Ice-covered freshwater lakes :

natural laboratories for investigation of buoyancy flows

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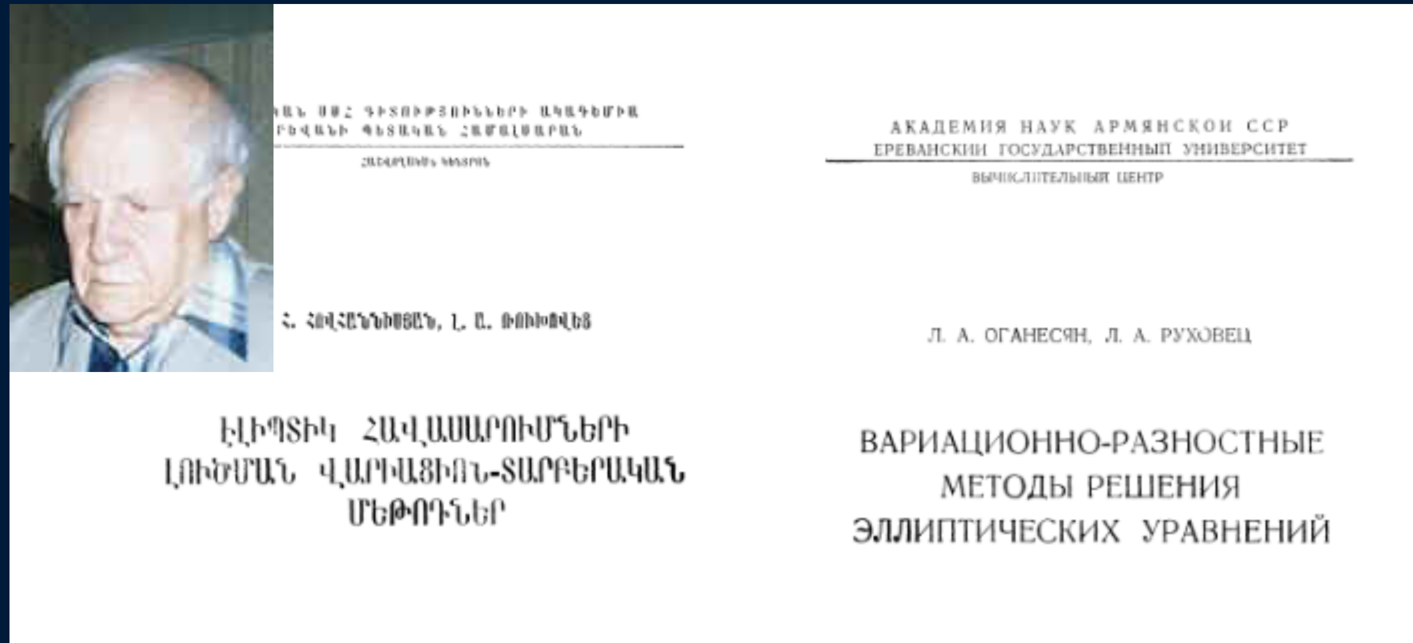
1993 - MSc in Physical Oceanography

Russian state Hydrometeorological University, S-Petersburg



1994-1999. Institute of Limnology
Russian Academy of Sciences, S-Petersburg

“Analytical solutions of coastal hydrodynamic problems (with application to Lake Ladoga circulation)”

Under supervision of L. Oganesyan

Since 1999:
Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin:
Department of Ecohydrology,
Workgroup "Lake Physics"

Ecosystem research

Lakes as a lab for the Ocean and the Atmosphere

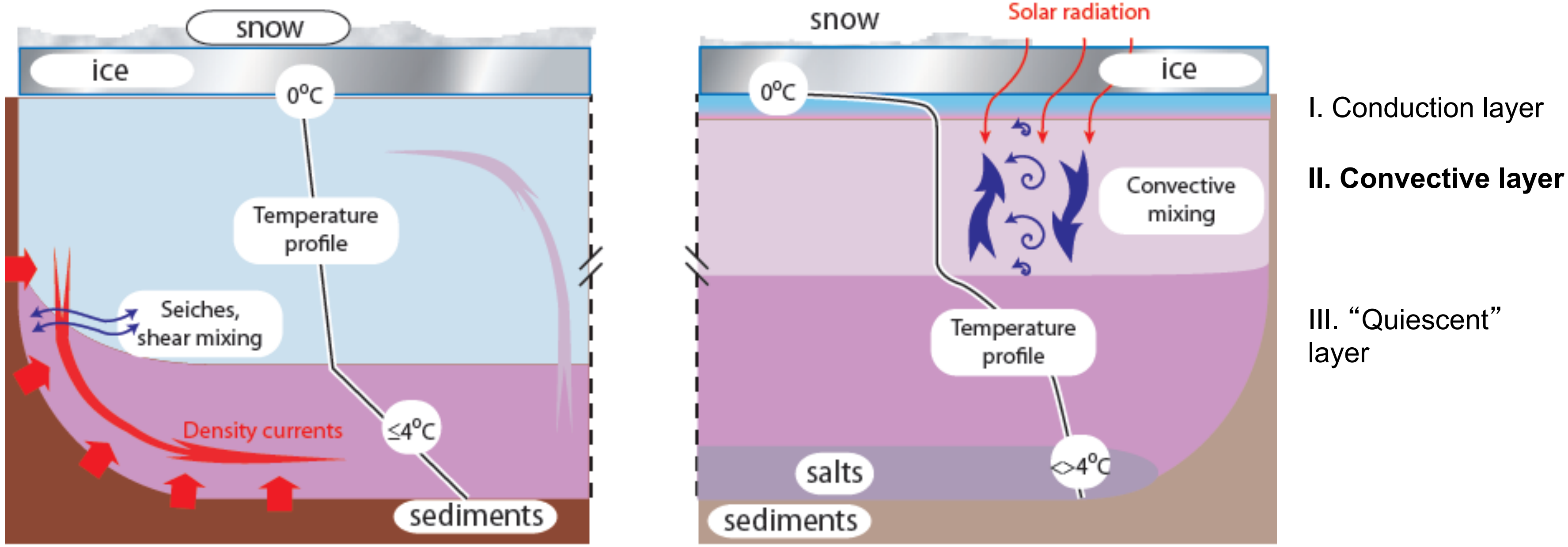
Climate change and freshwater resources

Physical Limnology

Outline

- Convection under lake ice: phenomenology and applications in geophysical fluid dynamics
- Microstructure measurements in the convective layer: aims, design, outputs
- Unresolved issues, areas of LES implementation
- Future field research plans

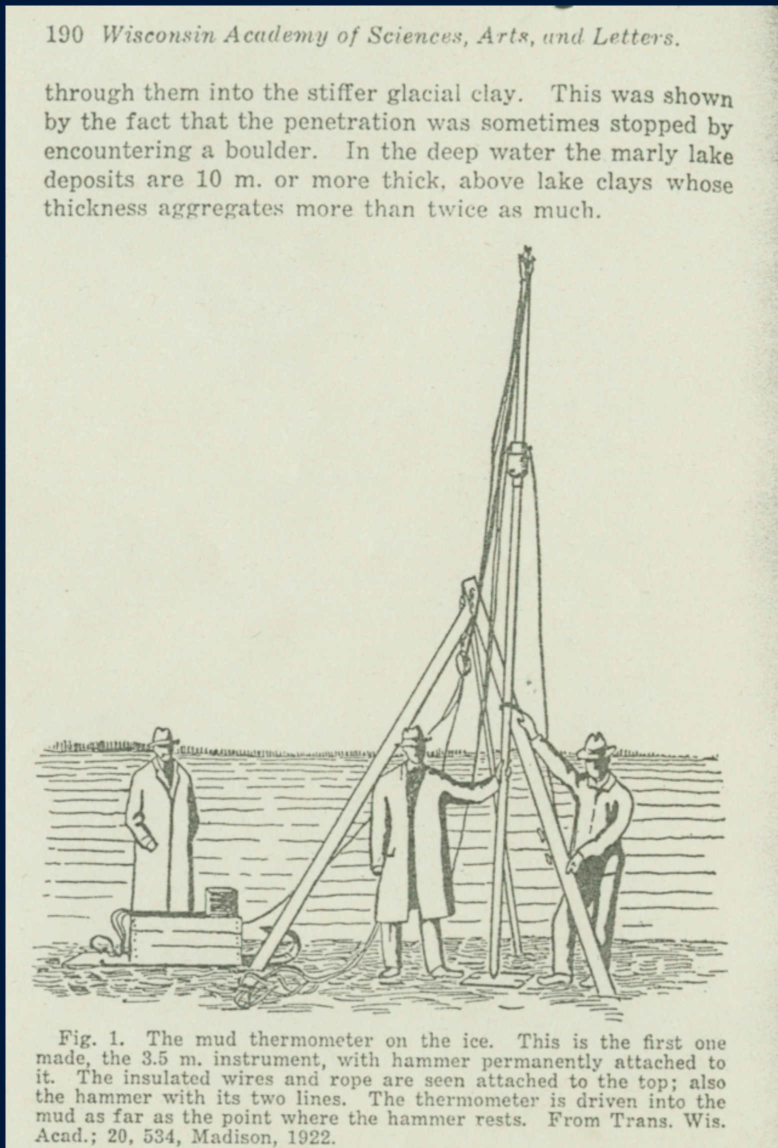
Temperature structure and water motions under lake ice



Ice- and snow-covered lake **Lake without snow cover**

-Without snow cover the solar radiation penetrates into the water column and produces gravitational instability

- Strong vertical mixing takes place in the convection layer and determines the structure of both conduction layer and quiescent layer


190 *Wisconsin Academy of Sciences, Arts, and Letters.*

through them into the stiffer glacial clay. This was shown by the fact that the penetration was sometimes stopped by encountering a boulder. In the deep water the marly lake deposits are 10 m. or more thick, above lake clays whose thickness aggregates more than twice as much.

Fig. 1. The mud thermometer on the ice. This is the first one made, the 3.5 m. instrument, with hammer permanently attached to it. The insulated wires and rope are seen attached to the top; also the hammer with its two lines. The thermometer is driven into the mud as far as the point where the hammer rests. From Trans. Wis. Acad.; 20, 534, Madison, 1922.

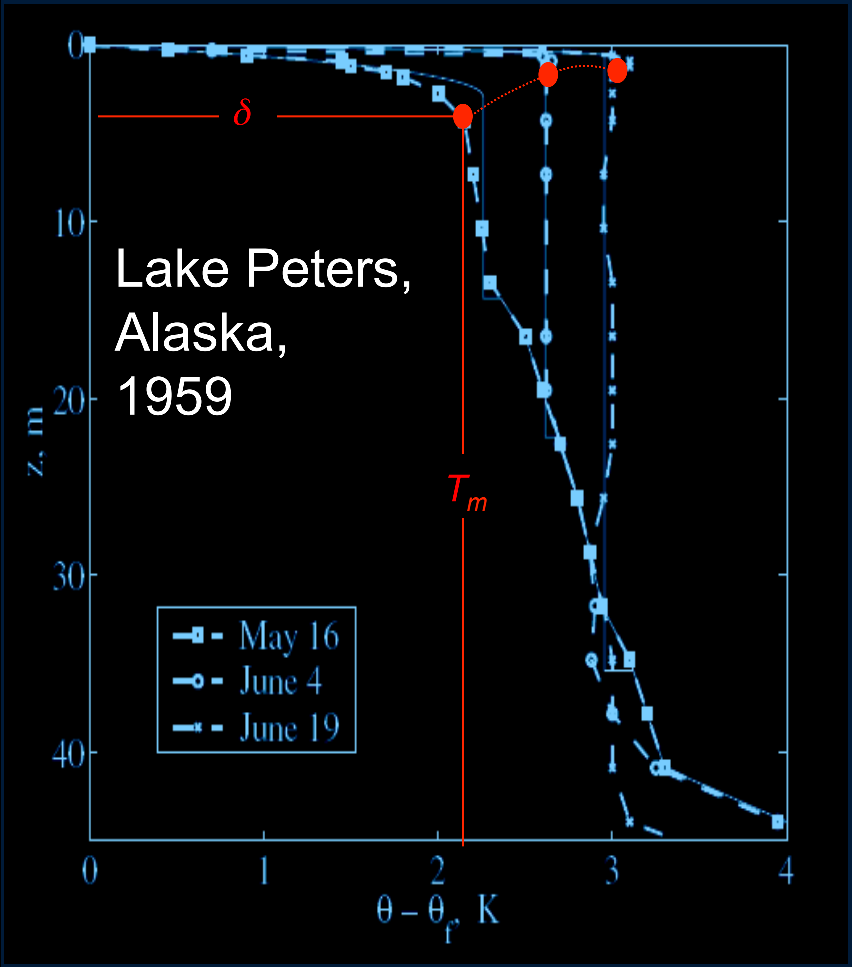
Convective temperature profiles under ice have been observed since early studies on lakes

Birge (Science, 1910) was apparently the first to mention that solar heating could produce convective mixing

Farmer (Quart. J. Roy Met Soc. 1975): first detailed measurements and convective mixing model

1995-Present: Continuous studies on under-ice dynamics in Lake Vendyurskoye, North-Western Russia (summarized by Mironov et al. JGR 2002)

Effect of convection on ice melting rate



modified from Barnes&Hobbie Geol. Surv. Res. 1960 and
Mironov et al. *J Geophys. Res.* 2002

Heat budget in the upper conduction layer is close to stationary balance between radiation consumption and heat diffusion

$$\kappa \frac{d^2T}{dz^2} = \frac{dI}{dz}; \quad T(\delta) = T_m; \quad T(0) = 0$$

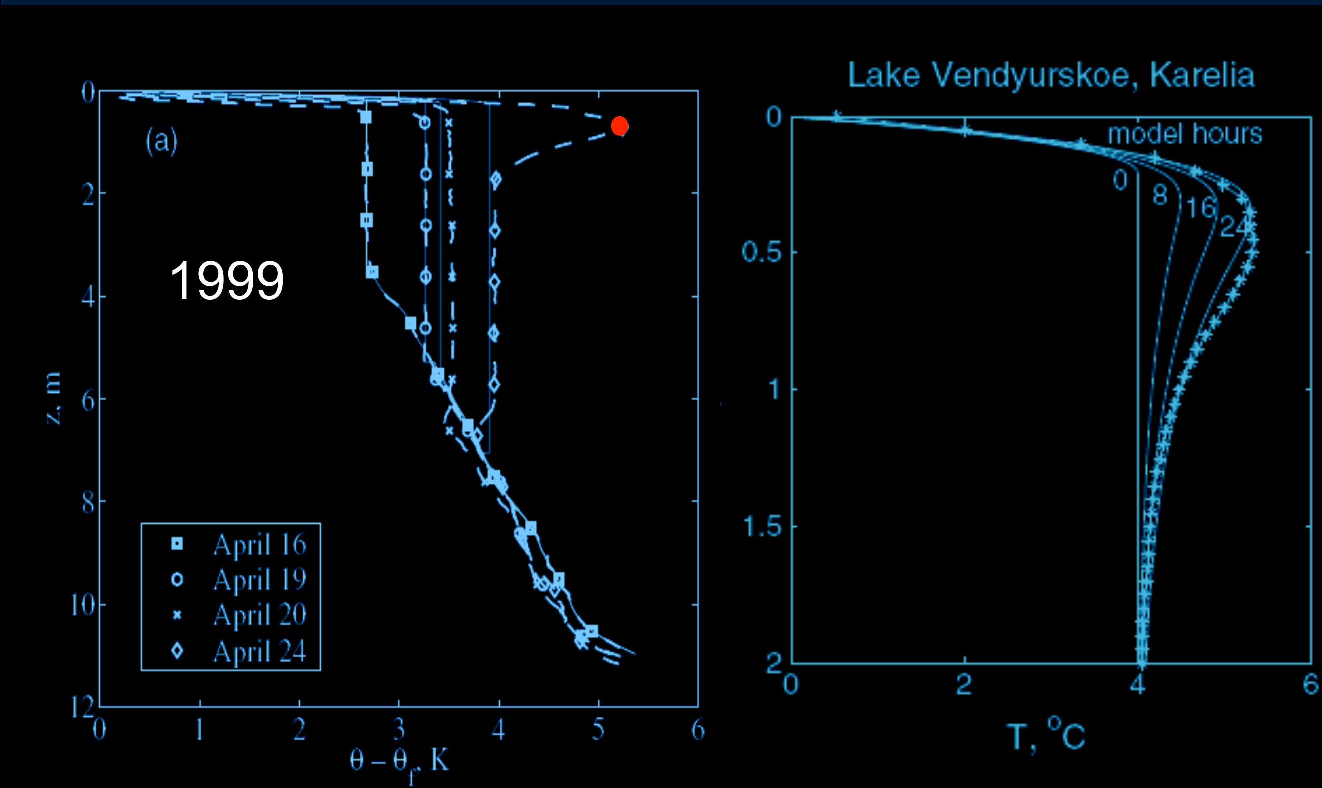
$$\frac{d^2T(\delta)}{dz^2} = 0 \quad \rightarrow \delta$$

$$T_m = ? \rightarrow \quad \frac{dT(0)}{dz} \rightarrow \quad melting\ rate$$

Temperature of the convective layer *Tm* and under-ice radiation level *I are sufficient to estimate the melting rate at the ice bottom*

Research for the future of our freshwaters

‘Special case’ Tm > 4°C: damping of convection



Modified from Kirillin&Terzhevik *Cold Regions Sci. Tech.* 2011

If water is warmed above the maximum density temperature a local temperature maximum develops,

In temperate lakes the phenomenon is of diurnal nature,
In polar lakes it could exist up to months;

The melting rate is approx. 2 times higher than during convection

$$\frac{\partial T(z,t)}{\partial t} - \varkappa \frac{\partial^2 T(z,t)}{\partial z^2} = -\frac{\partial}{\partial z} I_0 \exp(-\gamma z),$$

with the boundary conditions,

$$T(0,t) = 0, \quad T(\infty,t) = T_m, \quad T(z,0) = \begin{cases} \frac{I_0}{\varkappa\gamma}\left(1-e^{-\gamma z}\right)\left(1-\frac{z}{\delta}\right) + T_m\frac{z}{\delta} & \text{at} \quad 0<z<\delta, \\ T_m & \text{at} \quad z>\delta. \end{cases}$$

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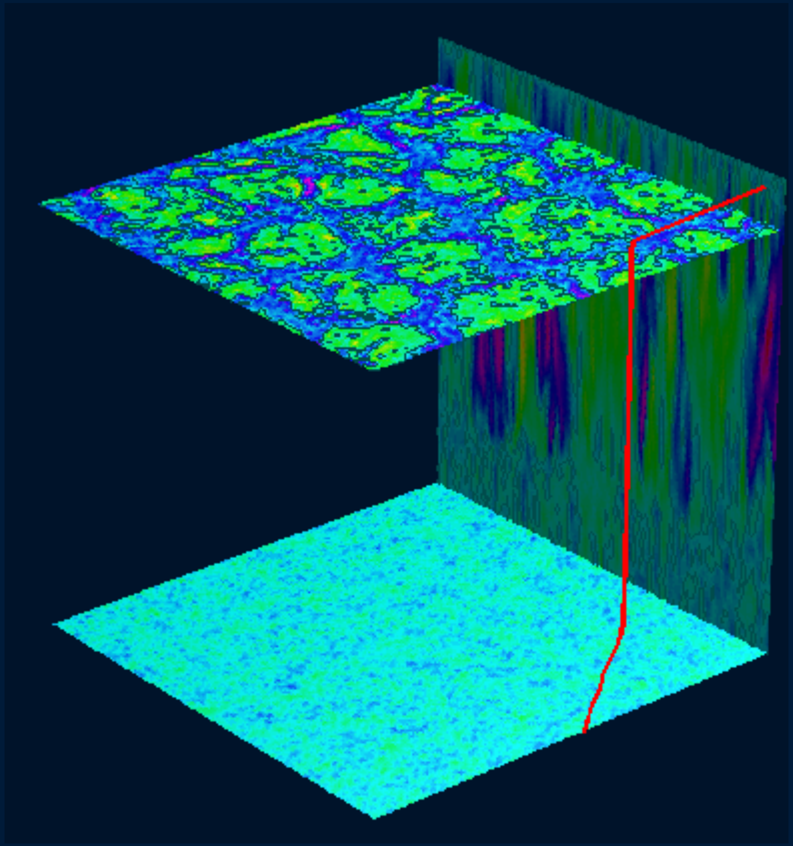
Anatomy of the convective layer: large eddy simulations



In contrast to the small-scale turbulence, convection produces regular patterns of coherent structures, motions are **non-homogeneous** at small scales.

Data of large eddy simulations courtesy D. Mironov (German Weather Service)

Convective patterns on lake ice

DONNERSTAG, 22. JANUAR 2009 / N

Hunderte Löcher im Eis

Seltenes Phänomen auf Seen entdeckt

BERLIN - Es ist ein Rätsel, nein, es sind dutzende, hunderte: mysteriöse Löcher im Eis auf einigen Gewässern in Berlin und Brandenburg. Südlich der Pfaueninsel im Wannsee etwa hat Maiciej Großer eine ganze Ansammlung dieser seltsamen Strukturen entdeckt. „Ich komme oft hier vorbei, schon seit Jahren, aber so etwas habe ich noch nie

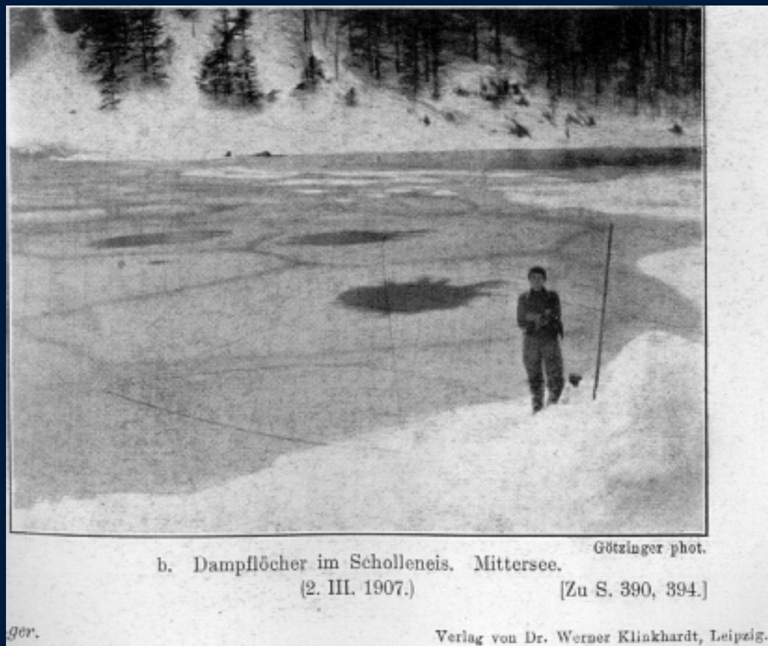
Wie Großer mögen auch andere Spaziergänger zunächst an einen Meteoritenschauer gedacht haben. Doch Jürgen Rendtel vom Astrophysikalischen Institut Potsdam sagt: „Dass ein Meteoritenschauer die Löcher ins Eis geschlagen hat, ist ausgeschlossen.“ Ein solches Ereignis wäre mit einem explosionsartigen Knall und einem Lichtblitz verbunden. „Schwer vorstellbar, dass so etwas im Ballungsraum Berlin unbemerkt geblieben wäre“, sagt Rendtel. Zudem seien die Eislöcher auf mehreren Seen zu finden. Er selbst habe sie auf dem bei Schlänitzsee bei Ketzin entdeckt; auch auf dem Müggelsee und auf der Havel seien sie zu sehen.

Foto: Kolle

Eisloch

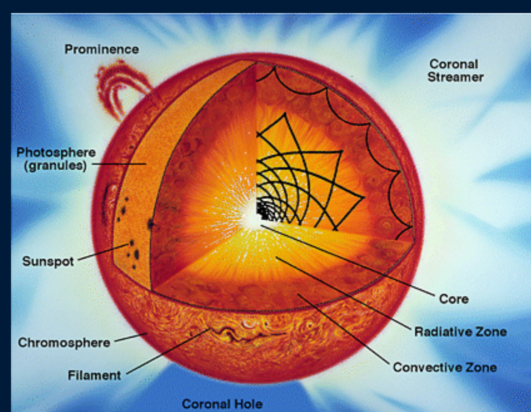
Picture of ice-covered pond Kleiner Kiel, Germany in spring, courtesy Marcus Seeger

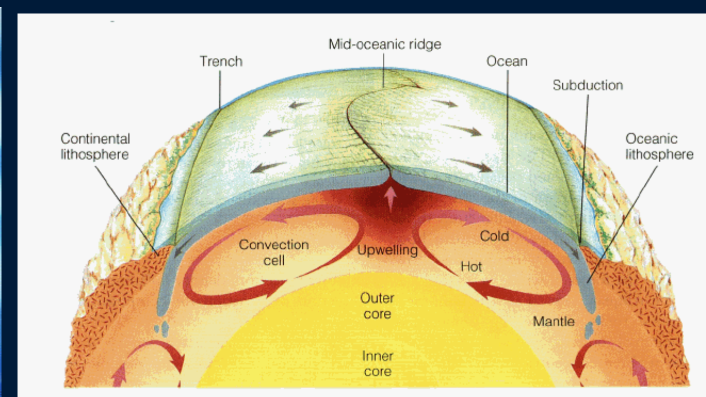
Convective patterns on lake ice

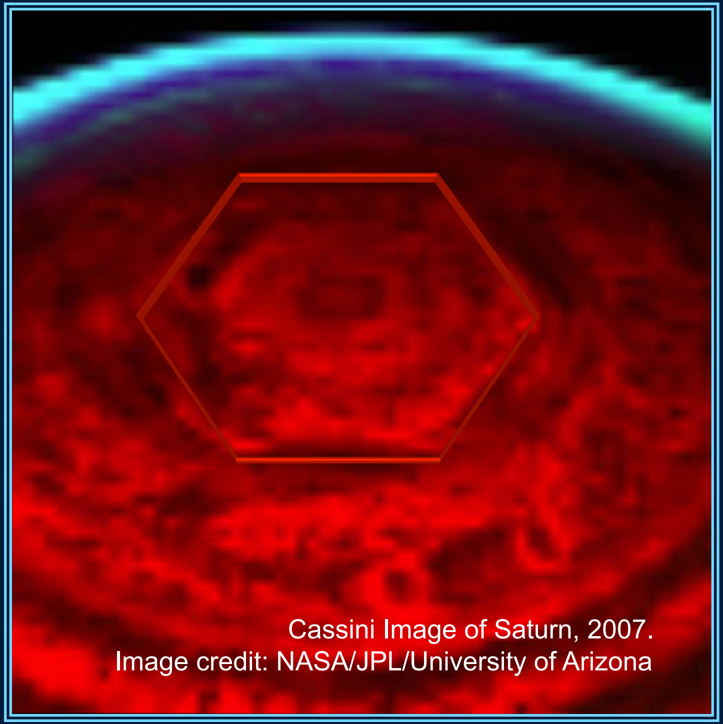


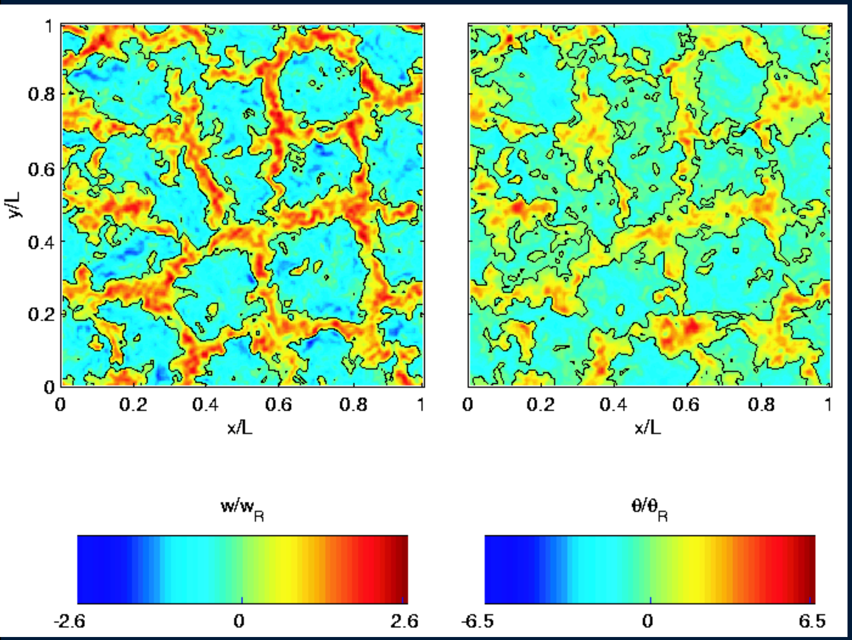
Convection driven by volumetric absorption of radiation is typical for convective flows in the atmosphere, stellar interior, magma convection.

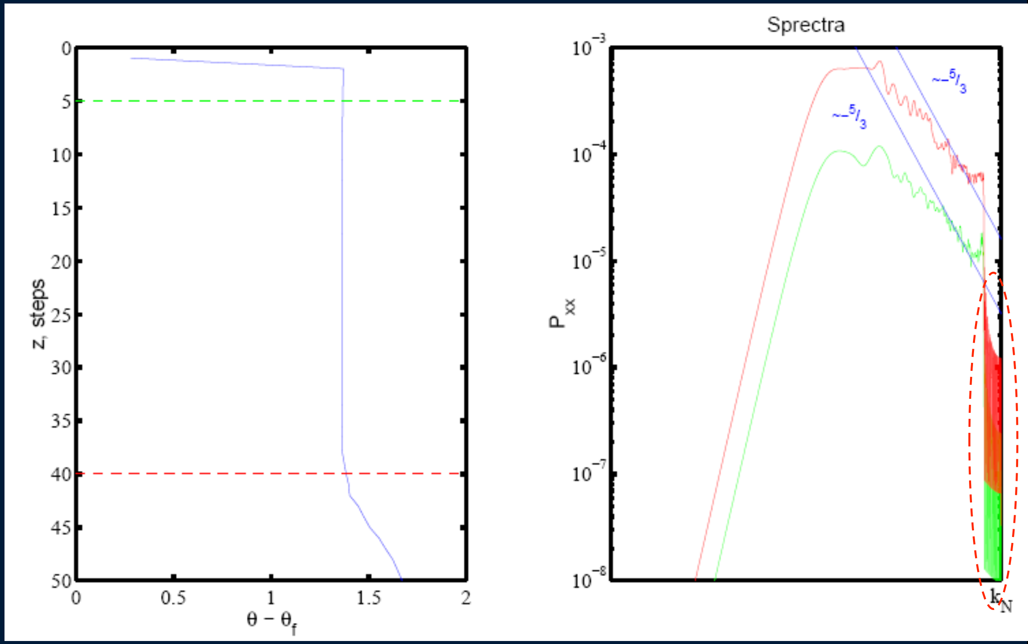
Lakes are ideal „natural laboratories“ for studying shear-free convection






Cassini Image of Saturn, 2007.
Image credit: NASA/JPL/University of Arizona



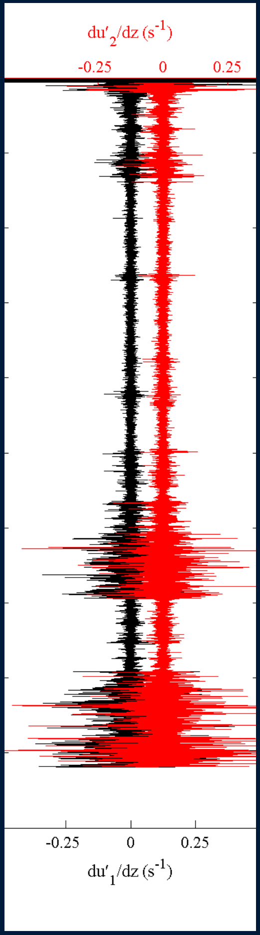


The energy transport from convective motions to small-scale mixing is unknown

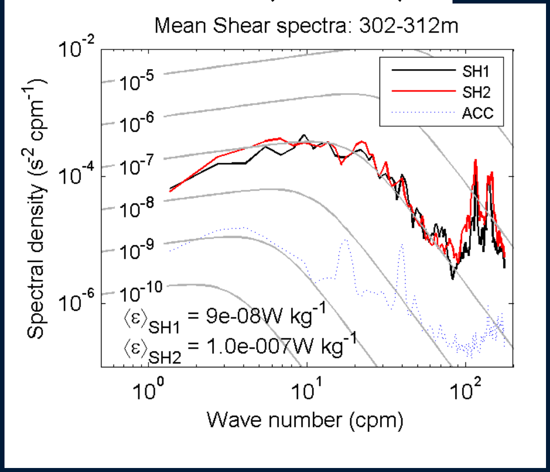
Research for the future of our freshwaters

Microstructure method

Shear microstructure methods allows direct estimation of velocity fluctuations and thereby the <u>dissipation rate of convective energy</u>



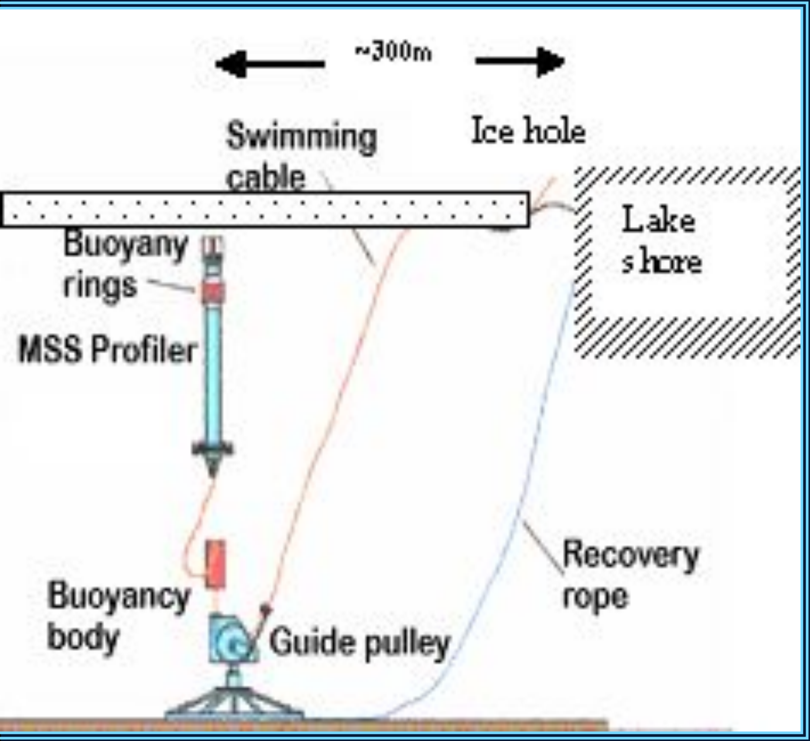
$$\varepsilon = \frac{15}{2}\nu\left(\frac{\partial U}{\partial z}\right)^2$$

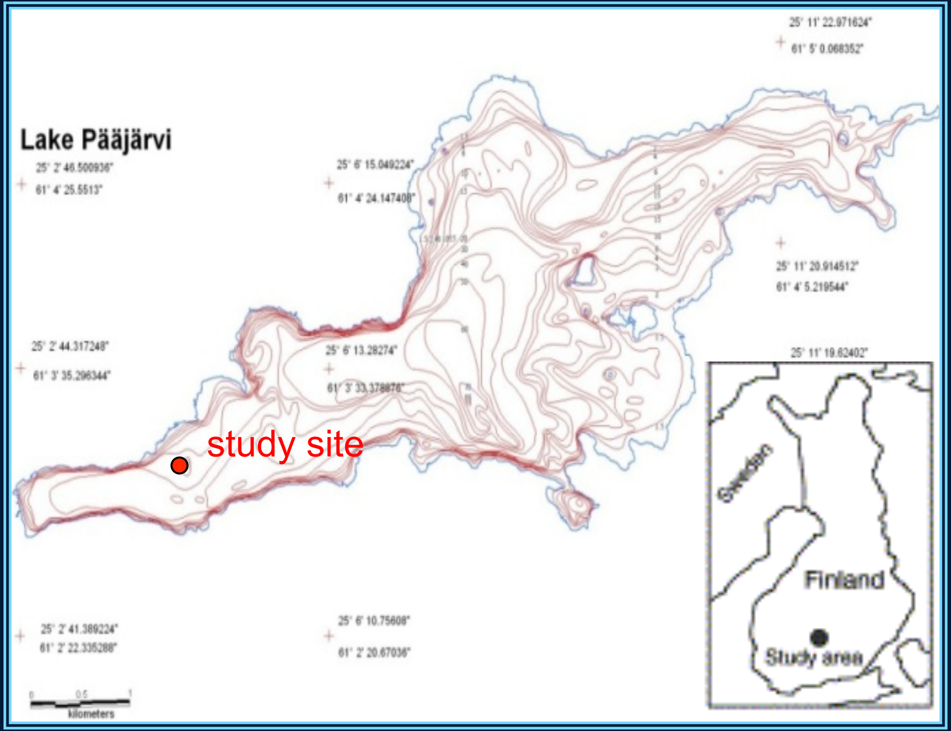


Aims and hypotheses for the field experiment

- Microstructure method validation for convection without mean shear (isotropy and homogeneity)?
- local production-dissipation balance?
- Diurnal variations of the convective mixing intensity?
- Mixing rates at the very end of the ice-covered period?
- Mixing ratio (ratio of energy spent for the mixed layer deepening to that spent for heating)

Experiment design and study site





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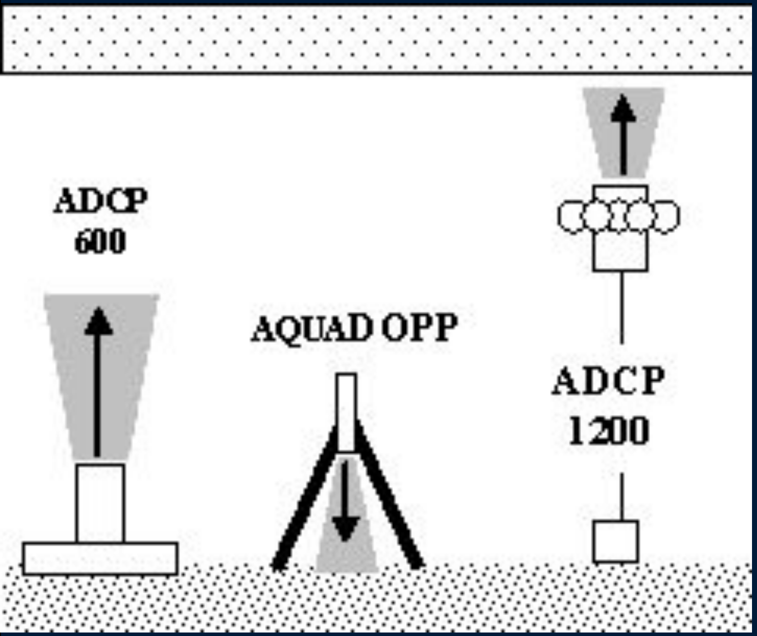
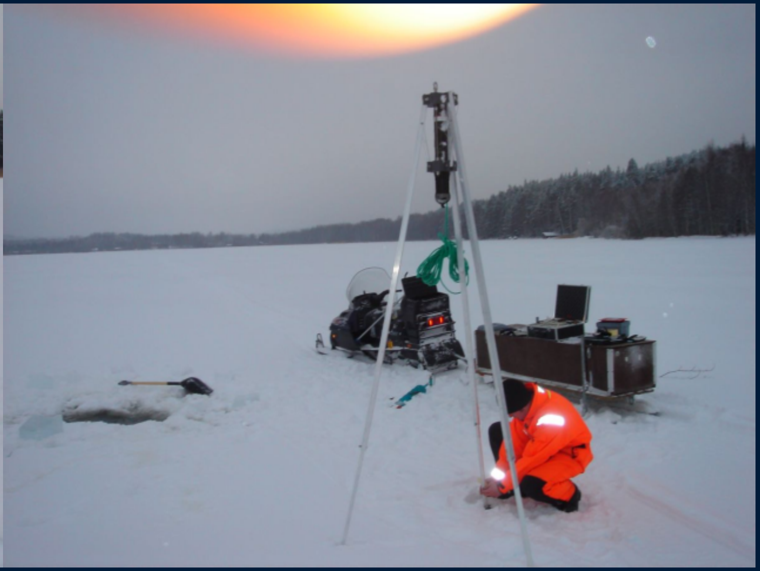
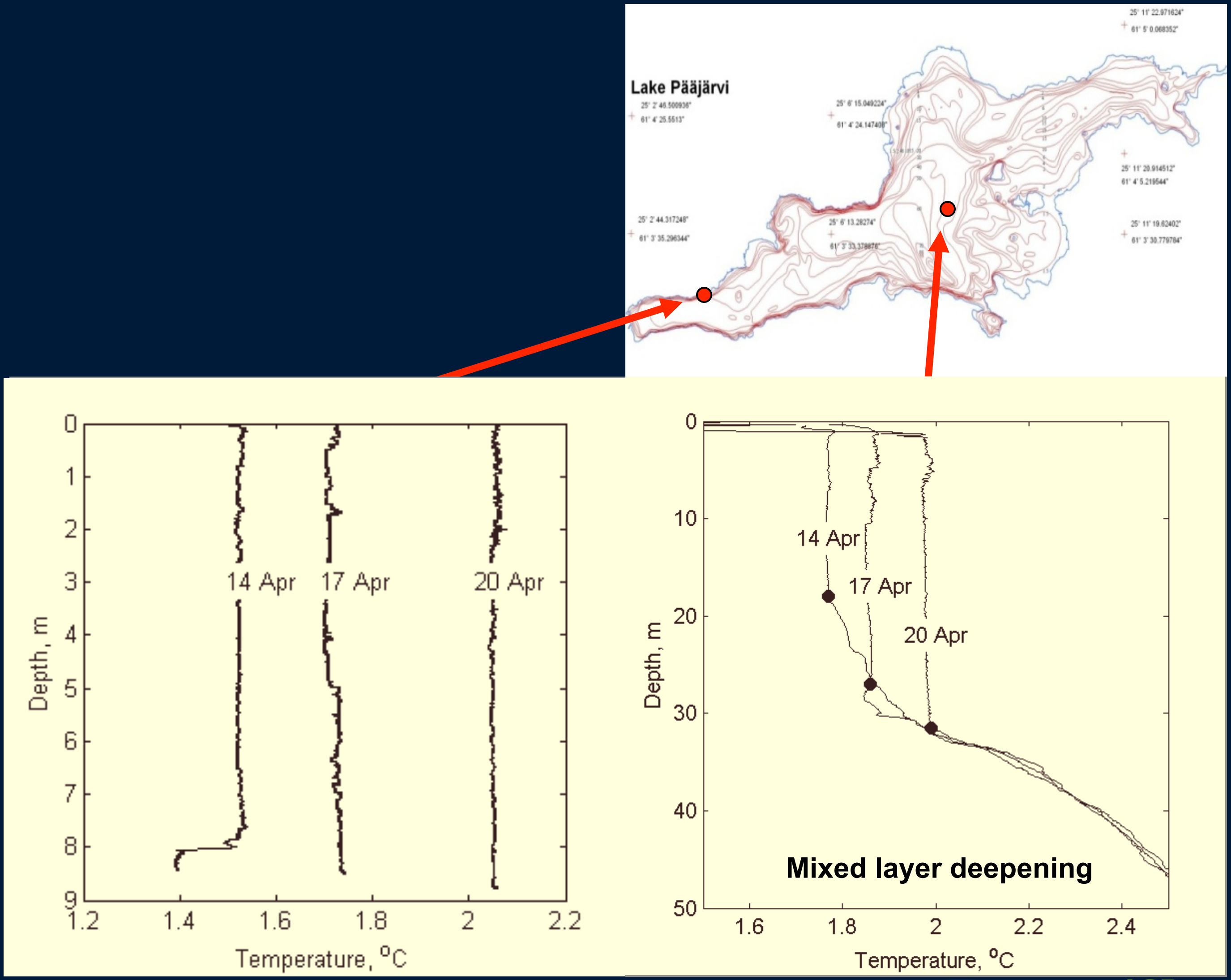
Experiment design and study site

Acoustic profiling of the velocity microstructure

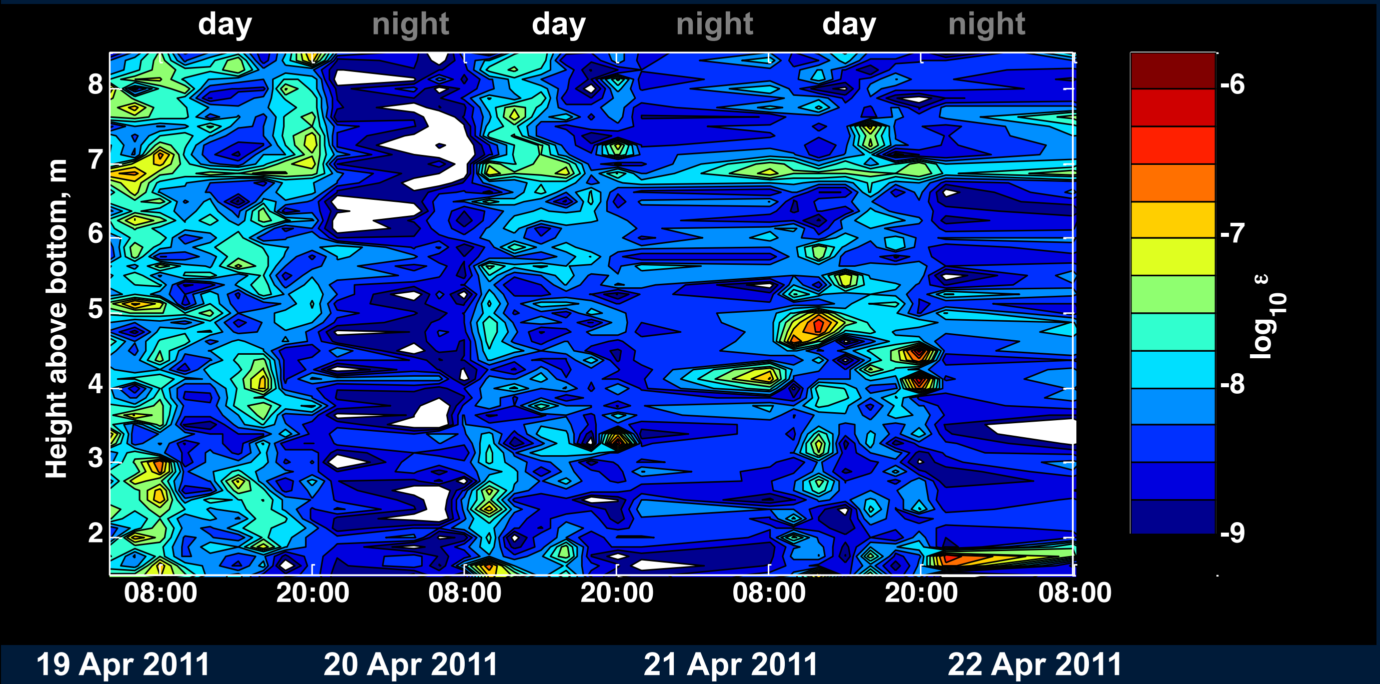




Background temperature structure

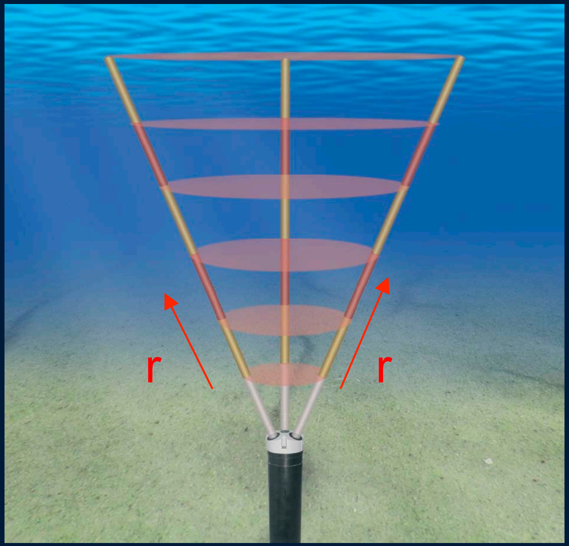


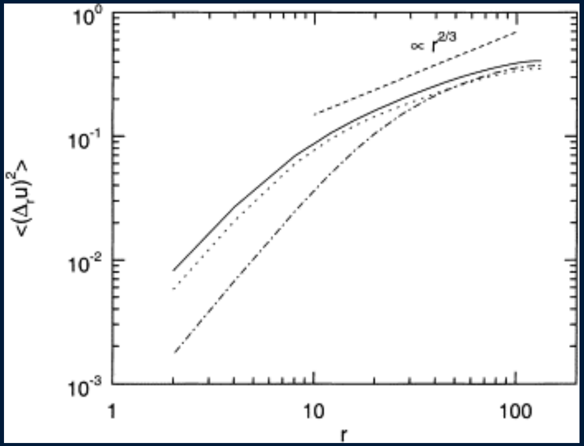
Dissipation rates from shear microstructure

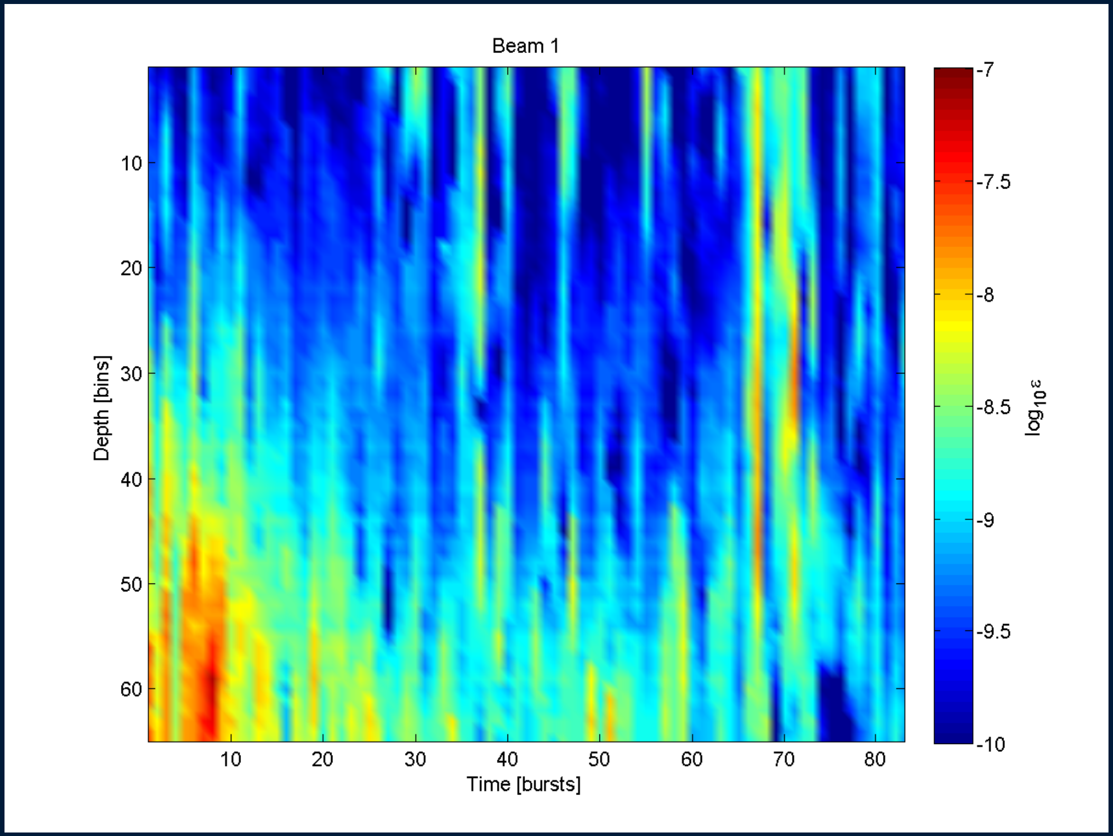


Dissipation rates near the bottom from acoustic soundings

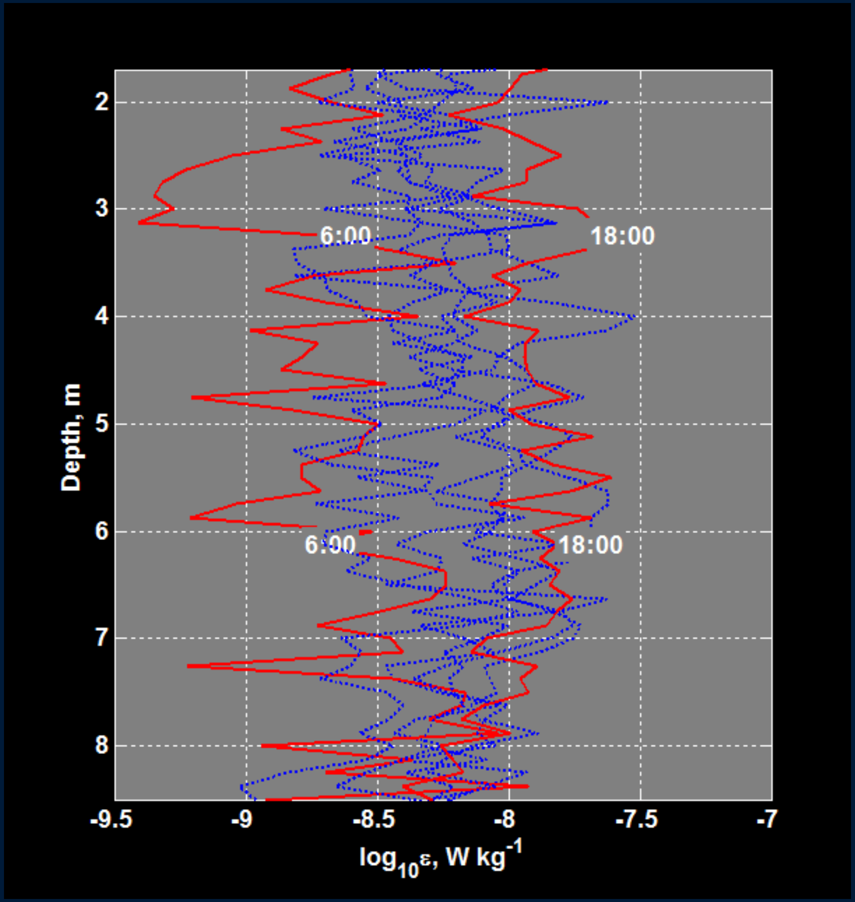
$$S_p(\mathbf{r}) = \langle (u(\mathbf{x}+\mathbf{r}) - u(\mathbf{x}))^p \rangle \sim (\varepsilon r)^{p/3}$$







Diurnal dynamics

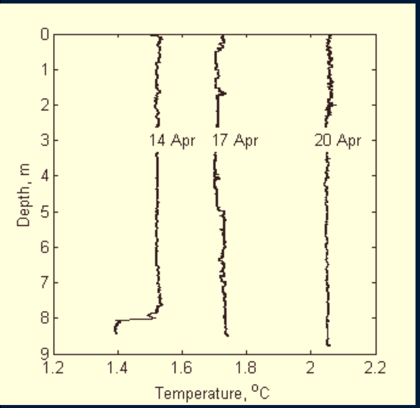


Recorded dissipation rates vary from <10^{-9} J/kg to >10^{-8} J/kg in the mean diurnal cycle. Instant values achieve >10^{-6} J/kg

For comparison:

- ice-free surface layer: $\varepsilon \sim 10^{-4}$ J/kg
- bottom mixing in lakes and on sea shelf: $\varepsilon \sim 10^{-7}$-10^{-6} J/kg
- 'Quiet' waters: $\varepsilon \sim 10^{-10}$-$10^{-9}$ J/kg

Mixing energy budget:



Integrated budget of mixing energy

de/dt = Prod + Flux↑+Flux↓ - Diss

$$\frac{d}{dt}\left(\int_0^h e dz\right) = -\int_0^h B dz + F_\delta - F_h - \int_0^h \varepsilon dz$$

~ 0

In a convective layer occupying the whole water column

Prod = Diss or $\int_\delta^h B dz = \int_\delta^h \varepsilon dz$

Buoyancy production in a mixed layer

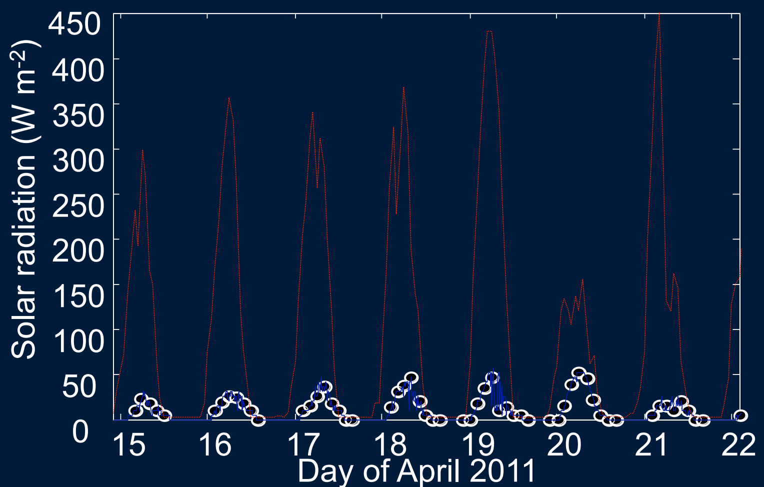
$$\int_0^h B\, dz = \alpha g \left(\frac{I(0) + I(h)}{2} - \frac{1}{h} \int_0^h I(z) dz \right)$$

Mixing energy budget: results

Solar radiation:

red: ice surface

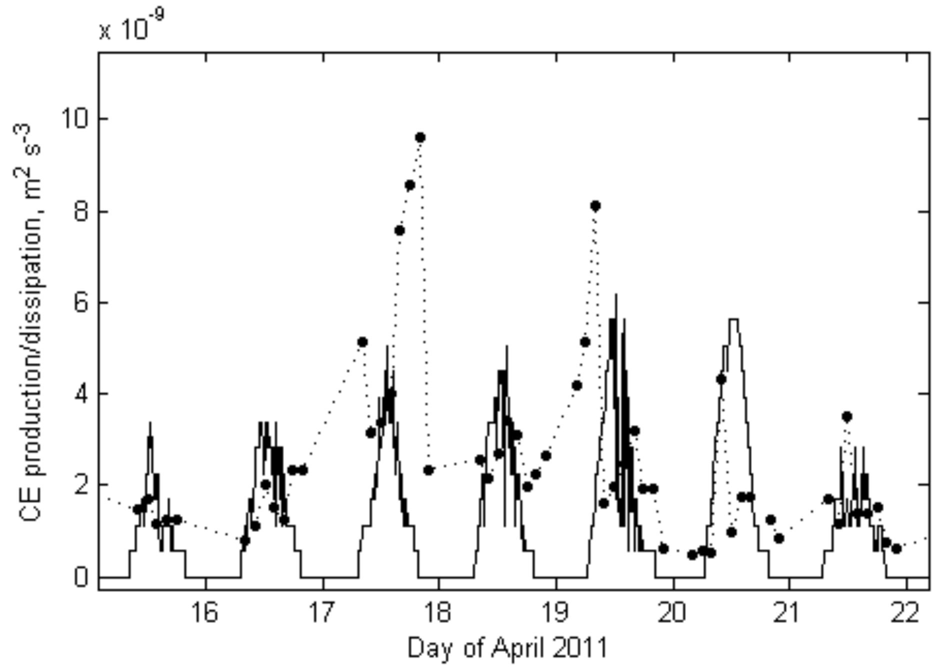
blue: ice bottom



Mixing energy budget:

solid line: production by radiation

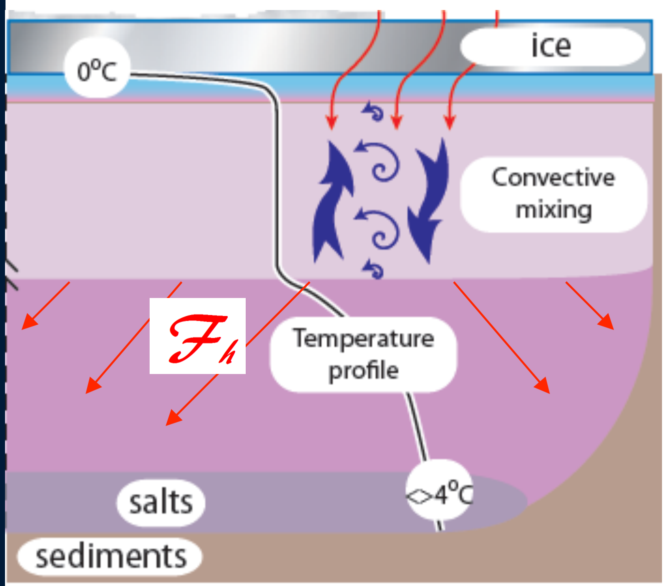
dotted line with circles: dissipation



Unresolved issues

Energy radiation by internal waves

$\sim w_R$



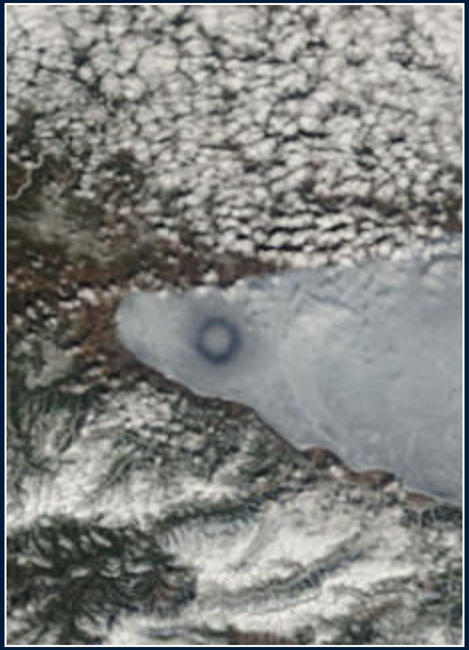
$$\frac{d}{dt}\left(\int_\delta^h e\,dz\right) = -\int_\delta^h \beta Q\,dz - \mathcal{F}_h - \int_\delta^h \epsilon\,dz,$$

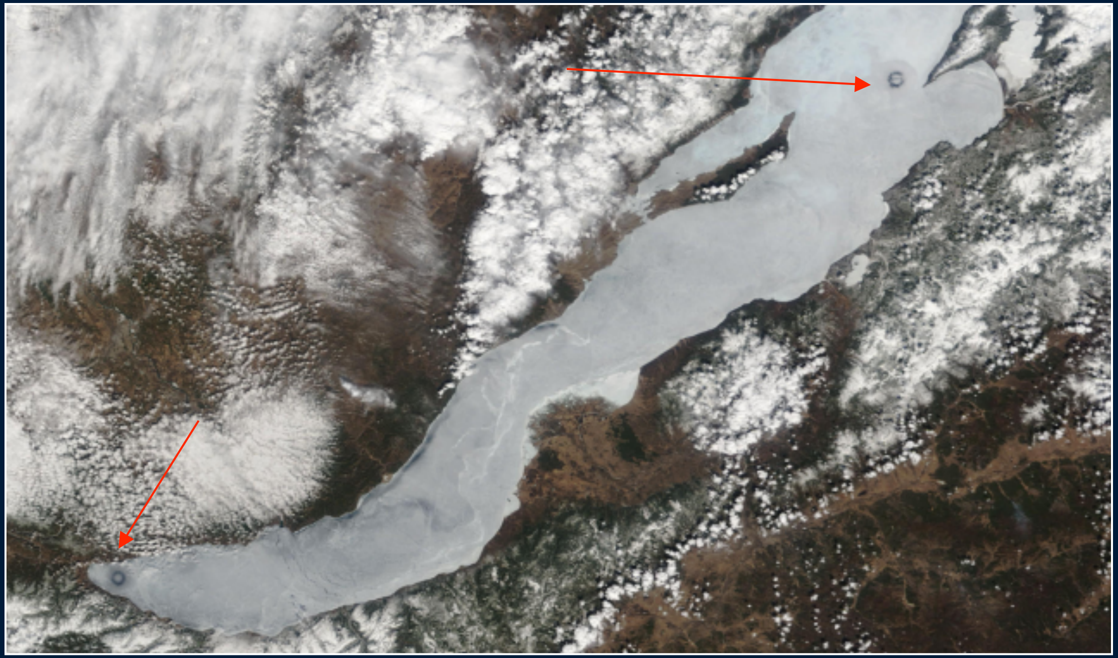
?

$w_* = (hB_s)^{1/3}$ Deardorff's convective scaling

$w_R = [-(h-\delta)B_R]^{1/3}$ Modified convective scaling

$$B_R = \beta[\theta(\delta)]I(\delta) + \beta[\theta(h)]I(h) - 2(h-\delta)^{-1}\int_\delta^h \beta(\theta) I\,dz,$$

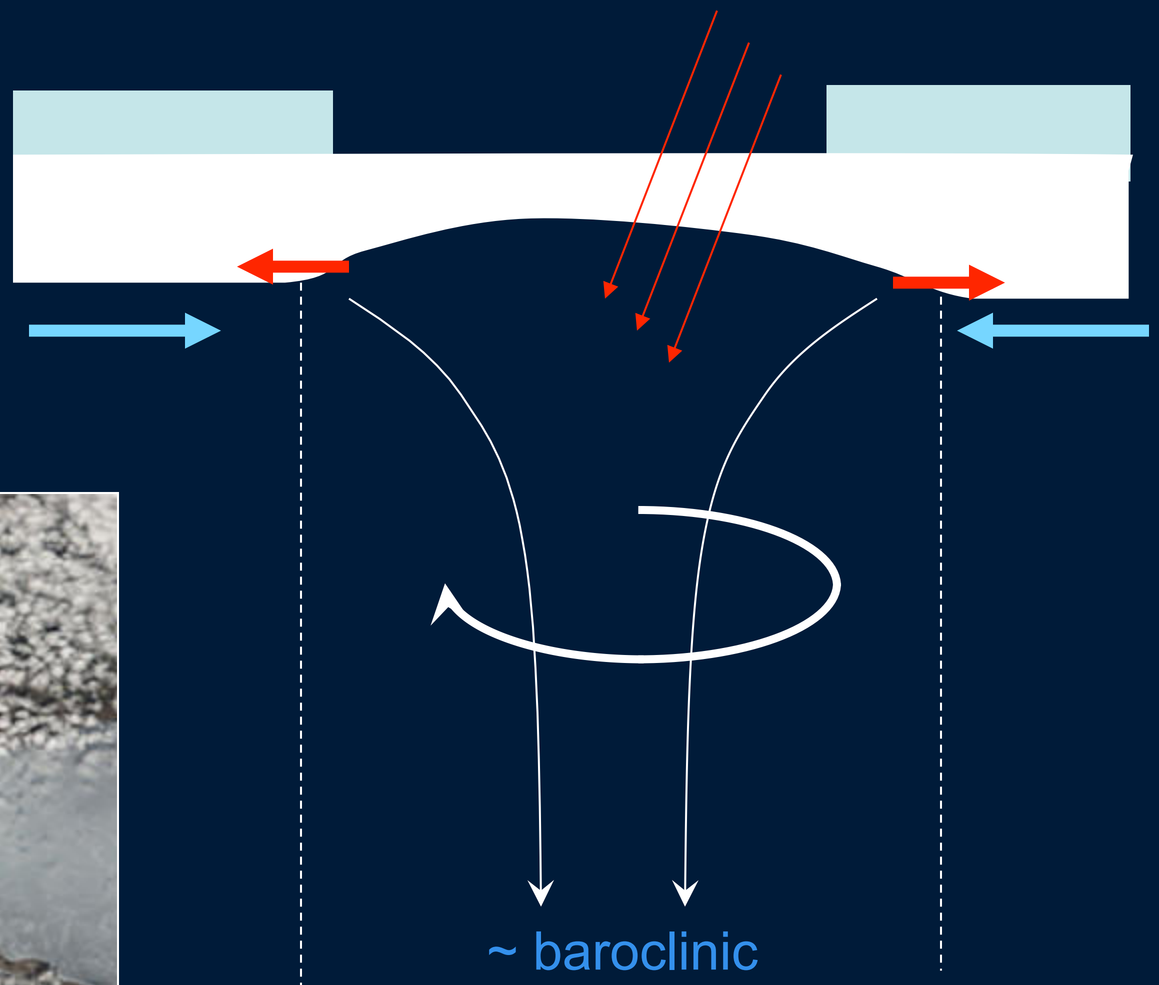




Rotation effects on convection: The mystery of Baikal rings

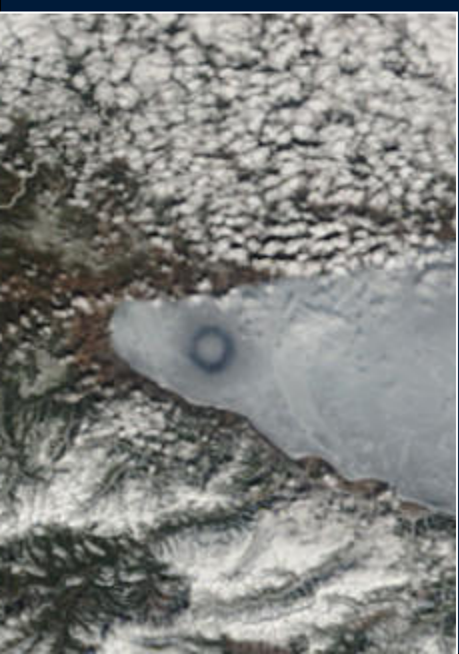
Initial forcing: heterogeneity in the radiation amount

Final dimensions of the gyre are determined by the Earth rotation



~ baroclinic

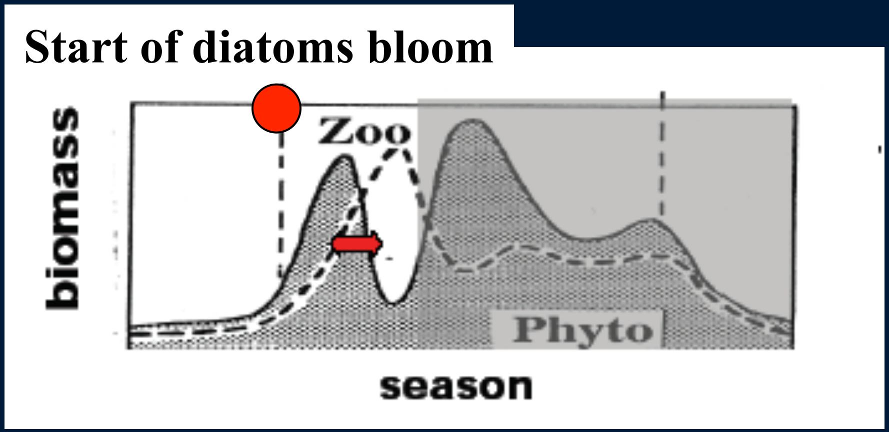
<- Rossby radius ->



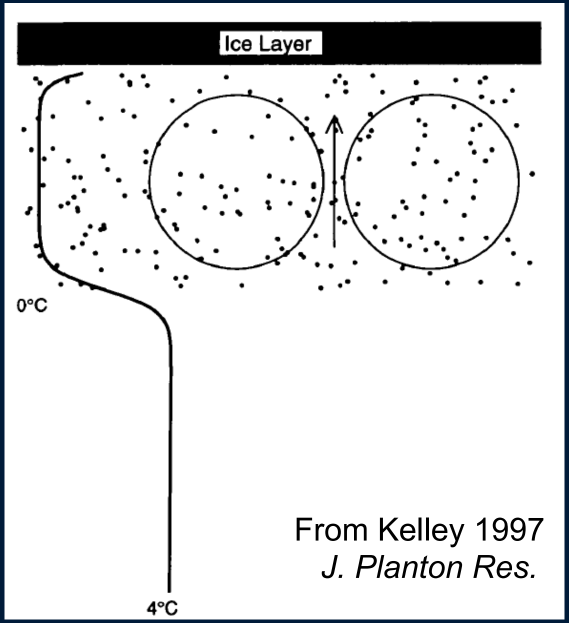
Research for the future of our freshwaters IGB

Ecological applications

Implications: lake ecology



Early production of diatoms under ice is a key phase of seasonal plankton succession in lakes



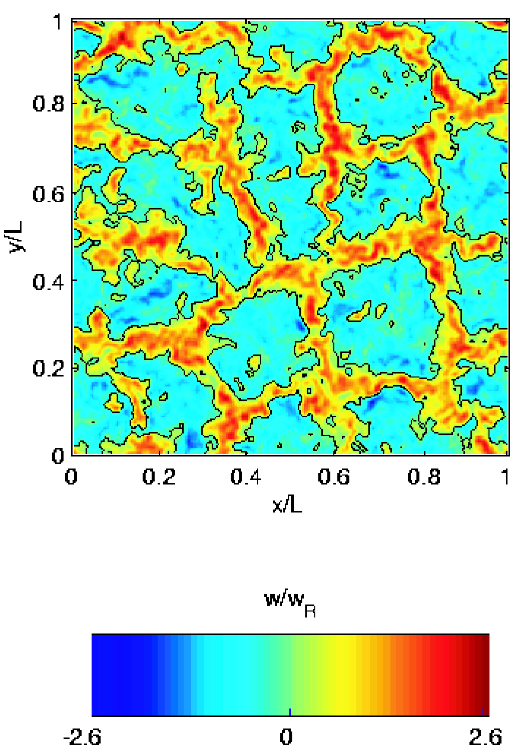
From Kelley 1997
J. Planton Res.

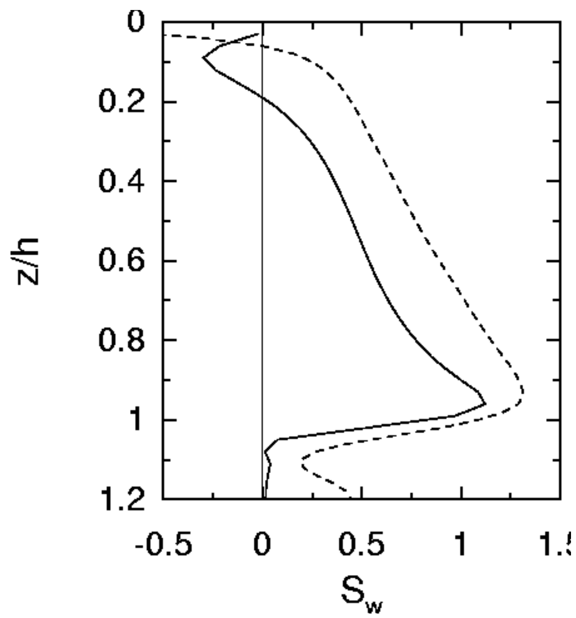
General hypothesis:

Vertical convective motions facilitate plankton growth under ice by supporting non-motile species in the upper water column and/or supplying nutrients from the deeper waters

Is convection able to support plankton in the upper water column?

Eddy-resolving modeling may provide the answer.



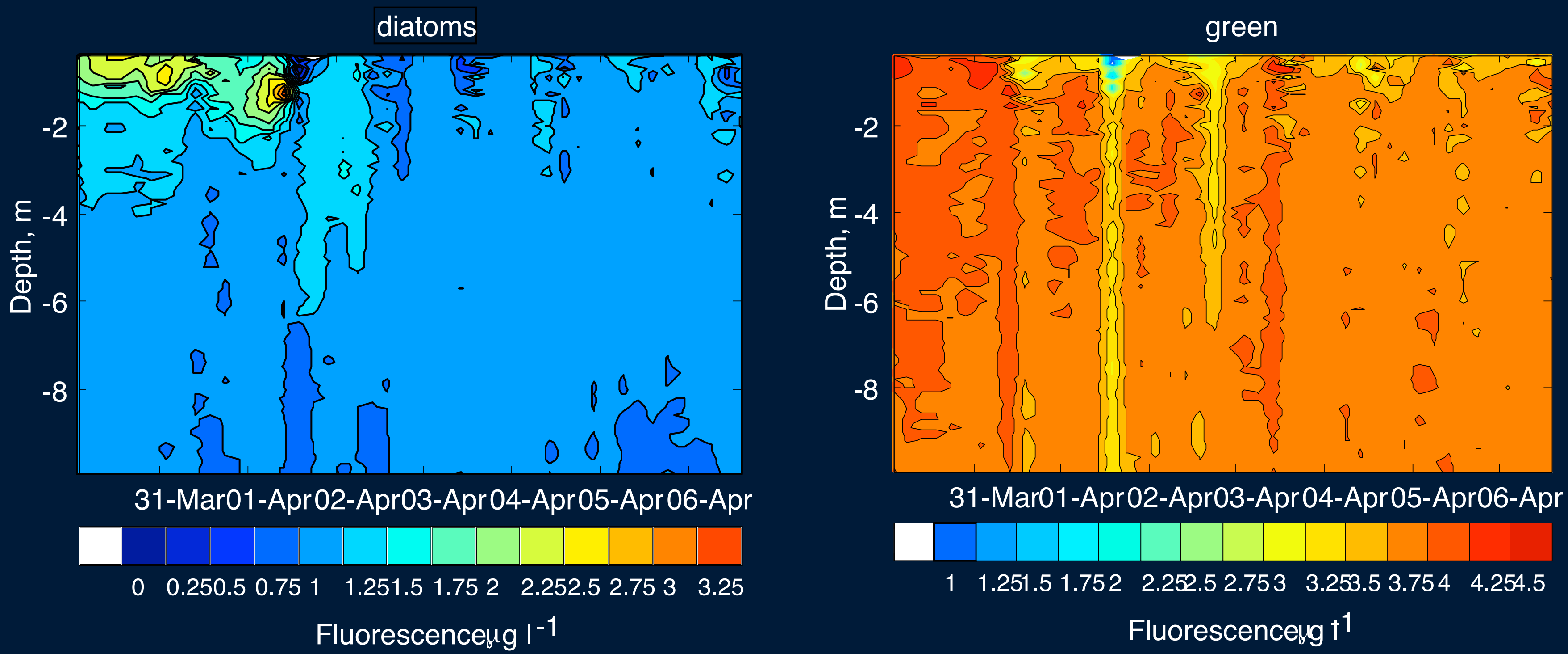


Vertical velocity skewness is positive in the bulk of the convective layer.

Downward motions are more localized than upward ones.

Favorable for (normally distributed) plankton.

Spectral fluorescence data, Lake Pääjärvi, Spring 2010



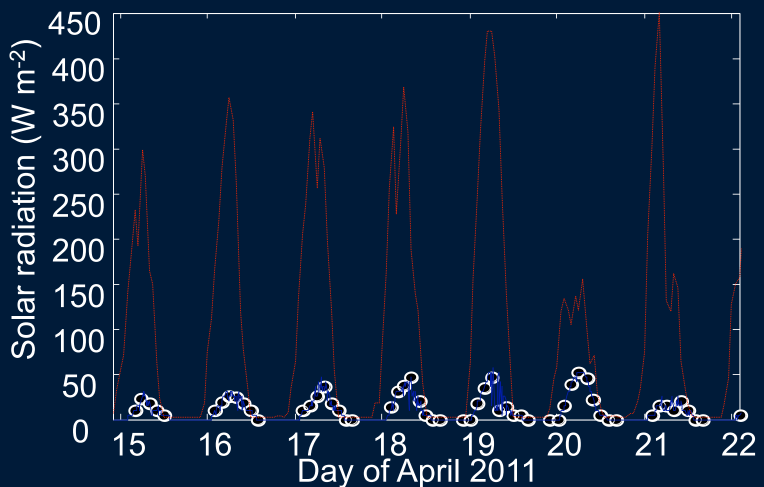
Large-scale effects

Mixing energy budget: results

Solar radiation:

red: ice surface

blue: ice bottom

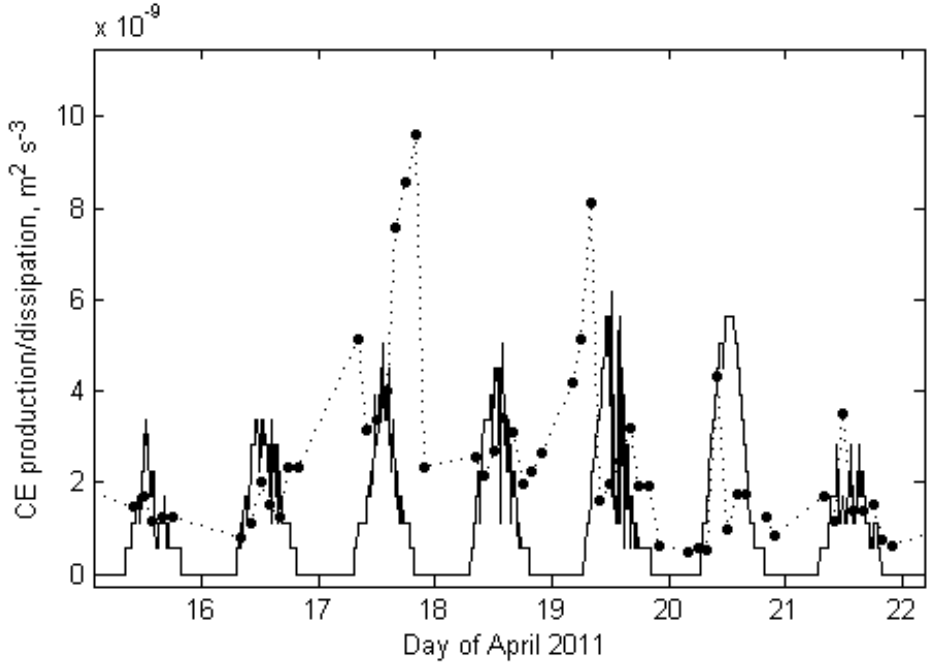


Dissipation rates at nighttime are surprisingly high

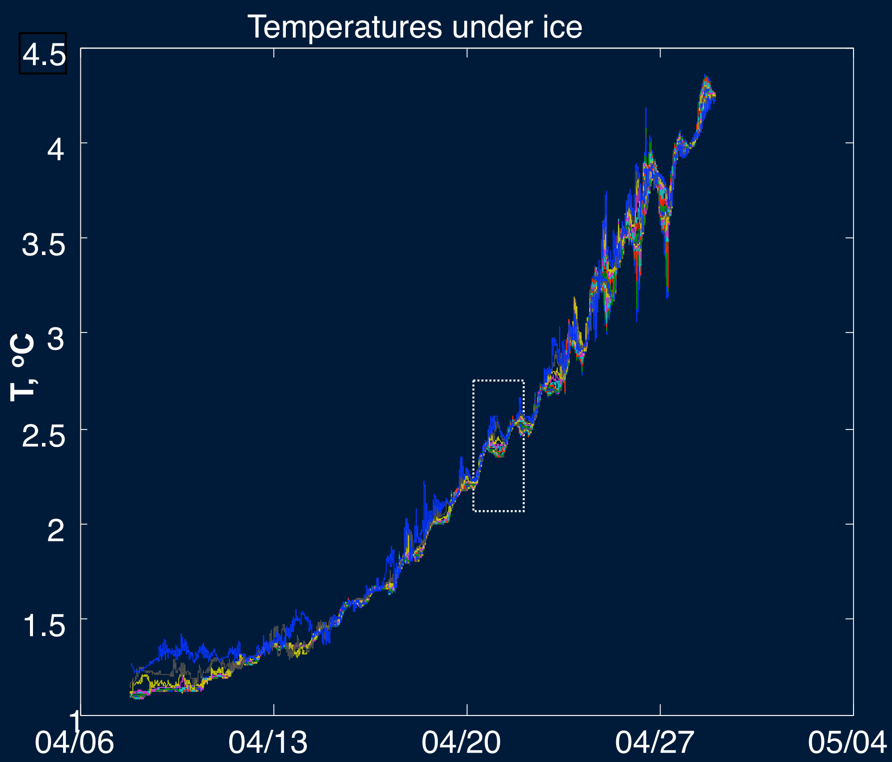
Mixing energy budget:

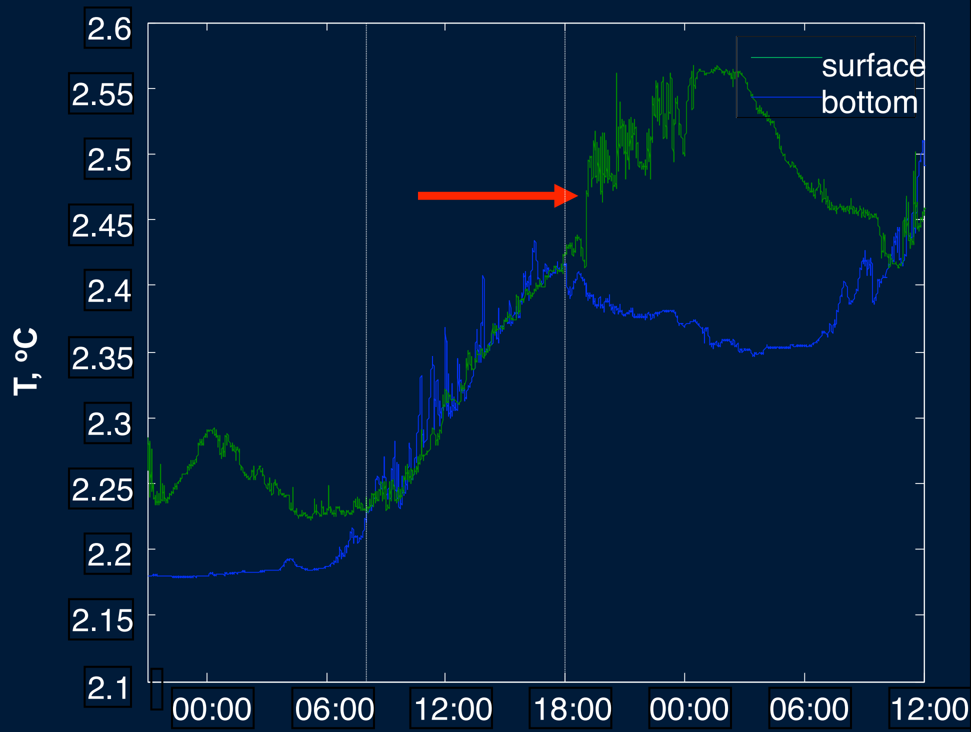
solid line: production by radiation

dotted line with circles: dissipation



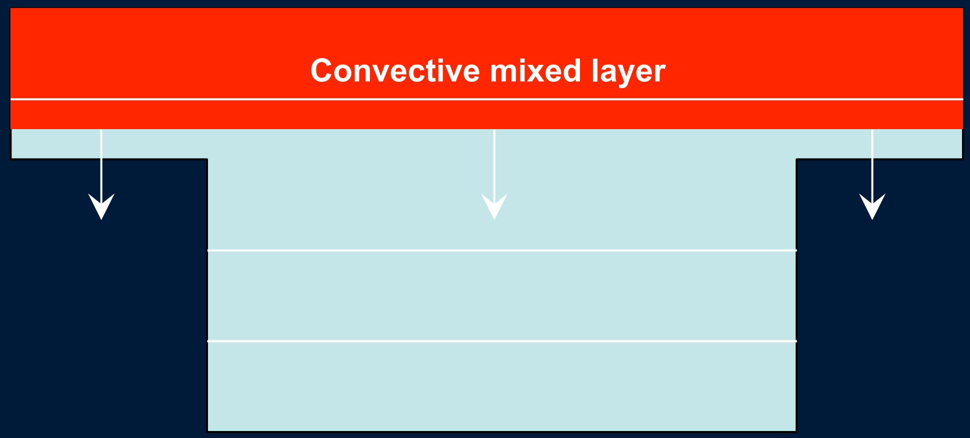
How mixing is produced during the nighttime?

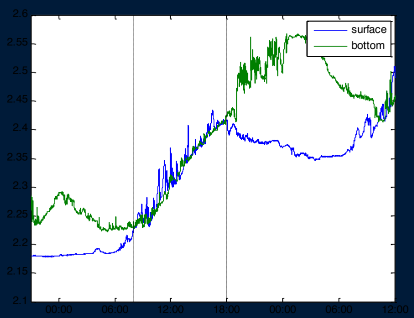


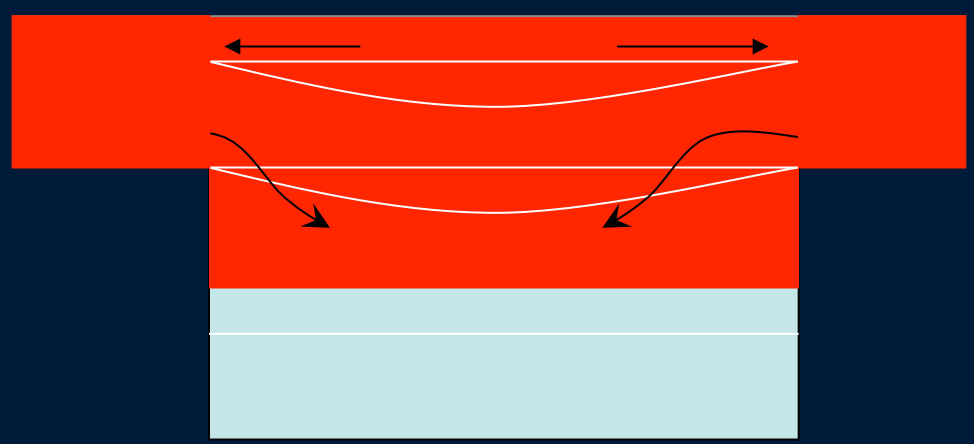


Temperature records from thermistor strings show fast development of stratification after sunset

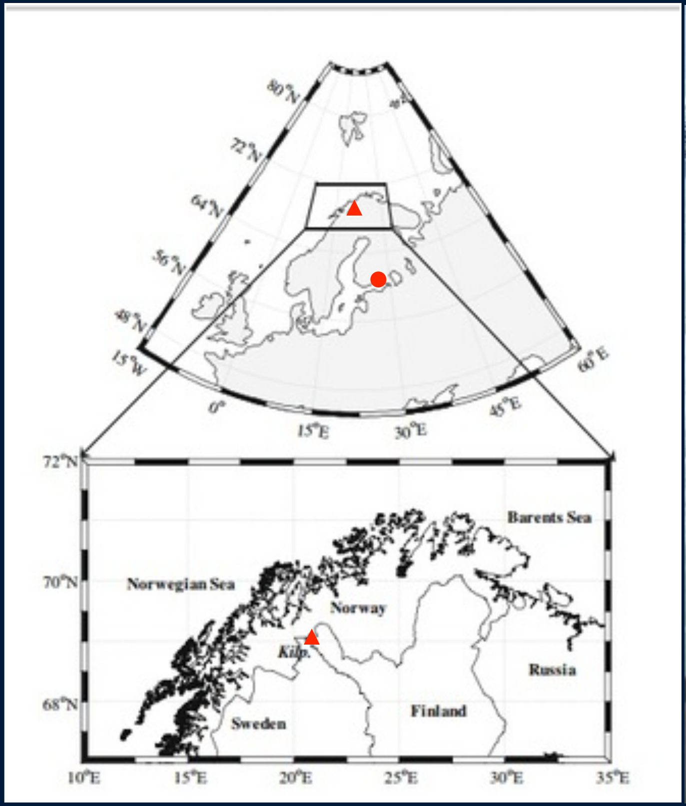
Mixing production by horizontal circulation?



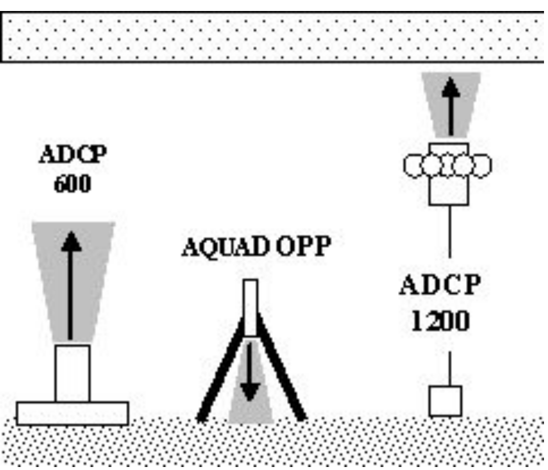


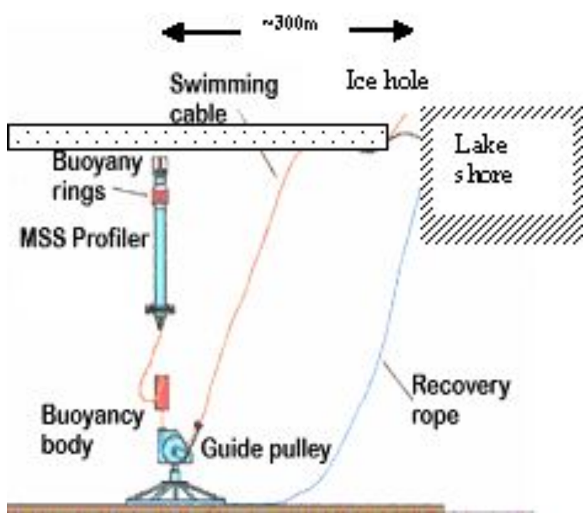


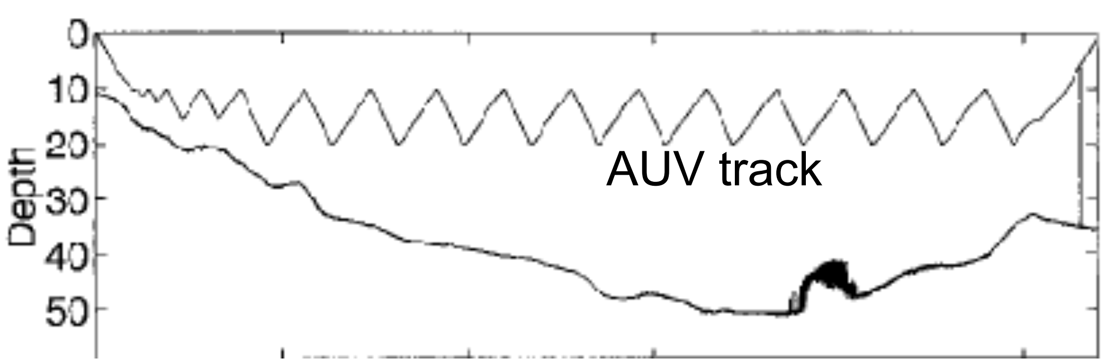
Future plans



AUV Gavia: the unmanned scientific submarine







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