Sea ice salinity and salt flux from a growing ice sheet in the presence of an oceanic heat flux

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1. Summary

Known:

- Growing sea ice is a source of dense brine
- Physical properties of sea ice depend on salinity
- Salinity and salt flux depend on growth conditions

Aim:
Determine the dependency of the stable sea ice salinity and salt flux on the growth velocity and temperature gradient in the ice in the presence of an oceanic heat flux.

Method:

- Treat sea ice as porous medium, porosity f
- 2-dimensional finite volume fluid dynamics simulations
  - impose oceanic heat flux F_w
  - impose heat exchange with atmosphere
  - determine salt flux Φ_s; sea ice salinity S
  - determine temperature gradient dT/dz; ice growth velocity v
  - find empirical relationship

$$\begin{aligned}\Phi_s &= \Phi_s(F_w; dT/dz; v)\\ S &= S(F_w; dT/dz; v)\end{aligned}$$

2. Governing equations

- Single set of governing equations for porous sea ice and ocean (*Petrich et al.*, 2006)
- Volume averaged equations → volume fraction of liquid, f
- Local physical properties: weighted averages of solid ($[\cdot]_s$) and liquid ($[\cdot]_l$)
- Isotropic permeability $\Pi(f)$

Mass conservation:

$$\left[1-\frac{\rho_s}{\rho_l}\right]\frac{\partial f}{\partial t}+\frac{\partial(fu)}{\partial x}+\frac{\partial(fw)}{\partial z}=0$$

Momentum conservation:

$$\rho_l\left[\frac{\partial(fu)}{\partial t}+\frac{\partial(fuu)}{\partial x}+\frac{\partial(fuw)}{\partial z}\right]=\mu\left[\frac{\partial^2(fu)}{\partial x^2}+\frac{\partial^2(fu)}{\partial z^2}\right]-f\frac{\partial p}{\partial x}-f\frac{\mu}{\Pi}fu$$

$$\rho_l\left[\frac{\partial(fw)}{\partial t}+\frac{\partial(fwu)}{\partial x}+\frac{\partial(fww)}{\partial z}\right]=\mu\left[\frac{\partial^2(fw)}{\partial x^2}+\frac{\partial^2(fw)}{\partial z^2}\right]-f\frac{\partial p}{\partial z}+f\rho g-f\frac{\mu}{\Pi}fw$$

Energy conservation:

$$\overline{\rho c}\frac{\partial T}{\partial t}+\rho_l c_l\frac{\partial(fuT)}{\partial x}+\rho_l c_l\frac{\partial(fwT)}{\partial z}=\frac{\partial}{\partial x}\left[\overline{k}\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial z}\left[\overline{k}\frac{\partial T}{\partial z}\right]-\left[T\Delta(\rho c)+L\rho_s\right]\frac{\partial f}{\partial t}$$

with

$$\begin{aligned}\overline{\rho c} &= f\rho_l c_l+(1-f)\rho_s c_s\\ \Delta(\rho c) &= \rho_l c_l-\rho_s c_s\\ \overline{k} &= f k_l+(1-f)k_s\end{aligned}$$

Solute conservation:

$$f\frac{\partial C}{\partial t}+\frac{\partial(fuC)}{\partial x}+\frac{\partial(fwC)}{\partial z}=\frac{\partial}{\partial x}\left[fD\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial z}\left[fD\frac{\partial C}{\partial z}\right]-C\frac{\partial f}{\partial t}$$

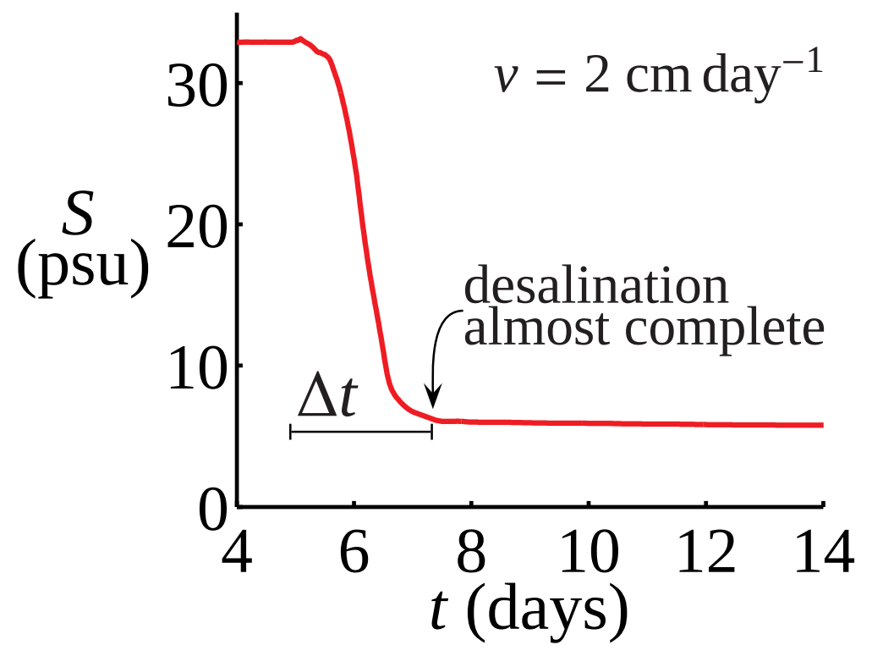
Local thermodynamic equilibrium:

$$T=T_F(C)$$

3. Background

Desalination occurs

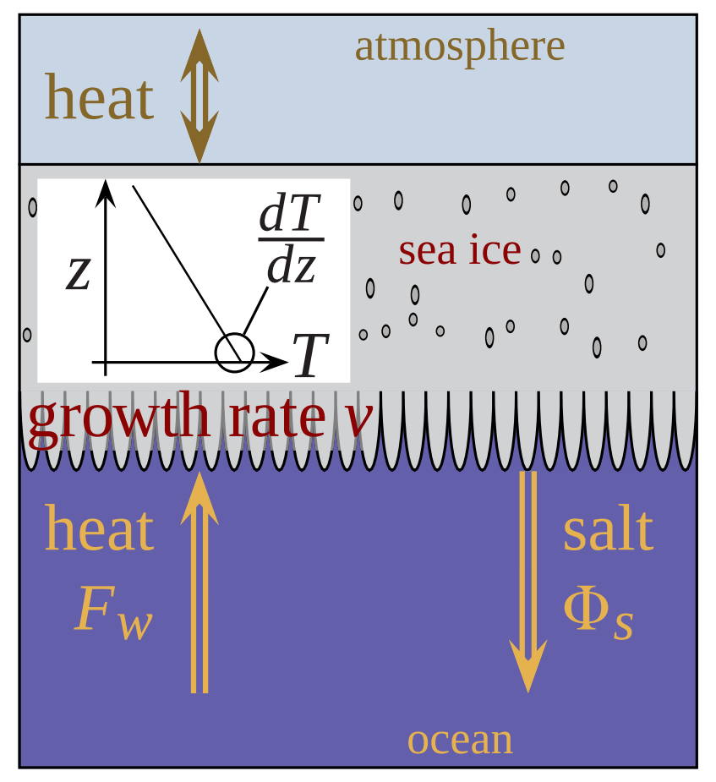
- over a relatively short period of time (Δt) after initial freezing (*Nakawo and Sinha*, 1981)
- close to the ice–ocean interface



Simulated desalination 0.3 m below the ice–air interface.

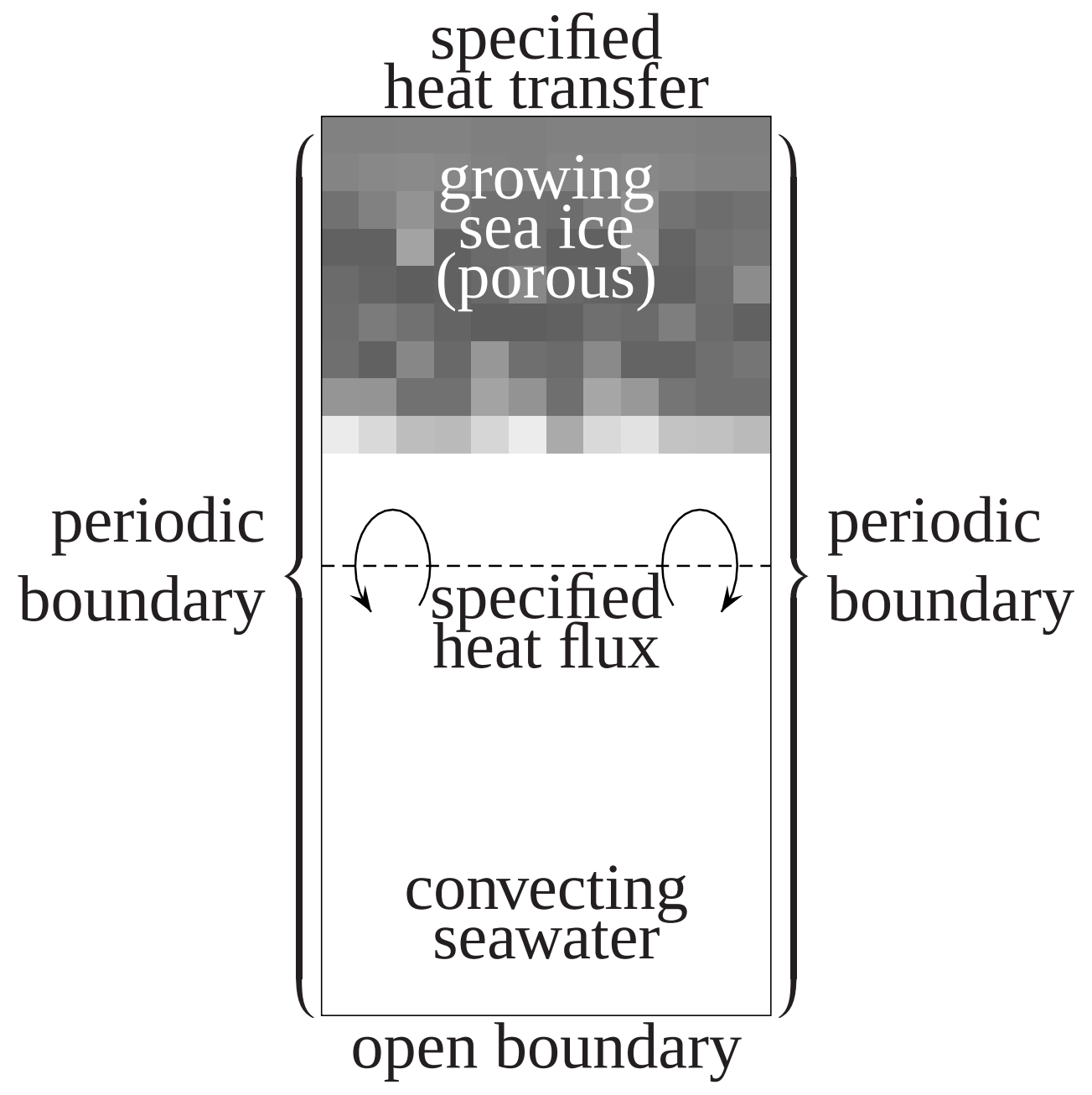
Energy balance at the ice–ocean interface:

$$F_w-\underbrace{v\rho L(1-f)}_{<0}+\underbrace{k\frac{dT}{dz}}_{<0}=0$$



4. Computational domain

- Oceanic heat flux
  - imposed 0.1 to 0.2 m below the sea ice–ocean interface
  - enforced by adjusting the temperature of upwelling water
- Sea ice–atmosphere interface: constant T, or constant dT/dz
- Domain is periodic horizontally



specified heat transfer

growing sea ice (porous)

periodic boundary

specified heat flux

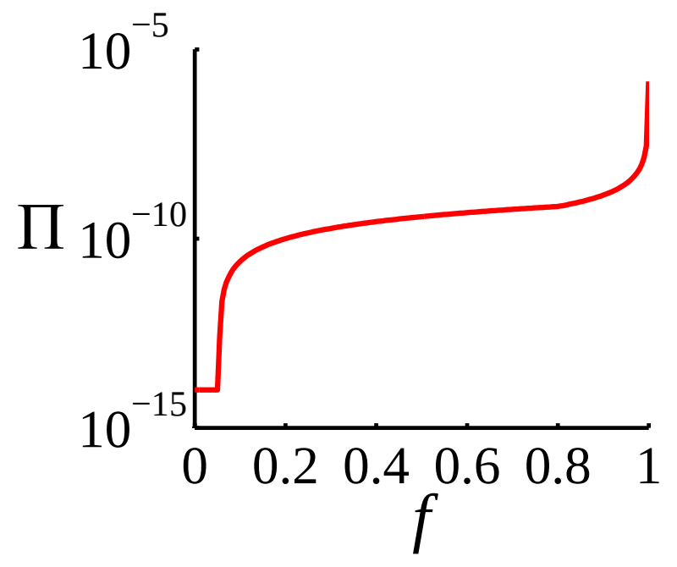
periodic boundary

convecting seawater

open boundary

5. Sea ice permeability

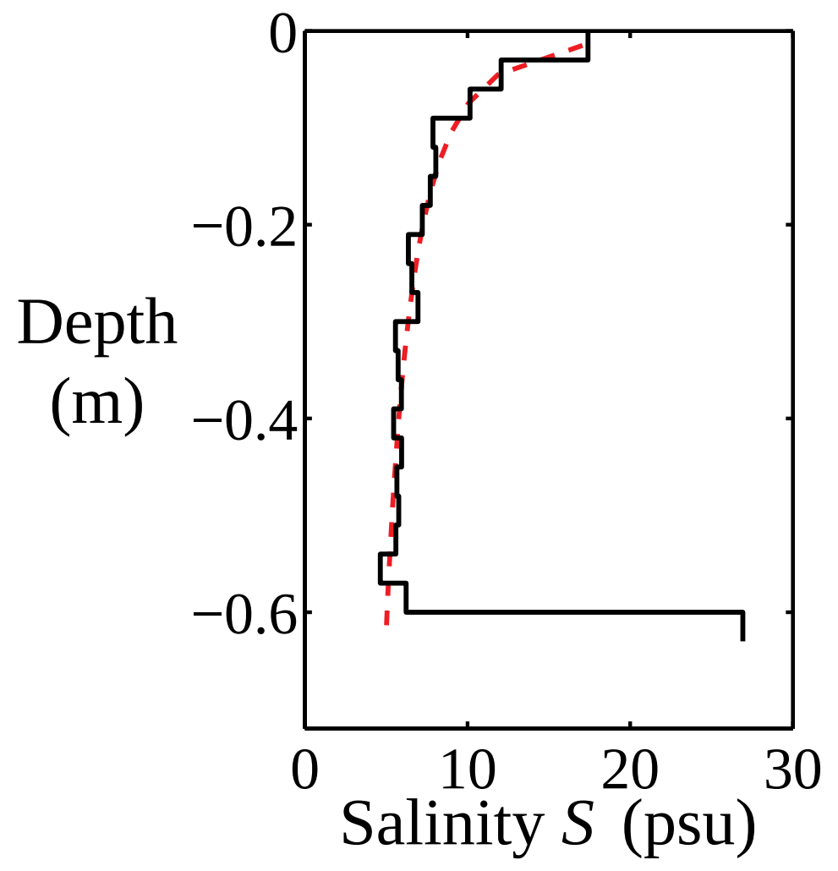
Permeability–porosity relationship is based on laboratory work of *Cox and Weeks* (1975) (*Petrich et al.*, 2006). The magnitude is calibrated to obtain salinities consistent with the model of *Cox and Weeks* (1988), assuming $F_w = 0$.



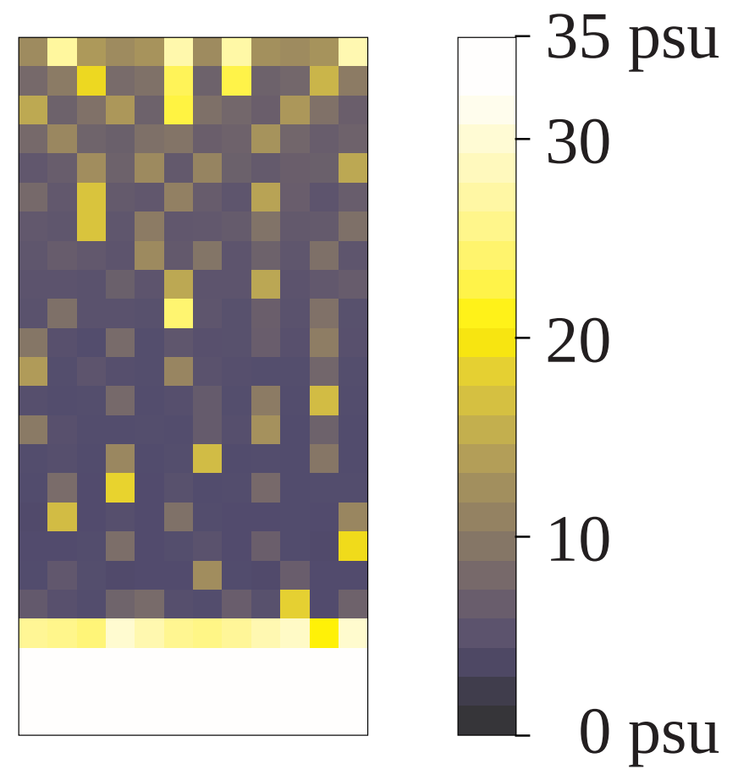
$$\Pi(f)=\begin{cases}\Pi(0.8)\left[1-\frac{f-0.8}{0.2}\right]^{-1} & \text{for}\quad 0.8<f\leq 1\\ 1\times10^{-9}\ \text{m}^2\,(f-0.054)^{1.2} & \text{for}\quad 0.054<f\leq 0.8\\ 1\times10^{-14}\ \text{m}^2 & \text{for}\quad f<0.054\end{cases}$$

6. Salinity profile

- Ice–air interface temperature −20 °C
- Oceanic heat flux $F_w = 0$ Wm^{-2}

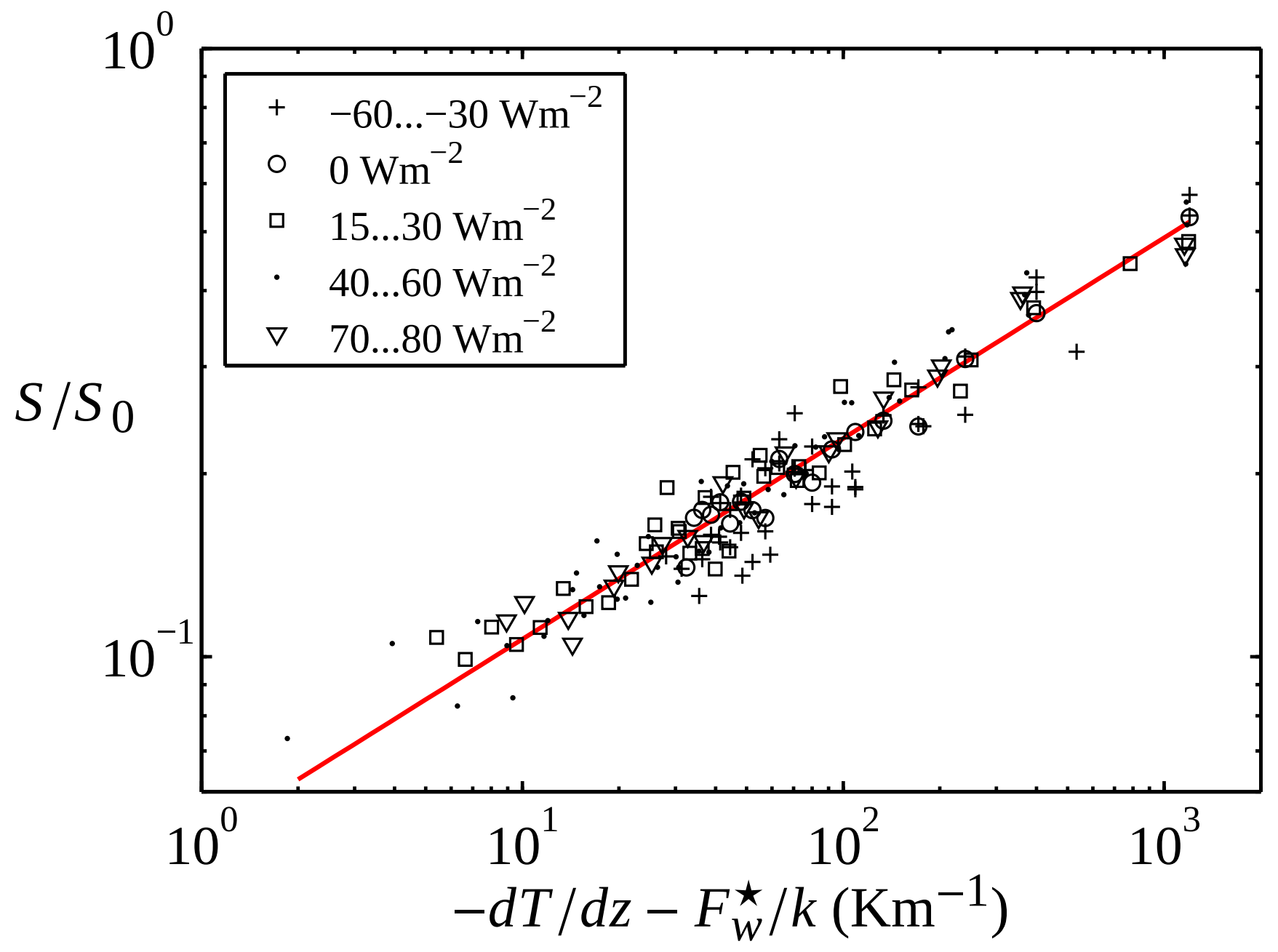


Average salinity profile (solid line), and parameterisation (dashed line) from Equation (1).



Corresponding vertical salinity profile.

7. Sea ice salinity



Ratio between stable salinity S and seawater salinity S_0 as a function of temperature gradient dT/dz and oceanic heat flux F_w of 10 computed salinity profiles. The solid line follows

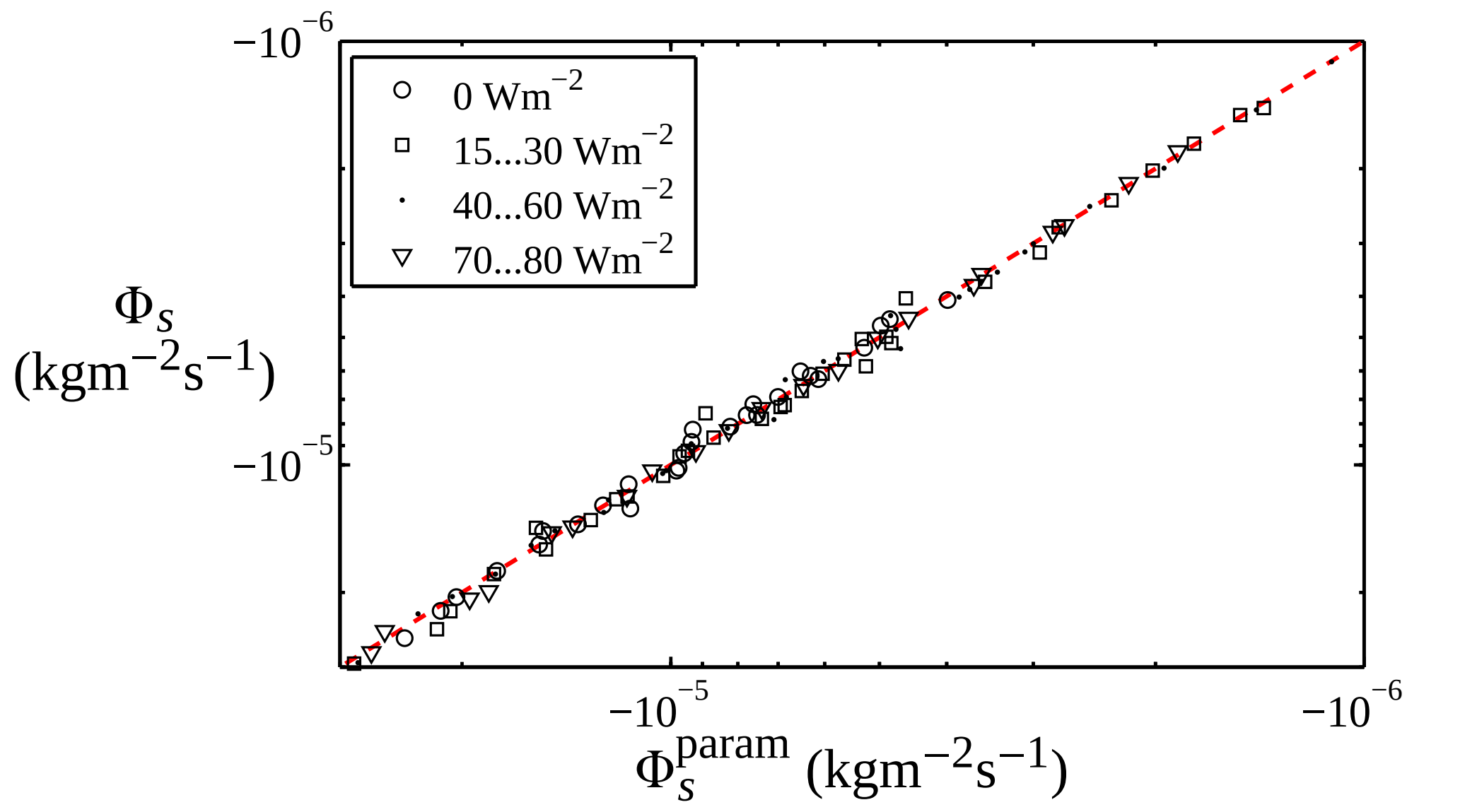
$$\frac{S}{S_0}=0.05\left(\frac{-dT/dz-F_w^\star/k}{1\ \text{Km}^{-1}}\right)^{0.33}\qquad(1)$$

where

$$F_w^\star=\begin{cases}F_w & \text{for}\quad F_w\geq 0\\ 0 & \text{for}\quad F_w<0\end{cases}$$

In the simulations, sea ice salinity appears to depend on both dT/dz and F_w for $F_w \geq 0$. Water of $F_w < 0$ contributes to the formation of an extended porous interfacial layer.

8. Salt flux



Comparison of the mean salt flux $\Phi_s = \langle Cw\rangle$ determined from the simulations with the parameterisation

$$\Phi_s^{\text{param}}=C_0 v\left(1-\frac{C_{\text{ice}}}{C_0}\right)\qquad(2)$$

for $F_w \geq 0$. C and w are the salt concentration and vertical velocity component, respectively, of the ocean water. The ice growth velocity v is determined from the simulation. C_0 and C_{ice} are the nominal salt concentration of the water and the salt concentration of the sea ice, respectively. C_{ice} is calculated from the sea ice salinity S of Equation (1).

9. Conclusion

- A fluid dynamics model has been used to determine parameterisations of the stable salinity and the salt flux of growing sea ice.
- In larger scale models, the stable salinity profile of a growing sea ice sheet can be parameterised based on the temperature gradient and oceanic heat flux. The relationship follows a power law.
- The salt flux depends on the growth velocity and the stable salinity of the ice.

10. Acknowledgements and References

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