Large Eddy Simulation of Heat Entrainment under Arctic Sea Ice

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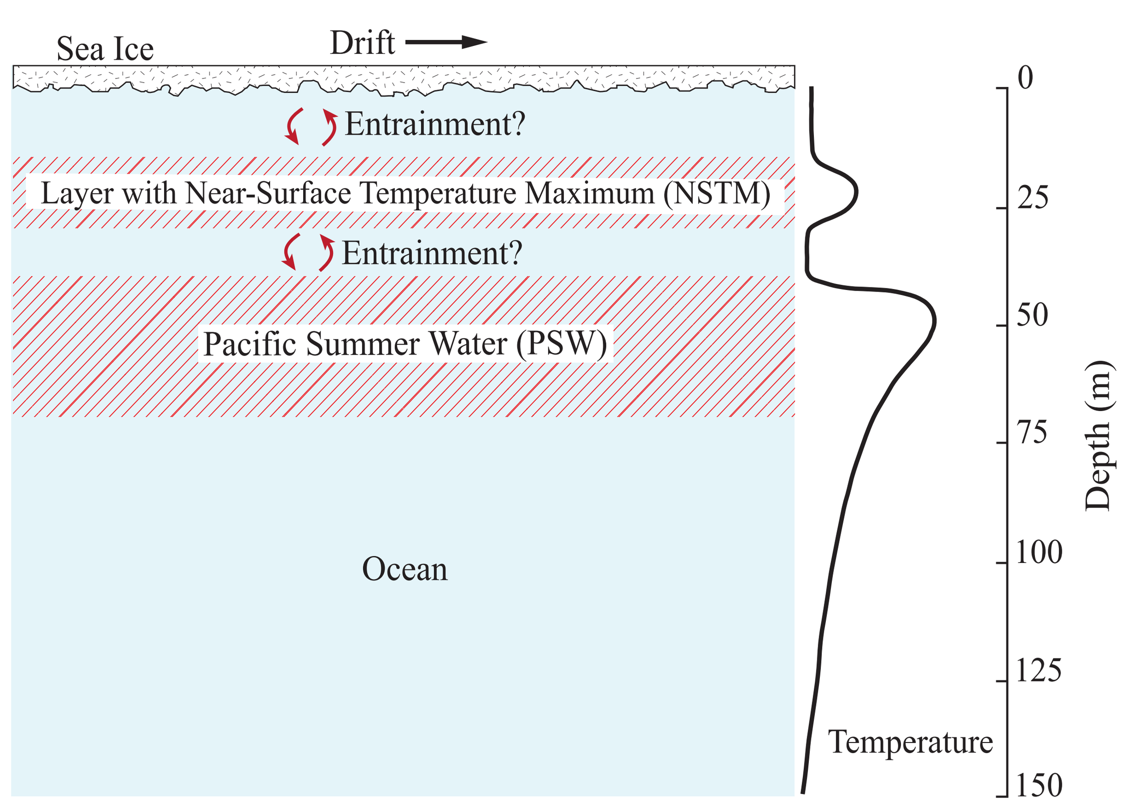
Abstract

Sea ice cover in the Arctic has declined rapidly in recent decades. This accelerated rate of melting of sea ice affects the strength of convection in the underlying ocean, which in turn will affect the strength of the Atlantic Meridional Overturning Circulation (AMOC). Given the important link that exists between Arctic sea ice and the AMOC, it is important to understand all the processes governing the rate of melting of sea ice in order to better predict changes in the AMOC. In this study, we investigate the entrainment of heat from the mixed layer up to the basal surface of sea ice by small-scale turbulence, a process that contributes to sea ice melting. In the Canadian Basin of the Arctic Ocean, relatively warm Pacific Summer Water (PSW) resides at the base of the mixed layer. In addition, the mixed layer itself is often characterized by a Near-Surface Temperature Maximum (NSTM) where solar radiation is stored as heat. We use large eddy simulation (LES) to explore whether heat can be entrained from the PSW and NSTM layers to a moving basal ice surface. The LES model is based on a high-fidelity spectral approach on horizontal planes, and includes a Lagrangian dynamic subgrid model that reduces the need for empirical inputs for subgrid-scale viscosities. This LES tool allows us to investigate physical processes in the mixed layer at a very fine scale. We focus our study on summer conditions. We show the turbulent heat fluxes from the mixed layer to the basal surface of sea ice for a range of ice-drift velocities and a range of peak temperatures of the NSTM. Using these results, our next objectives include modeling the direct effect sea ice melting due to turbulent entrainment of heat has on circulation in the Arctic and subsequently on the AMOC.

Motivation

- Arctic sea ice thinning is accelerating.
- The Canadian Basin in the Arctic is characterized by a Near-Surface Temperature Maximum layer and a Pacific Summer Water layer, in which a significant amount of heat is stored.
- Is heat entrained from these layers by small-scale turbulence to the basal surface of sea ice?



Schematic diagram of the water mass structure of the Canada Basin in the Arctic

References

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Model

Governing Equations

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j\left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i}\right) = -\frac{\partial \tilde{p}}{\partial x_i} + \epsilon_{ij3} f \tilde{u}_j - \delta_{i3} g\left(1 - \frac{\rho(\tilde{\theta}, \tilde{S})}{\rho_0}\right) - \frac{\partial \tau_{ij}}{\partial x_i}$$

$$\rho(\tilde{\theta}, \tilde{S}) = \text{computed using GSW toolbox}$$

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_i \frac{\partial \tilde{\theta}}{\partial x_i} = -\frac{\partial q_{T,i}}{\partial x_i}$$

$$\frac{\partial \tilde{S}}{\partial t} + \tilde{u}_i \frac{\partial \tilde{S}}{\partial x_i} = -\frac{\partial q_{S,i}}{\partial x_i}$$

Tilde denotes a resolved variable; *i,j* denote directions; u = fluid velocity; f = Coriolis parameter; p = pressure; ρ = fluid density; θ = temperature; S = salinity; τ = sub-grid scale shear stress; q_T = sub-grid scale heat flux; q_S = sub-grid scale salt flux.

The sub-grid scale terms are parameterized using a state-of-the-art large eddy simulation model.

Boundary Conditions

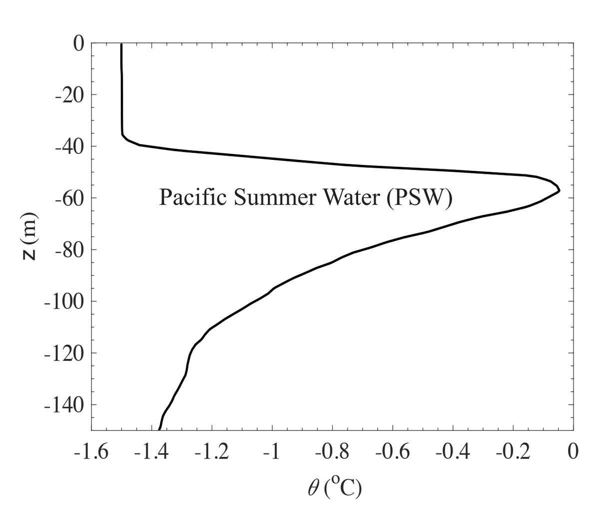
- Prescribed velocity of ice-drift at the top.
- Heat flux at the top computed from Monin-Obukhov similarity law.
- Virtual salt flux at the top computed from heat and salt balance at ice-ocean interface.
- Stress at the top computed using standard log law.
- Momentum roughness length = 0.0012 cm
- Stress-free and no heat and salt fluxes at the bottom surface.
- Periodic on the lateral surfaces.

Set-Up

- Physical domain: Lx, Ly, Lz = 300 m, 300 m, 150 m.
- Computational domain: Nx, Ny, Nz = 128, 128, 256.

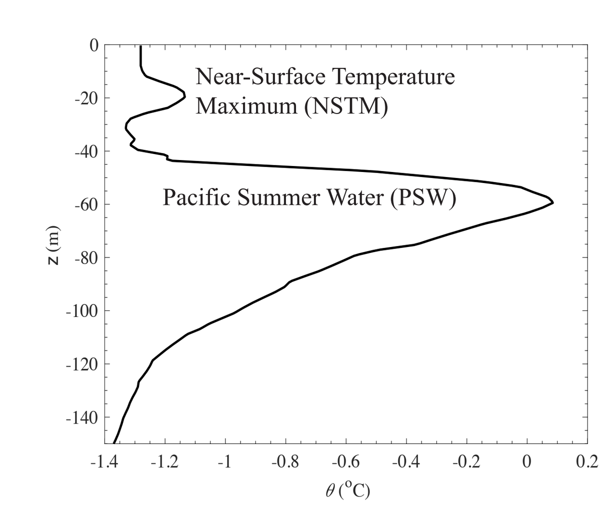
Initial temperature

PSW only



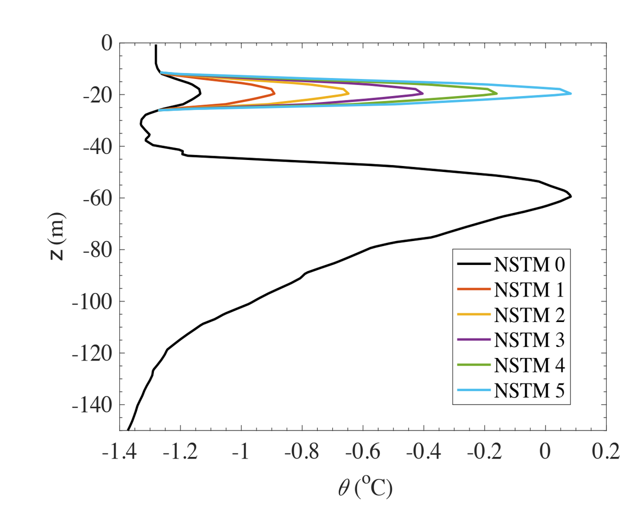
Collected by Ice-Tethered Profiler 77 on June 14, 2014

PSW+NSTM



Collected by Ice-Tethered Profiler 77 on July 14, 2014

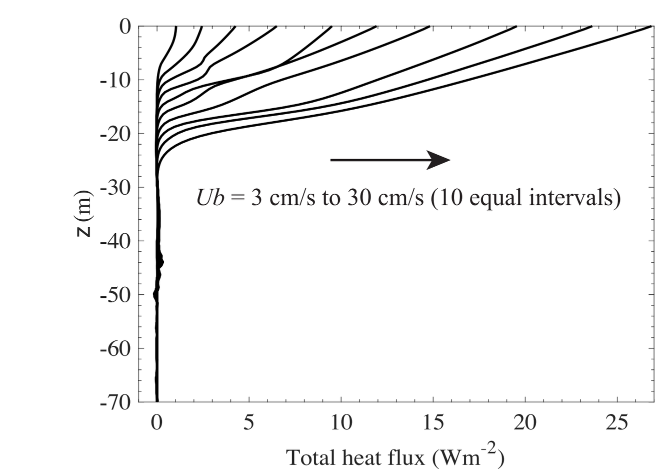
Modified NSTM



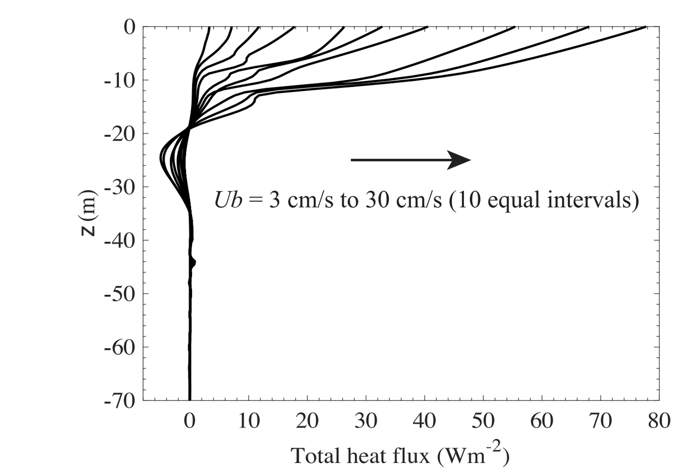
NSTM modified artificially

Results: A. PSW only vs. PSW+NSTM

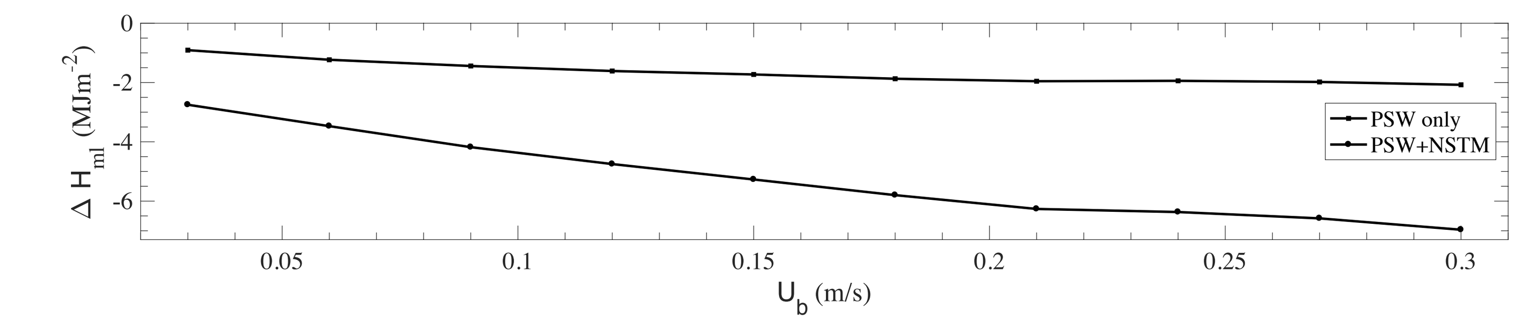
PSW only



PSW vs. NSTM



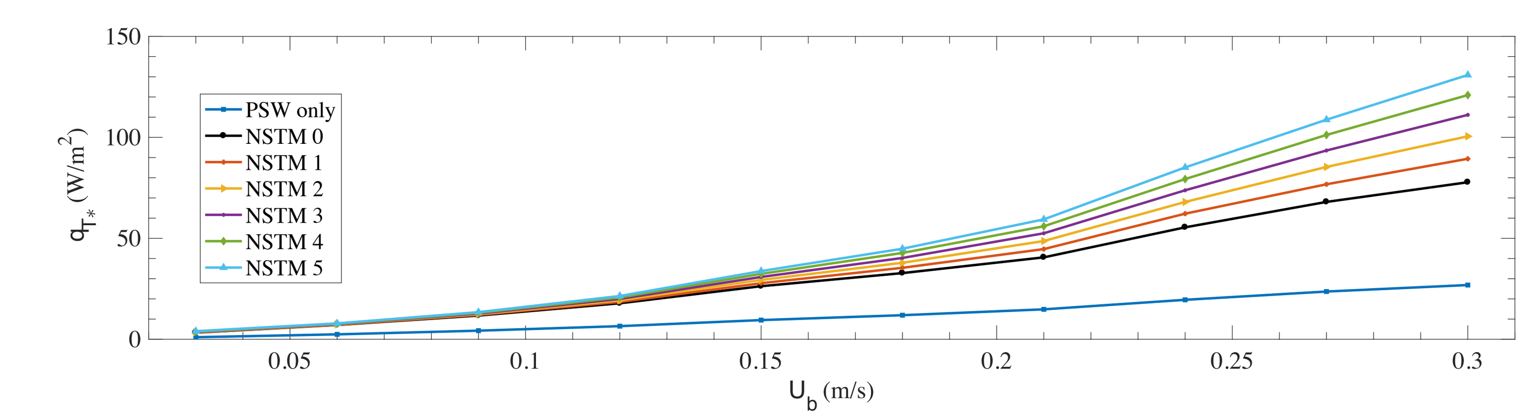
Horizontally-averaged heat flux (resolved + SGS) from simulations for ice-drift velocities from 3 cm/s to 30 cm/s



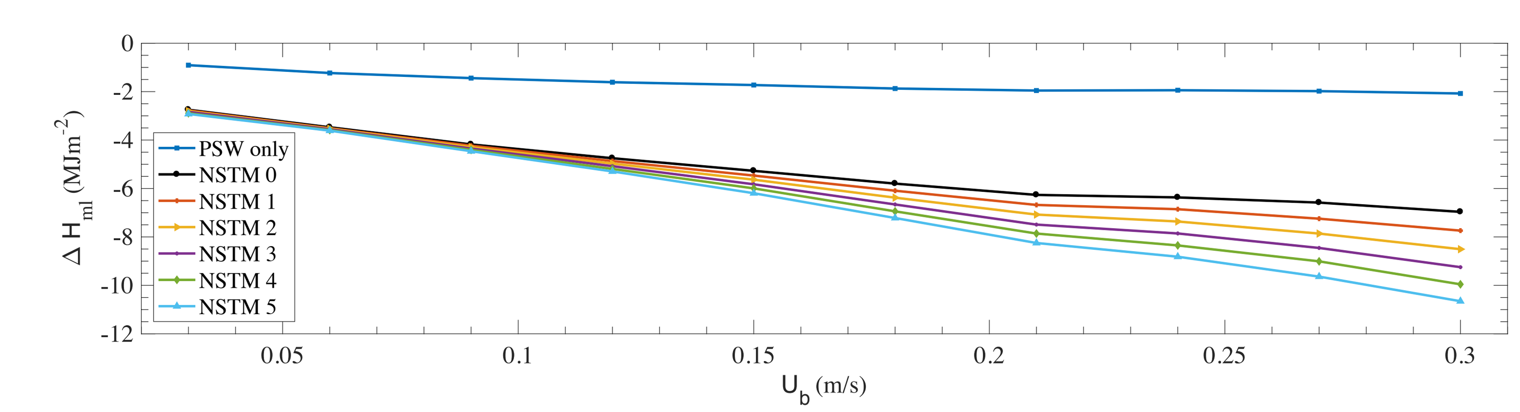
Change in heat content ΔH_{ml} of mixed layer (-40 m < z < 0) between initial and final conditions

$$\Delta H_{\text{ml}} = \int_{z_m}^{0} \rho c_\ell (T - T_0) dz$$

Results: B. Modified NSTM



Basal surface heat flux q_{T*} for modified profiles 'NSTM 0' through 'NSTM 5' for all U_b. q_{T*} for PSW only and 'NSTM 0' are plotted for comparison.



Change in heat content ΔH_{ml} for modified profiles 'NSTM 0' through 'NSTM 5' for all U_b. ΔQ for PSW only and 'NSTM 0' are plotted for comparison.

Conclusions

- Our LES experiments reveal that there is no entrainment of heat from below the pycnocline. This is because the pycnocline is strongly-stratified by salinity.
- In the presence of the NSTM, the heat that leaves the mixed layer and the heat flux to the basal surface of sea ice is ~3 times larger.
- The changes in heat content and heat fluxes increase monotonically with ice speed.
- The resolution of the NSTM is critical for capturing changes in Arctic sea ice. This opens questions about Arctic optical feedbacks.