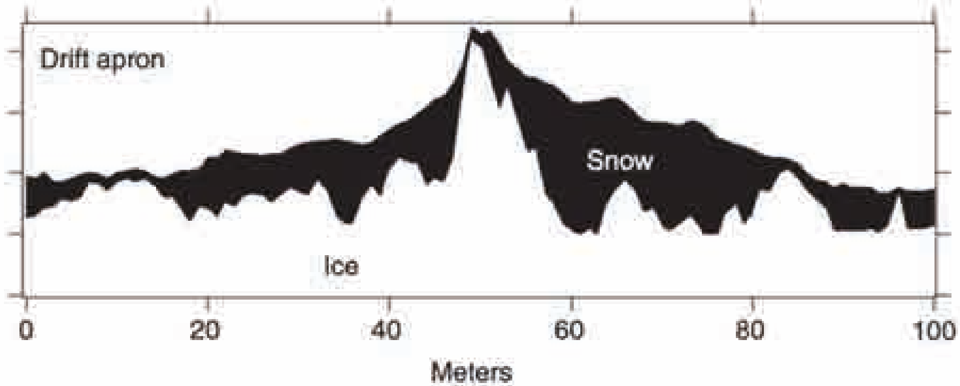
Snow depth (cm) evolution @Soviet NP-22 station
(Warren et al 1999)

Snow on Antarctic sea ice

- Lots of snowfall
- Wind redistribution
- Interaction with topography
- Snow ice formation





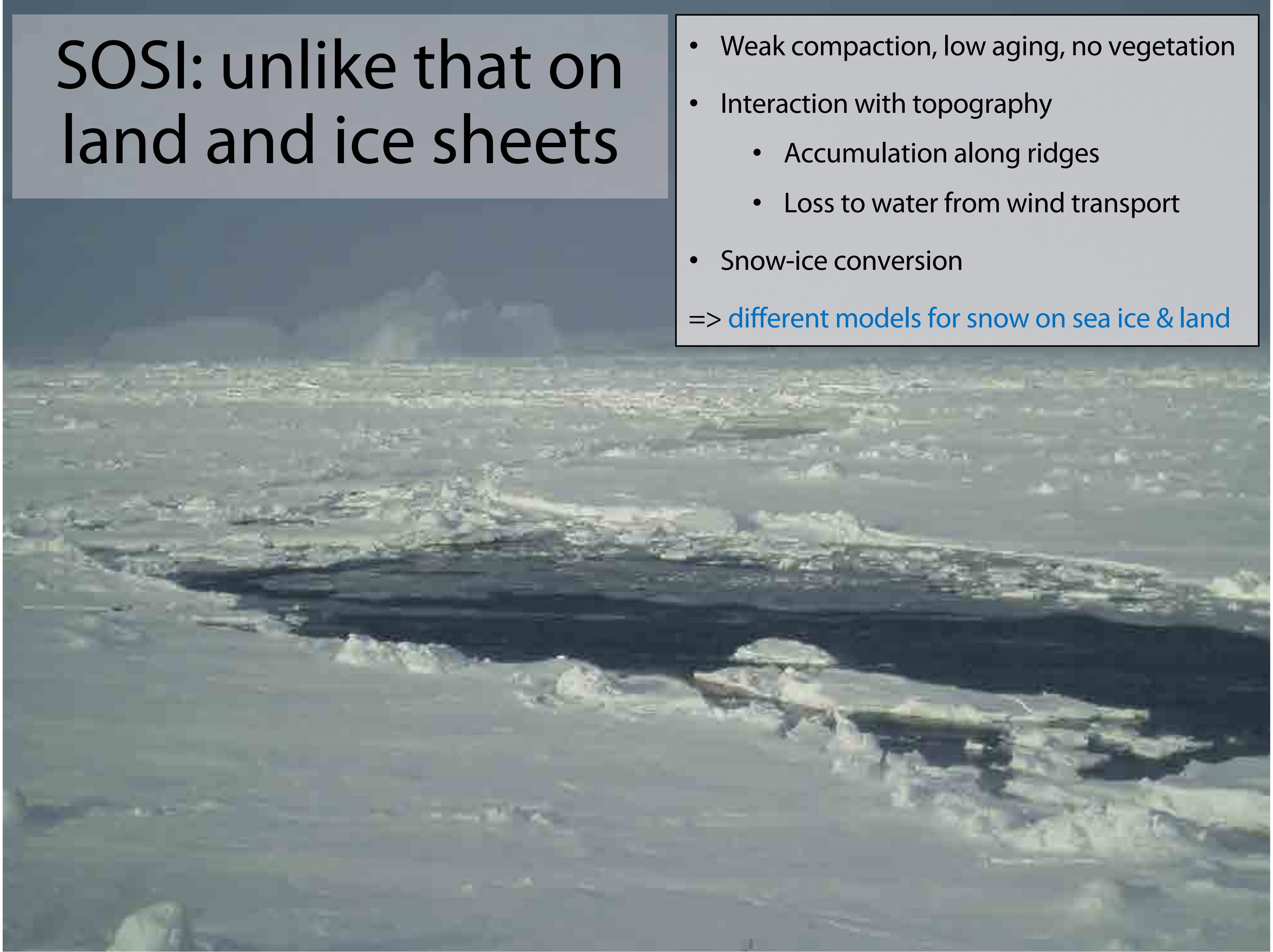


Sturm and Massom 2017

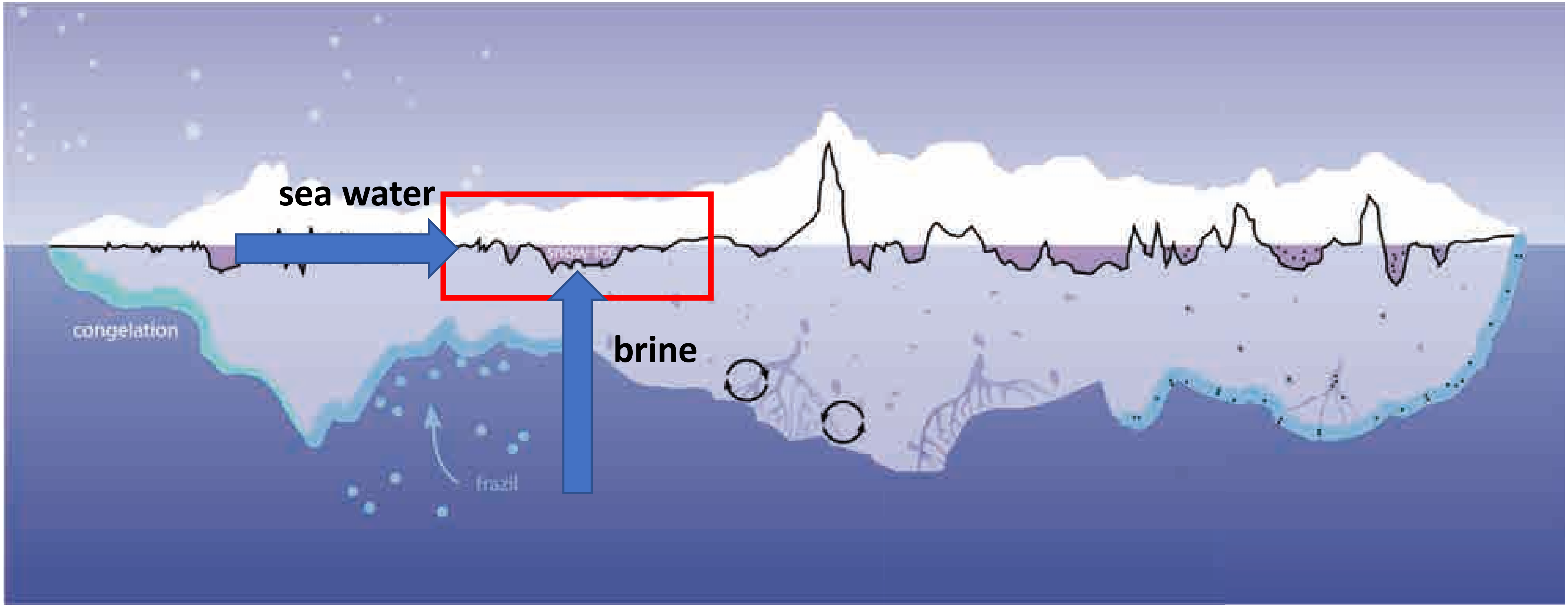
SOSI: unlike that on land and ice sheets

- Weak compaction, low aging, no vegetation
- Interaction with topography
  - Accumulation along ridges
  - Loss to water from wind transport
- Snow-ice conversion

=> different models for snow on sea ice & land



Snow under sea level is flooded, which forms sea ice

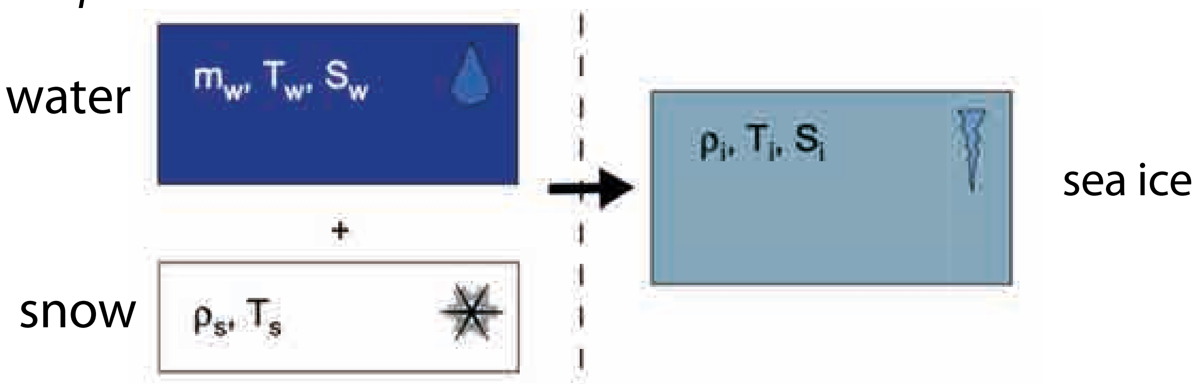


1/3 of the Antarctic sea ice mass is snow ice
(Jeffries et al 1997; Worby 1998; Vancoppenolle et al 2009)

Snow ice ? A **snow** + **salt water** mixture turning into warm and salty ice

flooding seen in a snow pit

a sea ice core



- Freezing energetics dominated by latent heat of the snow
- Equilibrium temperature set by salinity of flooding water
- More or less encased brine depending on snow density and water salinity

Jutras et al (2016)

Snow on sea ice
in the ESM world

Key snow properties

- ***Albedo* — 0.65 - 0.90** (function of snow depth & wetness)

  higher than on land (cleaner)

  (Shine & Henderson-Sellers, 1985)

- ***Thermal conductivity* — 0.1 - 0.5** W/m/K

  uncertain because of density, wind pumping & latent heat transport

  (Yen 1991; Huwald et al 2005; Lecomte et al 2013)

Snow on sea ice in ESMs

- In **sea ice** component: simple
- In **atmospheric** component: ignored/rudimentary
- Ongoing work toward more elaboration

Why having snow ? It matters…

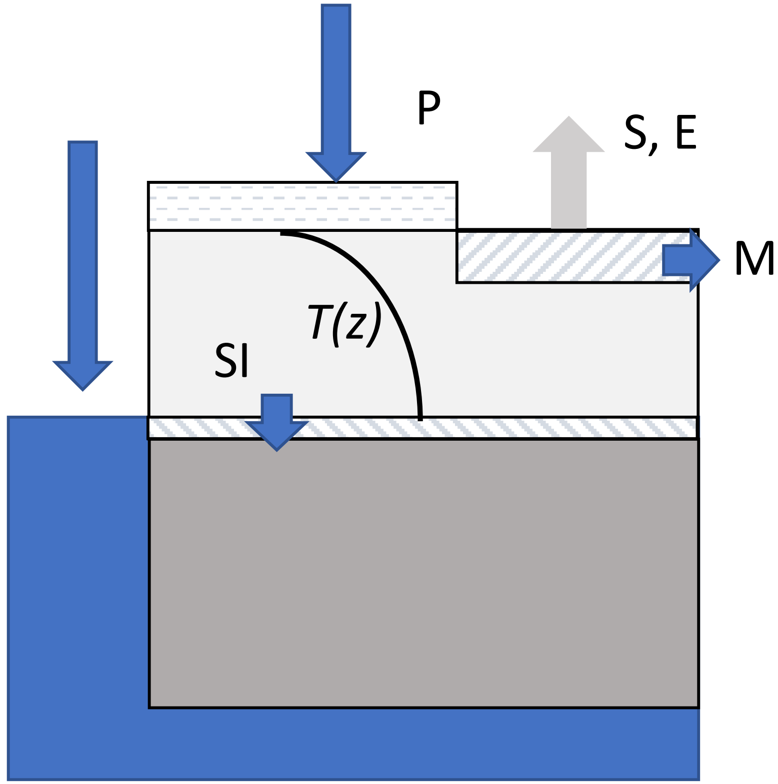
- Snow ultimately **freshens** the ocean
- Snow depth affects sea ice **growth**
  (Fichefet et al GRL99, Lecomte et al 2015)
  - **Basal** growth set by heat conduction (Untersteiner 1964)
  - **Surface** growth by snow-ice formation (Eicken et al 1994)
- Snow affects winter air temperature (Batrack and Muller 2019)
- Useful tuning parameters for sea ice volume in ESMs
  (Boucher et al 2021)

SOSI in sea ice ESM components (SI^3)

- ***Mass balance*** — $\Delta M/\Delta t$ = **P** – S – E – **M** – **SI**
  (Fichefet and Morales Maqueda, 1999)
  - P = Precip (partly in open water)
  - S = Sublimation
  - E = Erosion
  - M = melt
  - **SI** = Snow-Ice

  (weak compaction & aging, no interaction with vegetation)

- ***Surface energy balance*** — B(T_{su}) = 0
  - ***Albedo*** : function of snow depth (0.65 – 0.90)



- ***Diffusion of heat***
  - ***Thermal conductivity*** : low, depends on density; density low and complex
  - ***No radiation absorption***

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right)$$

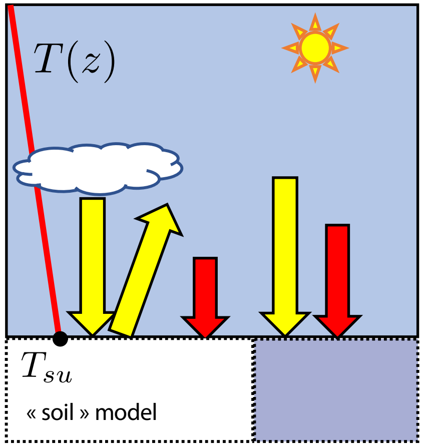
Snow on sea ice in the future ?

- **SOSI decreases** in this century
  despite increased snow fall
  according the few CMIP-based analyses
  (Hezel et al 2013; Webster et al. 2021; Meiners et al. 2024)

- Due to **longer open water season** (Arctic)
  and to **snow-ice formation ?** (Antarctic)

SOSI in atmospheric ESM components (LMDZ)

- Absent or **rudimentary**
  - Snow mass budget
  - Albedo function of snow age
  - Prescribed conduction *



$$\frac{dm_{sn}}{dt} = P - E - M(T_{su})$$

$$\alpha = \alpha_i \cdot [1 - f_{sn}(m_{sn})] + \alpha_{sn}(age) \cdot f_{sn}(m_{sn})$$

$$\rho c_p H \frac{dT_{su}}{dt} = Q_{net}(T_{su}) - \frac{k}{H}(T_{su} - T_f)$$

*effective time scale of 30 days imposed,
corresponding to a constant thickness H = 1.5 m of ice

SOSI in atmospheric ESM components (LMDZ)

- Absent or **rudimentary**
- Snow on sea ice affects T_{air} over sea ice
  Neglecting it largely biases reanalyses (>5°C)
  (Batrack & Muller 2019)

Some perspectives

In the atmospheric component

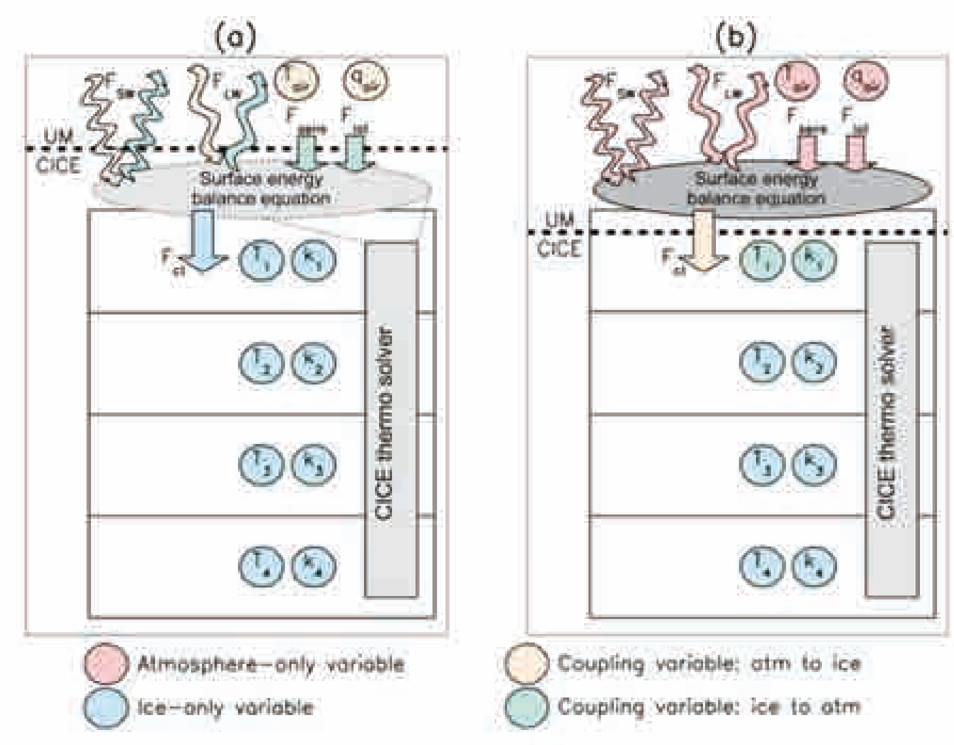
In the sea ice component

In LMDZ

- Improve representation of sea ice and snow in LMDZ
  - ATM-ONLY
    - Resolve sea ice mass balance (Semtner 1976)
    - Account for snow in surface energy budget
  - COUPLED
    - Move the coupling interface position in the snow (following West et al 2016)

- PhD of Nicolas Michalezyk (IPSL)

Conductive heat flux (CHF) coupling



Better numerics
Reduced Tsu and surface flux errors

www.geosci-model-dev.net/9/1125/2016/
West et al (2016)

In SI^3

- Couple more elaborate snow models to SI^3
  - Split of the snow-sea ice interface
  - Replacement of 1-layer snow model of SI3 by ISBA-ES (MeteoFrance simple snow model)
  - Rewrite snow ice for varying snow density
  - Implementation of snow ice loss into ISBA-ES
  - See what happens
- Several parallel projects (US, Switzerland, Finland, Spain, …)

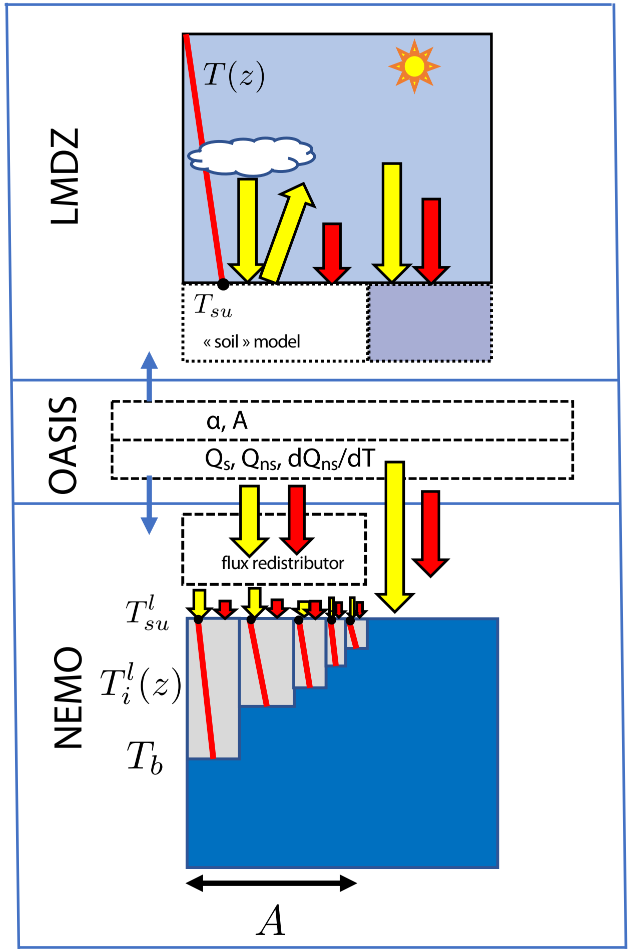
Ongoing work by **Theo Brivoal** (CNRM) in the framework of CrIces project

Summary

- Snow on **sea ice** unlike that on **land** and **ice sheets**
- ESM representation fairly simple in SI^3 and rudimentary in LMDZ
- Ongoing improvements on both aspects

Appendices

Good old IPSL coupling



$$\frac{dm_{sn}}{dt} = P - E - M(T_{su})$$ Snow mass budget

$$\alpha = \alpha_i \cdot [1 - f_{sn}(m_{sn})] + \alpha_{sn}(age) \cdot f_{sn}(m_{sn})$$ Snow/ice albedo

$$\rho c_p H \frac{dT_{su}}{dt} = Q_{net}(T_{su}) - \frac{k}{H}(T_{su} - T_f)$$ Snow/ice temperature*

*effective time scale of 30 days imposed, corresponding to a constant thickness H = 1.5 m of ice

$$\begin{cases} Q^l_{ns} = < Q_{ns} > + \dfrac{\partial Q_{ns}}{\partial T} \cdot (T^l_{su} - < T_{su} >) \\ Q^l_{sr} = < Q_{sr} > \cdot \left(\dfrac{1 - \alpha_l}{1 - < \alpha >} \right) \end{cases}$$

Flux redistributor
`ice_flx_dist in icesbc.F90`

$$\begin{cases} Q_{sr} + Q_{ns}(T^l_{su}) - Q_{tr} = Q_c[T^l_{su}, T^l(z)] \rightarrow T^l_{su} \\ \dfrac{\partial q(S,T)}{\partial t} = \dfrac{\partial Q_c(T^l, S^l)}{\partial z} \rightarrow T^l(z) \end{cases}$$

Surface energy balance
`icethd_zdf_bl99.F90`

Heat equation

Temperature solver is iterative (non-linear terms), which includes non-solar flux.
This is important to get ice growth right. The generates a small heat imbalance thrown into the ocean.