Radiative heating on melt ponds

A numerical study of turbulent heat transfer in a pond

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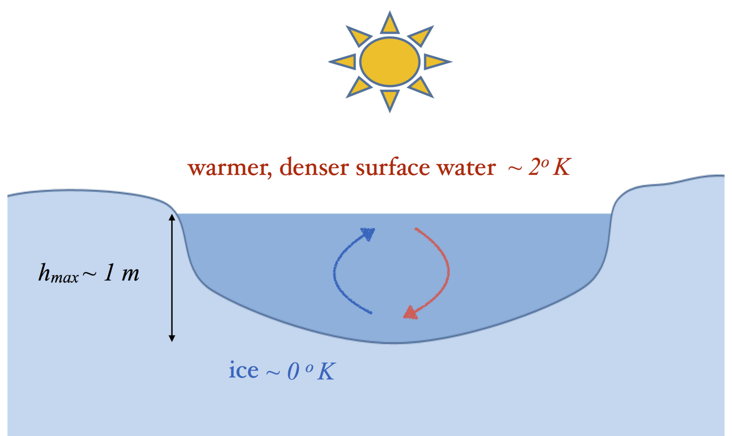
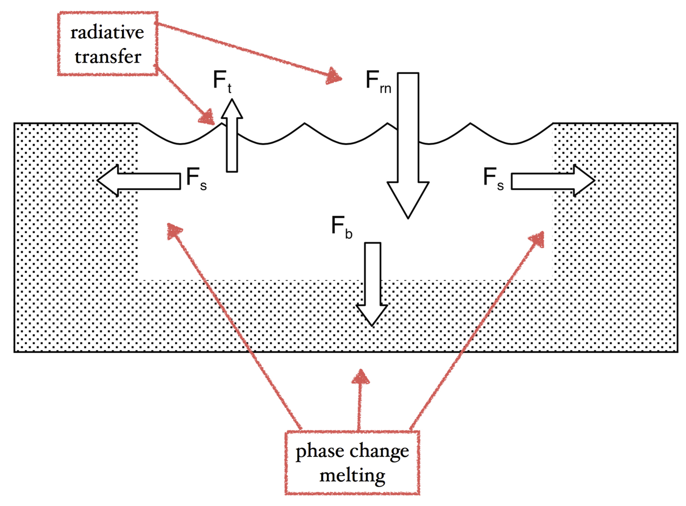
Abstract

High-resolution numerical simulations and stability analysis are used to investigate the effects of external radiative heating on melt ponds. We focus on the small-scale process of convective heat transfer inside a single pond. The pond is modeled as an upside-down Rayleigh-Bénard cell with transparent boundaries, submitted to an external shortwave-radiation source.

Current Global Climate Models operate at a quite low resolution and the dynamics of melt ponds, when not neglected, is only accounted for by rather simple parametrizations. The present analysis can provide further insight on the small-scale mechanisms affecting the internal dynamics and evolution of ice-melt ponds during summer in the Arctic ocean. The small-scale results can then be used to improve the parametrizations of melt ponds in large scale models.

Introduction





High-resolution 2D Direct Numerical Simulations is used to study turbulent convective heat transfer in melt ponds. The main goal of the present work is to investigate the influence of solar radiation on heat fluxes across a single pond. Phase change is not taken into account. Moreover, salinity effects are neglected, consistently with the low salinity content of Arctic waters. We use an idealized model, based on the Beer-Lambert law :
$I = I_0 \, e^{-\alpha \, z}$
Radiative energy flux in ponds :

$$F_r(z) = F_r^{(in)} + F_r^{(out)}$$

with $F_r^{(in)} = I_0(1 - e^{-\alpha \, z})$
I_0 is the irradiance at the top $[W \; m^{-2}]$
α is the absorption coefficient $[m^{-1}]$
Note that the out coming energy flux $F_r^{(out)}$, which is proportional to the bottom wall albedo, is not accounted for in the present model.

An idealized model system

We model a single pond as a cubic Rayleigh-Bénard cell, heated from above, and with a monochromatic short-wave radiation source. Imposed temperature and no-slip boundary conditions are applied to the horizontal walls, while periodicity is imposed on the vertical walls.
The thermo-hydrodynamic governing equations in dimensional form are

$$\begin{cases} \partial \cdot \mathbf{u} = 0 \\ \partial_t \mathbf{u} + (\mathbf{u} \cdot \partial)\mathbf{u} = -\frac{1}{\rho_0}\,\partial p + \nu\,\partial^2 \mathbf{u} + \beta(T - T_0) g \,\mathbf{e}_z \\ \partial_t T + (\mathbf{u} \cdot \partial) T = \kappa\,\partial^2 T + \frac{1}{\rho_0 c_p}\,\partial_z F_r(z) \end{cases}$$

ν	Kinematic viscosity $[m^2 s^{-1}]$	κ	Thermal diffusivity $[m^2 s^{-1}]$
β	Thermal expansion coefficient $[K^{-1}]$	g	Gravity acceleration $[m \; s^{-2}]$
ρ_0	Fluid density at temperature T_0 $[Kg \; m^{-3}]$	c_p	Specific heat capacity $[J \; Kg^{-1} K^{-1}]$

And in dimensionless form

$$\begin{cases} \tilde\partial \cdot \tilde{\mathbf{u}} = 0 \\ \partial_{\tilde t} \tilde{\mathbf{u}} + (\tilde{\mathbf{u}} \cdot \tilde\partial)\tilde{\mathbf{u}} = -\tilde\partial \tilde p + Pr\,\tilde\partial^2 \tilde{\mathbf{u}} + Pr\; Ra\; \tilde T \,\mathbf{e}_z \\ \partial_{\tilde t} \tilde T + (\tilde{\mathbf{u}} \cdot \tilde\partial)\tilde T = \tilde\partial^2 \tilde T + \frac{Ra_r}{Ra}\, E_r\, e^{-E_r\,\tilde z} \end{cases}$$

where $Ra = \frac{g\,\beta\,\Delta T\, H^3}{\nu\,\kappa}$ is the Rayleigh number, $Ra_r = \frac{g\,\beta\, I_0\, H^4}{\rho_0\, c_p\, \nu\, \kappa^2}$ is th radiative Rayleigh number, $E_r = \alpha\, H$ is the extinction ratio, and $Pr = \frac{\nu}{\kappa}$ is the Prandtl number.

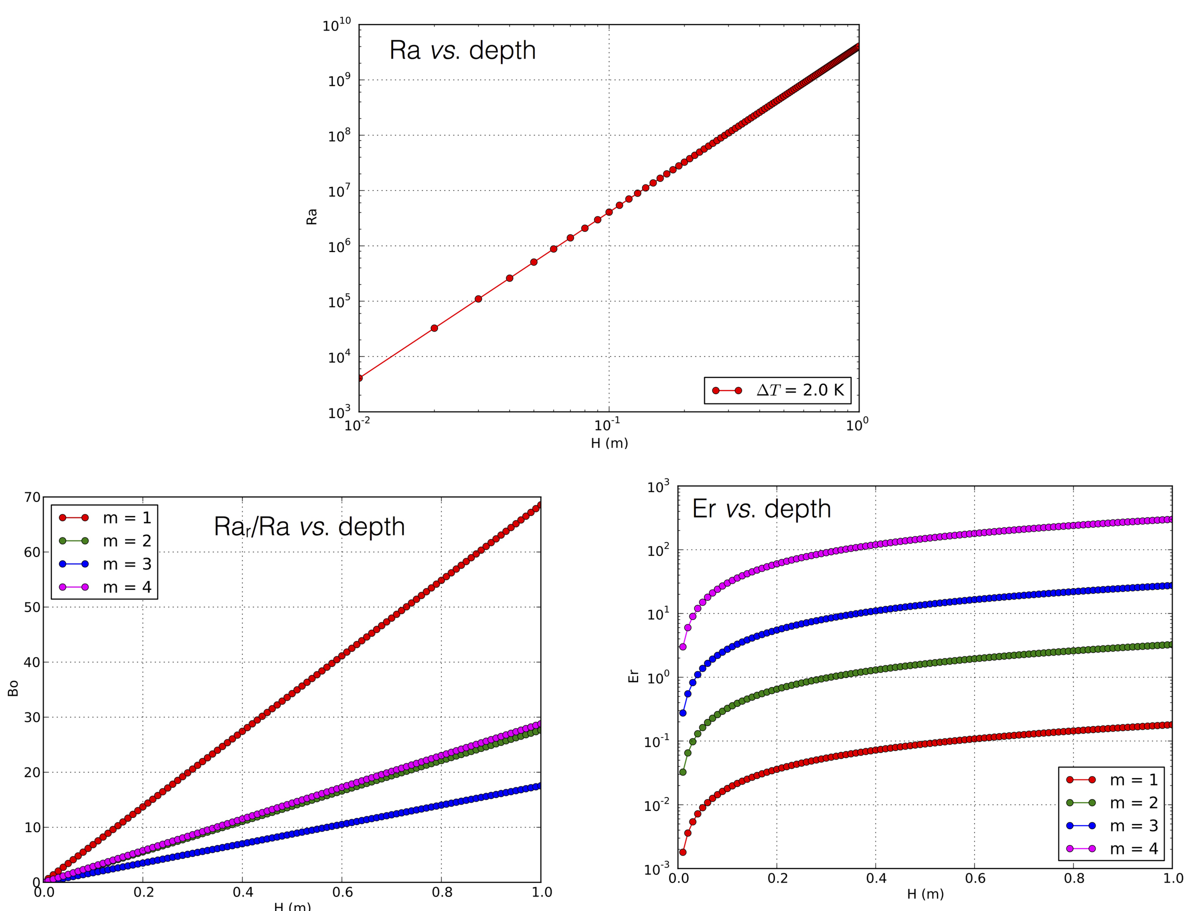


Figure 1: Dimensionless parameters for realistic ponds ($\Delta T = 2\ K$ and $Pr = 13$). Solar radiation is divided into four bands of different wavelengths, denoted by m = 1 (350-700nm), 2 (700-900nm), 3 (900-1100nm), 4 (>1100nm), as defined in *Skyllingstad & Paulson, J. Geophys. Res. 112 (2007)*.

Results

At first, a linear stability analysis of the quiescent conductive state has been performed. From Figure 2 it can be seen that radiation always destabilizes the system, even when the external temperature gradient is stabilizing ($Ra < 0$). The optimal value to promote the onset of convection is $E_r \sim 6$.

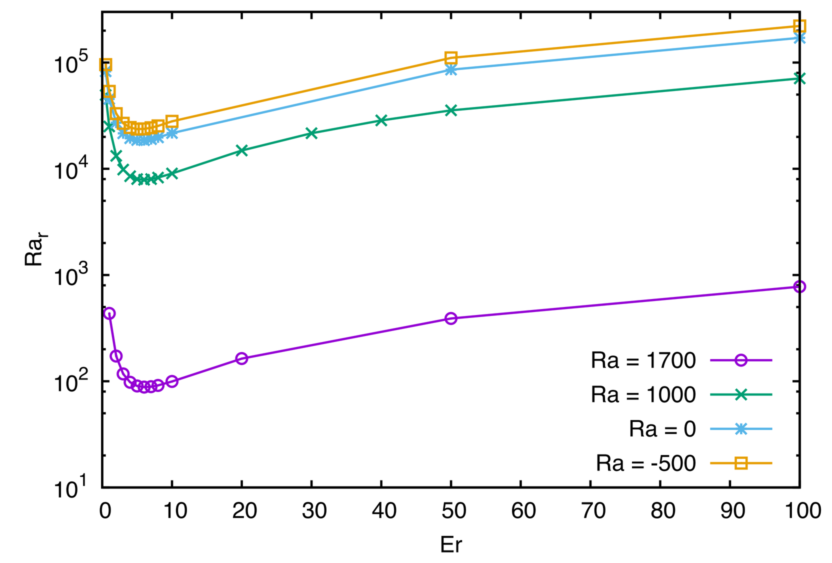


Figure 2: Linear stability thresholds for the onset of convection : critical radiative Rayleigh number as a function of the extinction ratio.

We shall now consider higher values of Rayleigh number, as the turbulent convection regime can be easily attained in melt ponds. The following figures show the main results obtained from DNS using a Lattice Boltzmann algorithm. The simulations were performed for a square geometry, with $Pr = 1$. Details on the numerical scheme can be found in *Shrestha et al., Phys. Rev. E 9393 (2016)*.

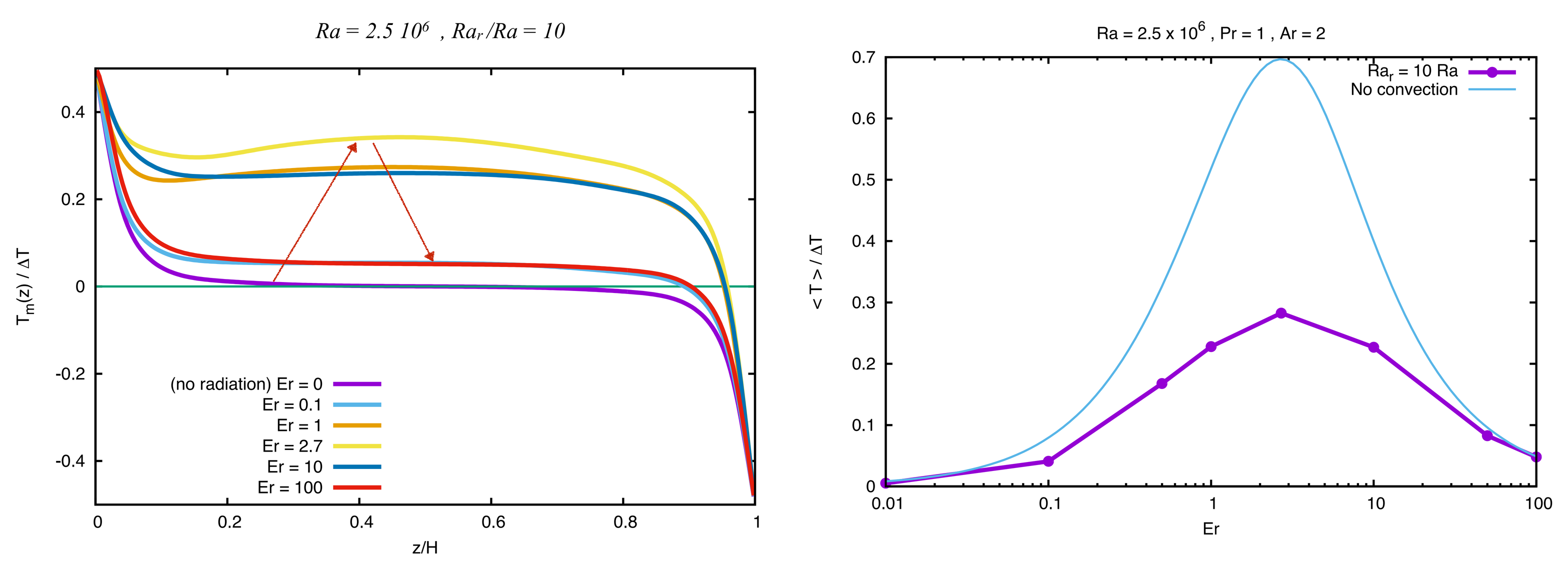


Figure 3: DNS results showing the non-monotonous behavior with E_r. On the right : the mean global temperature maximum at $E_r \sim 3$ reflects the conductive state trend.

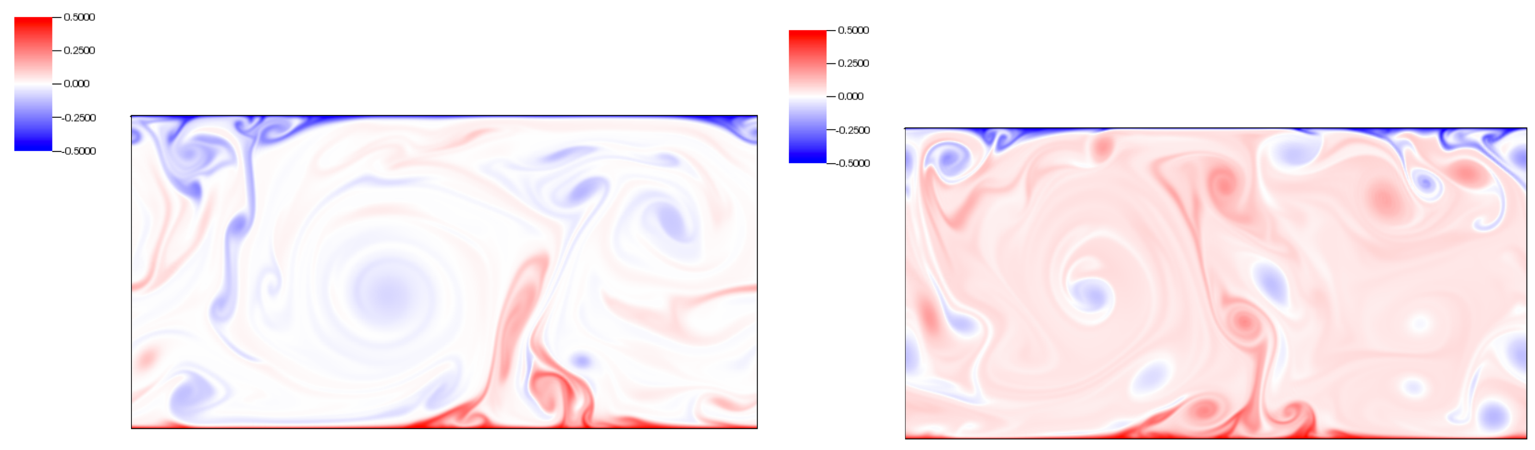


Figure 4: Comparison of system temperarure with (left : $Ra_r/Ra = 10$ and $E_r = 10$) and without (right) radiation heating, for $Ra = 10^9$ and $Pr = 1$.

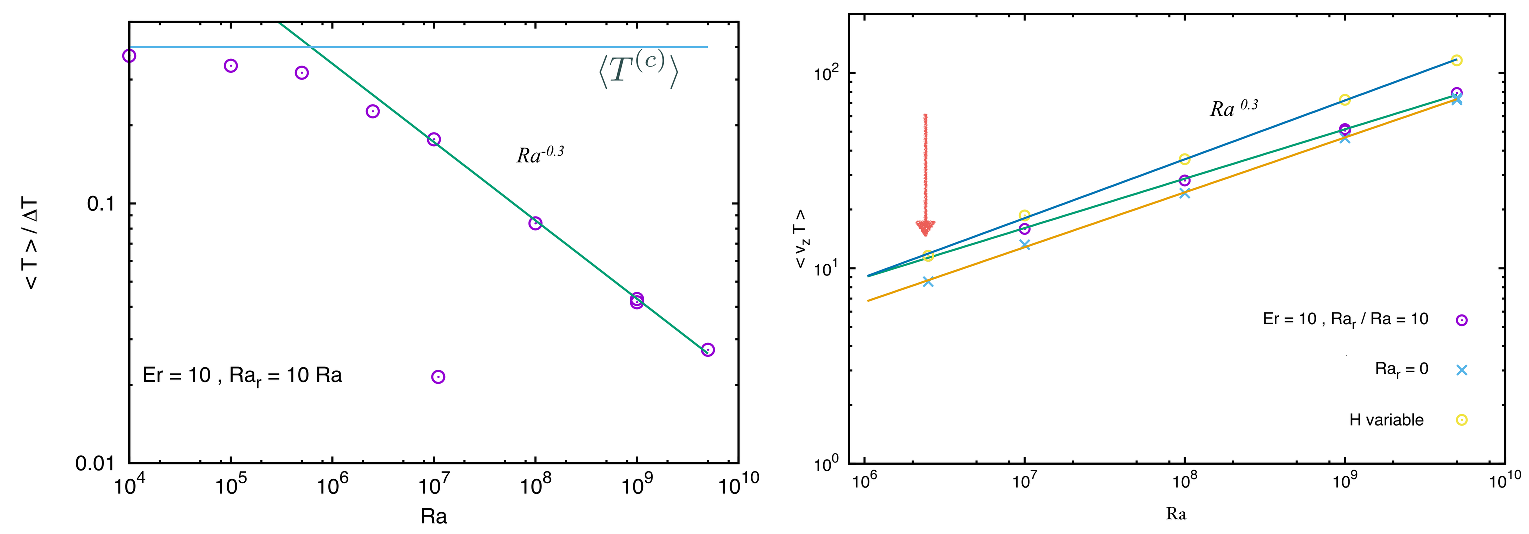


Figure 5: Mean global temperature (left) and global heat flux (right) vs. Ra. Note that radiation heating increases the heat flux, and becomes negligible as turbulence (Ra) increases. When increasing pond depth (H), the relative importance of radiation can not be overlooked.

Conclusions & Perspectives

It has been shown, by means of a linear stability analysis, that radiation favors the onset of convection. At high Rayleigh numbers, DNS results show that radiative heating increases the mean global temperature of the system and the heat flux. Furthermore, there exists an optimal value of the extinction ratio that maximizes the mean global temperature of the system. The effects of radiation can not be neglected when pond depth increases ($Ra \sim h^3$, $Ra_r \sim h^4$), even in well-mixed ponds.
Future research includes :

- Extension to three-dimensions;
- Use of more realistic boundary conditions (radiative bc, upper wind shear, ...);
- Introduction of phase change and study of the evolving pond topography.

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