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Energy and gas exchange in aquatic ecosystems

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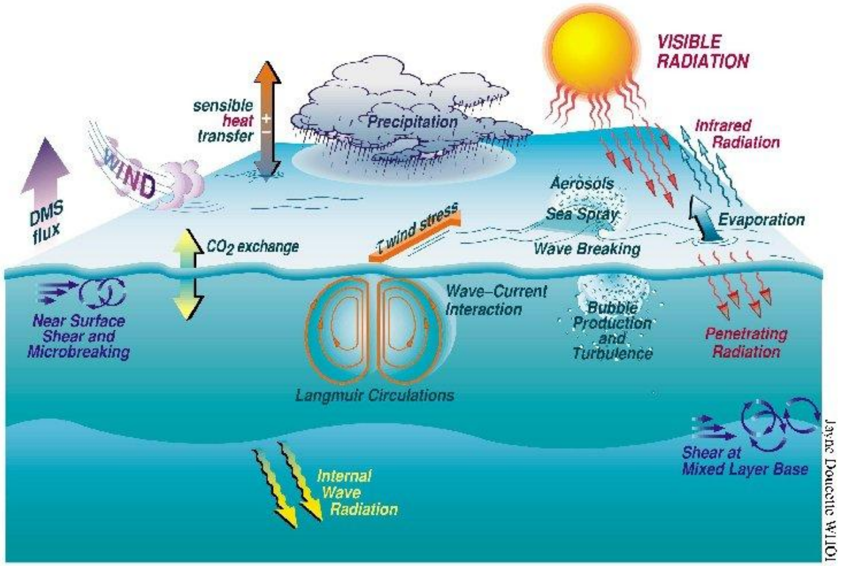
Podgrajsek et al (2013) **Diurnal cycle of methane flux from a lake, with high emissions during nighttime caused by convection in the water.**

Sahlée et al (2013) **Influence from surrounding land on the turbulence measurements above a lake**

Interesting lake work also done in studies by Vesala, Ojala, Nordbo, Houtari, Eugster and others

What do we mean by aquatic ecosystems

- (Marine ecosystems)
- Freshwater ecosystems
  - ✓ Lakes
  - ✓ Streams



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Why aquatic ecosystems?

Oceans:

- 70% of the globe-surface is covered by oceans
- Differences compared to land areas:
  - Waves
  - Different response to radiation (no strong diurnal forcing)
  - Another timescale of the exchange mechanisms

Lakes:

- Significant GHG source.
- Mixing in lakes important for biogeochemical processes in lakes.
- Lakes are important in the climate system

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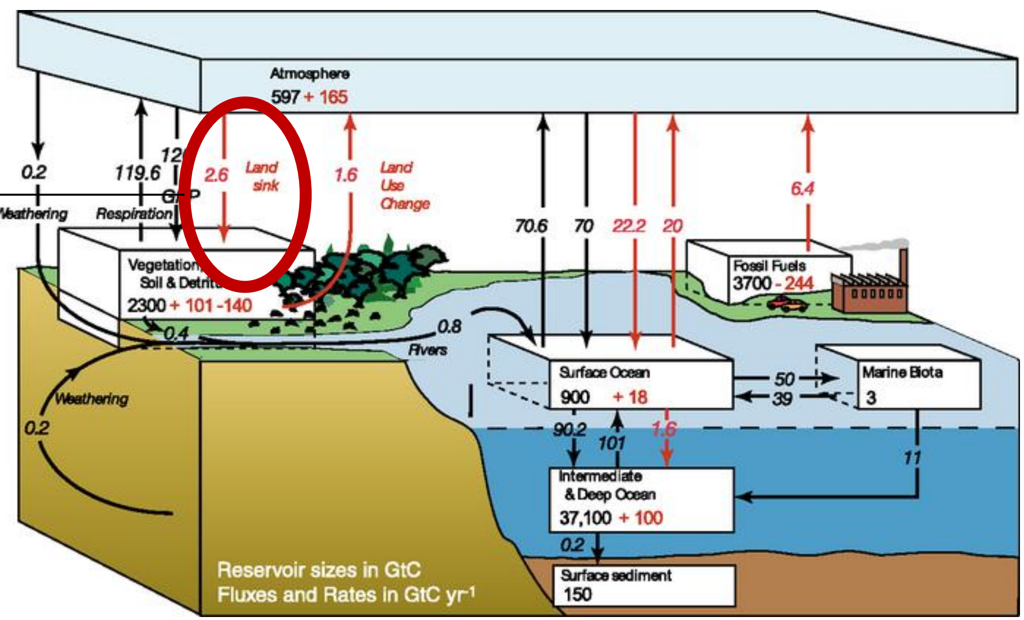
GHG fluxes

- Lake-to-air fluxes play an important role in the global carbon cycle, currently not considered in global budgets. Recent estimates show that lakes could offset the terrestrial GHG sink by 25% (*Bastviken et al. 2011, Science*).

Lakes CH_4 emissions might decrease this by 25% (0.65 GtC)



IPCC (2007)

Climate

Lakes also important when determining climate at local and regional scale (*Krinner 2003, Samuelsson et al. 2010*).

From the 3D regional climate model RCA (Rossby Centre, SMHI)

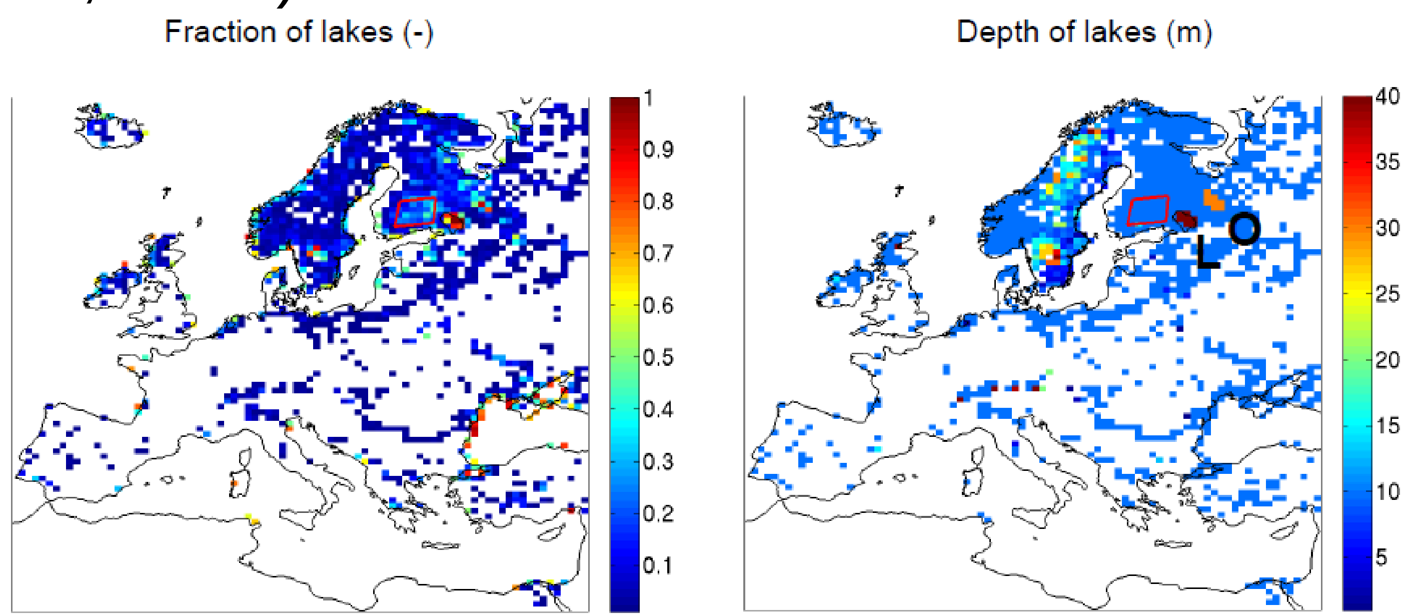


Figure 1. Total fraction of lakes and depth of lakes in the model domain. Note the relatively large fraction in southern Finland (denoted by the red rhombus) represented by many small and moderately deep lakes (10 m in the simulation). Note also the large and deep lakes Ladoga (L, 40m) and Onega (O, 30m) in western Russia.

Climate

Climate simulation

From the 3D regional climate model RCA (Rossby Centre, SMHI)

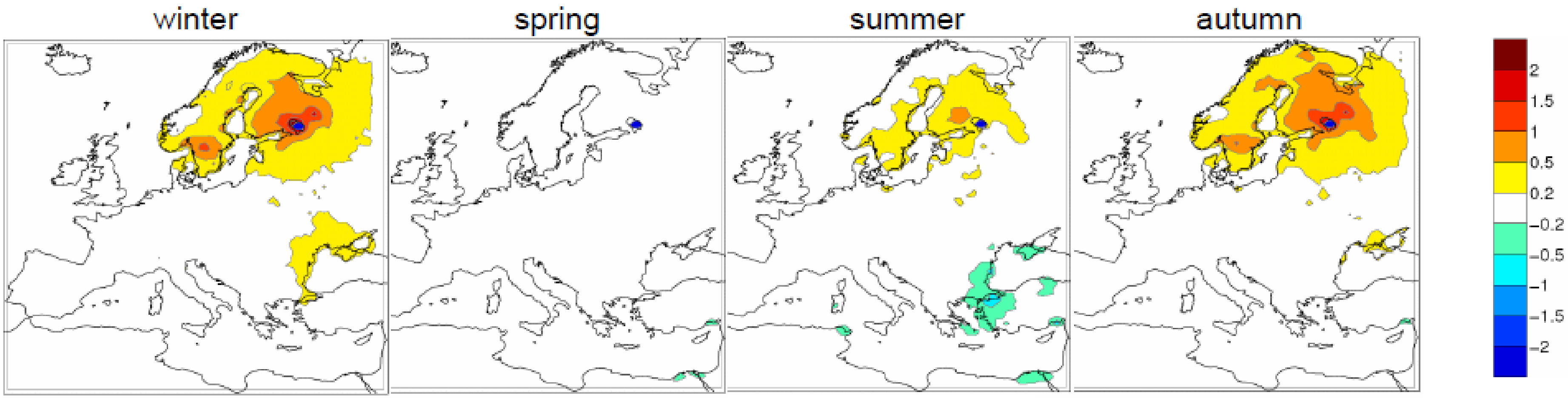


Figure 3. Difference in 2m open-land temperature (°C) between the two experiments (EX_lake – EX_land) fo
four different seasons.

Climate

Local very large impact.

From the 3D regional climate model RCA (Rossby

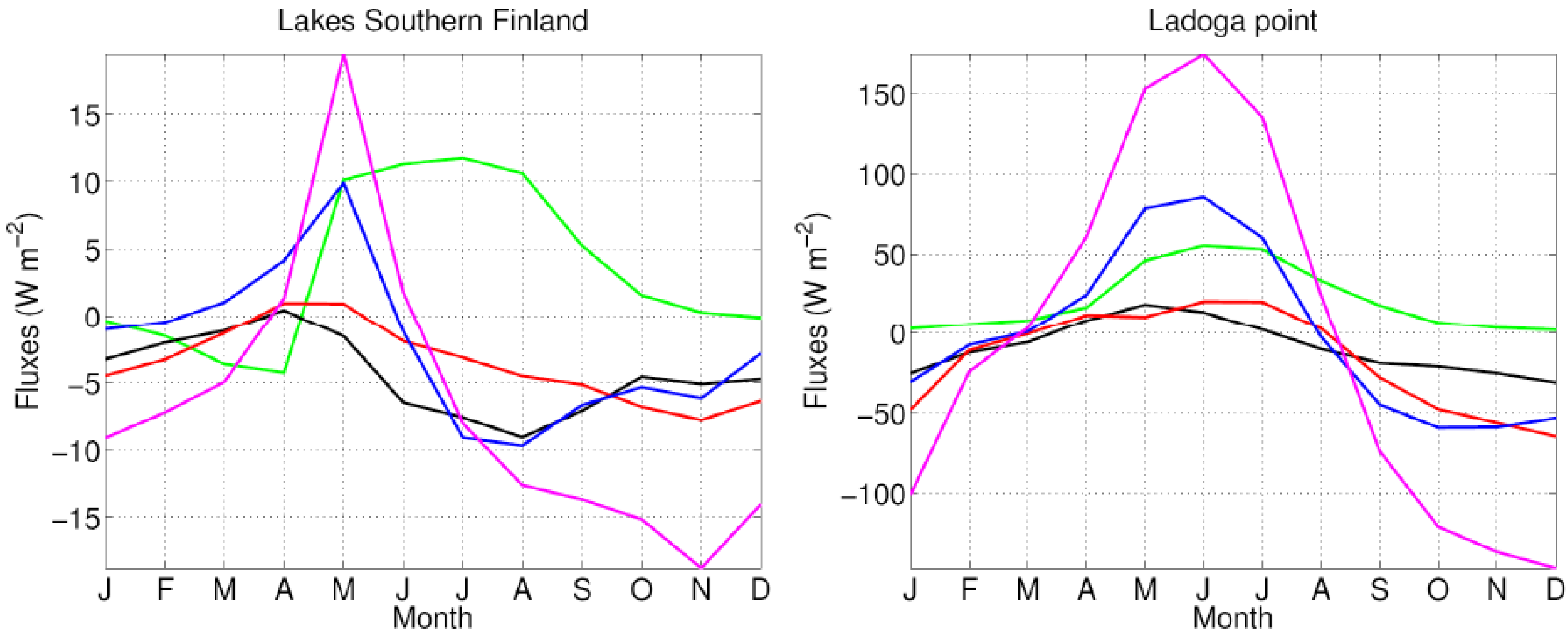
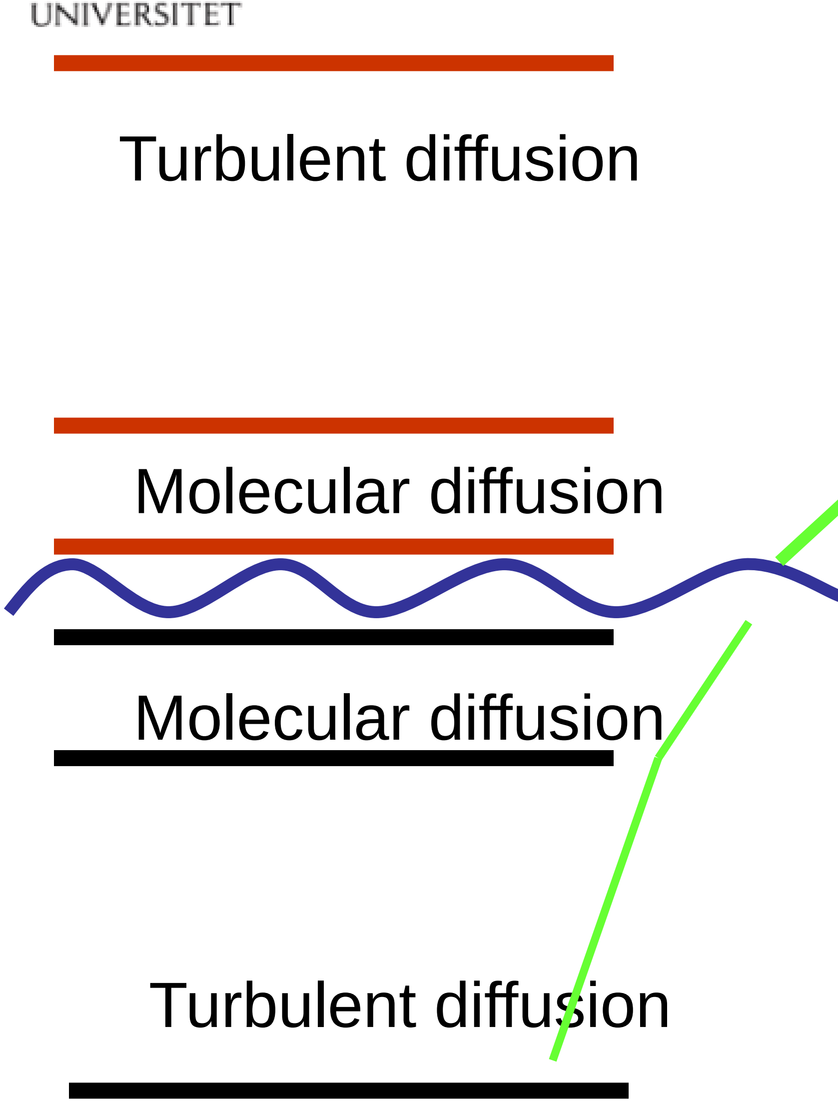


Figure 6. Annual cycle of difference in fluxes (EX_lake – EX_land) for the area in southern Finland (as marked in Figure 1) and for a point over Lake Ladoga. The lines represent SWnet radiation (green), LWnet radiation (black), sensible heat flux, H, (red), latent heat flux, LE, (blue), and net flux, SWnet+LWnet+H+LE, (magenta). Note that positive LE difference means less evaporation in EX_lake.

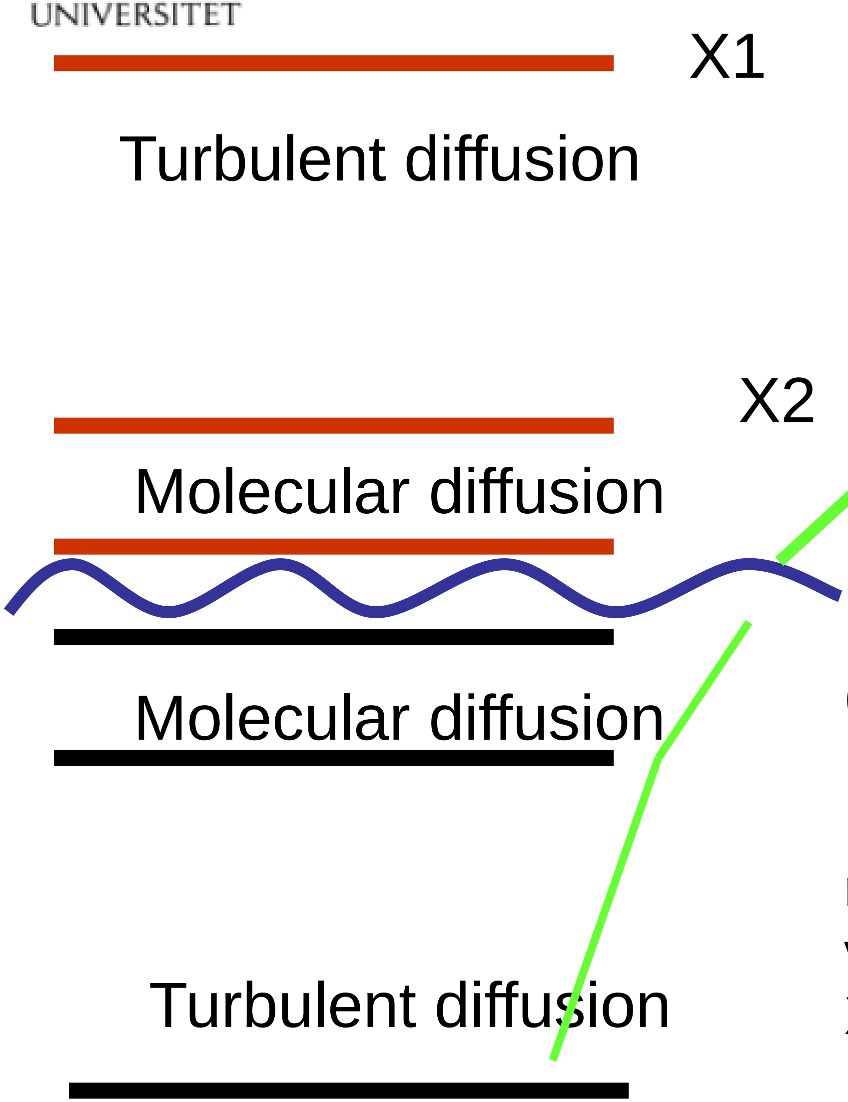
What controls the air-water exchange?



Air-water exchange controlled by the gradient i e the difference of the parameter in the layer, and the efficiency of the exchange (or resistance).

4 layers of possible importance

What controls the air-water exchange?



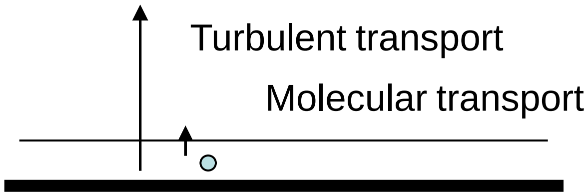
(parallell to a circuit)
Flux =(X1-X2)/r=(X1-X2)v

r=resistance
v=transfer velocity
X1-X2=difference in layer

1. momentum, heat and humidity – atmosphere limiting

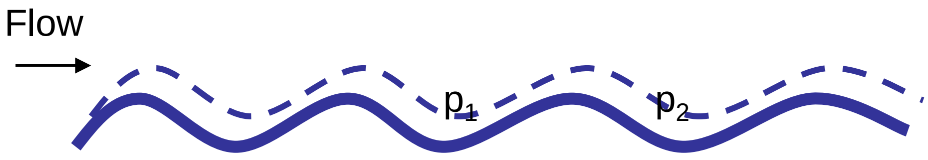
Smooth surface, resistance for all parameters are the same

$r_d \sim r_q \sim r_h$



Rough surface, momentum different

$r_d \neq r_q \sim r_h$



The pressure difference on each side of the roughness element result in a momentum transport and an additional resistance

$$\frac{1}{r_{D1}} + \frac{1}{r_{D2}} = \frac{1}{r_D} \rightarrow r_D \leq r_H$$

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Surface roughness related to the Drag coefficient, C_D:

C_D depends on:

- stratification (z/L) given by MO similarity theory
- wind-speed (U)
- waves (c_p/U) - fetch
- gustiness
- Other processes…

$$\tau = \rho_a u_*^2 = \rho_a C_D U_{10}\left(U_{10} - U_0\right) \approx \rho_a C_D U_{10}^2$$

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Drag coefficient, C_D:

C_D depends on:

- stratification (z/L) given by MO similarity theory.

Calculate the neutral counterpart C_{DN}

$$C_D = \frac{\kappa^2}{\left(\ln\left(\frac{z}{z_0}\right) - \Psi_m \right)^2} \quad or \quad C_D = \left(C_{DN}^{-1/2} - \frac{\Psi_m}{\kappa} \right)$$

Wind speed:

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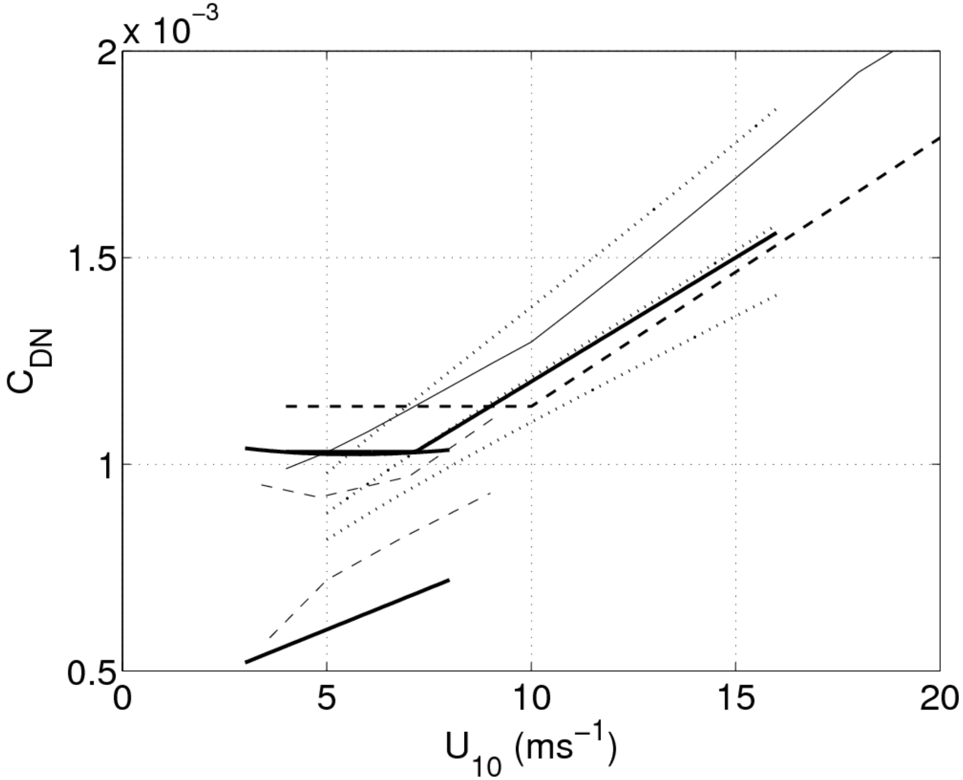
$$C_{DN}\cdot 10^3 = 0.8 + 0.065U_{10} \quad \text{(Wu)}$$

$$C_{DN}\cdot 10^3 = 1.2 \qquad 4 \le U_{10} \le 11 m/s$$

$$= 0.49 + 0.065U_{10} \quad 11 \le U_{10} m/s \quad \text{(Large and Pond)}$$

$$C_{DN}\cdot 10^3 = (0.07\mathrm{U}_{10} + 0.95) \quad \text{(Donelan et al, 1997)}$$



Full thin line is from the COARE 3.0 (2003) algorithm, the thick dashed line is from Large and Pond (1981) and the dotted lines are from Drennan et al. (2003) for wave ages [0.6, 0.8, 1.0] (counting downwards). The study of Larsén et al. (2003) is shown with thin dashed lines, the lower being following swell and the upper being cross swell. The present study is presented by the thick full lines for growing/mixed sea, following swell (the lowest) and counter swell (nearly coinciding with the growing/mixed sea).

Transfer coefficients for heat and humidity, Stanton and Dalton numbers, C_H and C_H:

C_E and C_H depends on:

- stratification (z/L) given by MO similarity theory
- UVCN-regime
- wind-speed ?
- waves ?
- Sea spray
- Deep convection
- Gustiness
- Skin effects
- Others…

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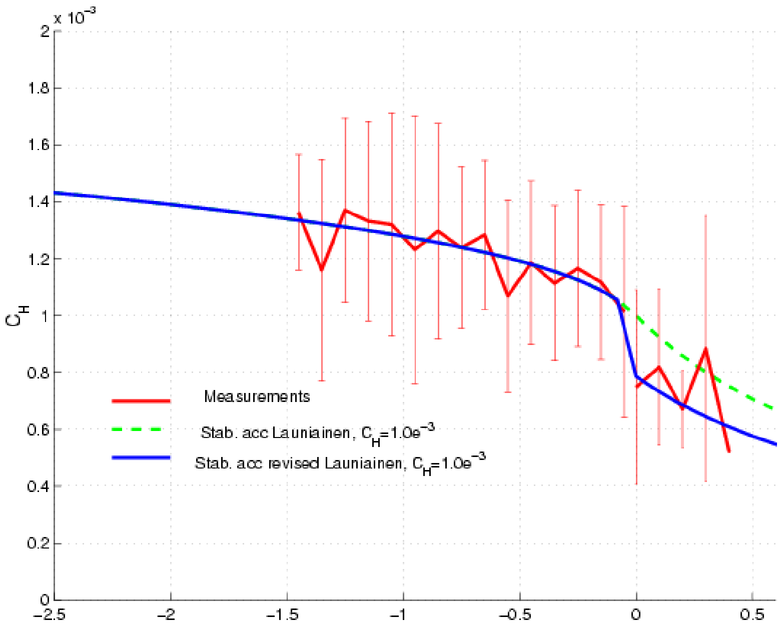
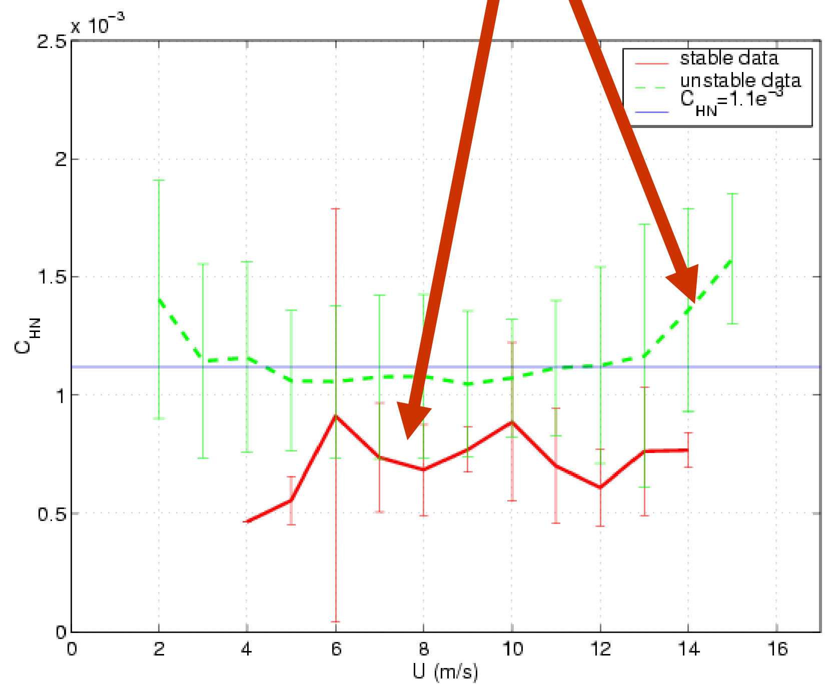
Traditionally C_H and C_E depend only on stratification (z/L), neutral values are assumed to be constants.

$$C_{HN} \approx C_{EN} \approx 1 \cdot 10^{-3}$$

Problems:
Stable stratification
High winds speed





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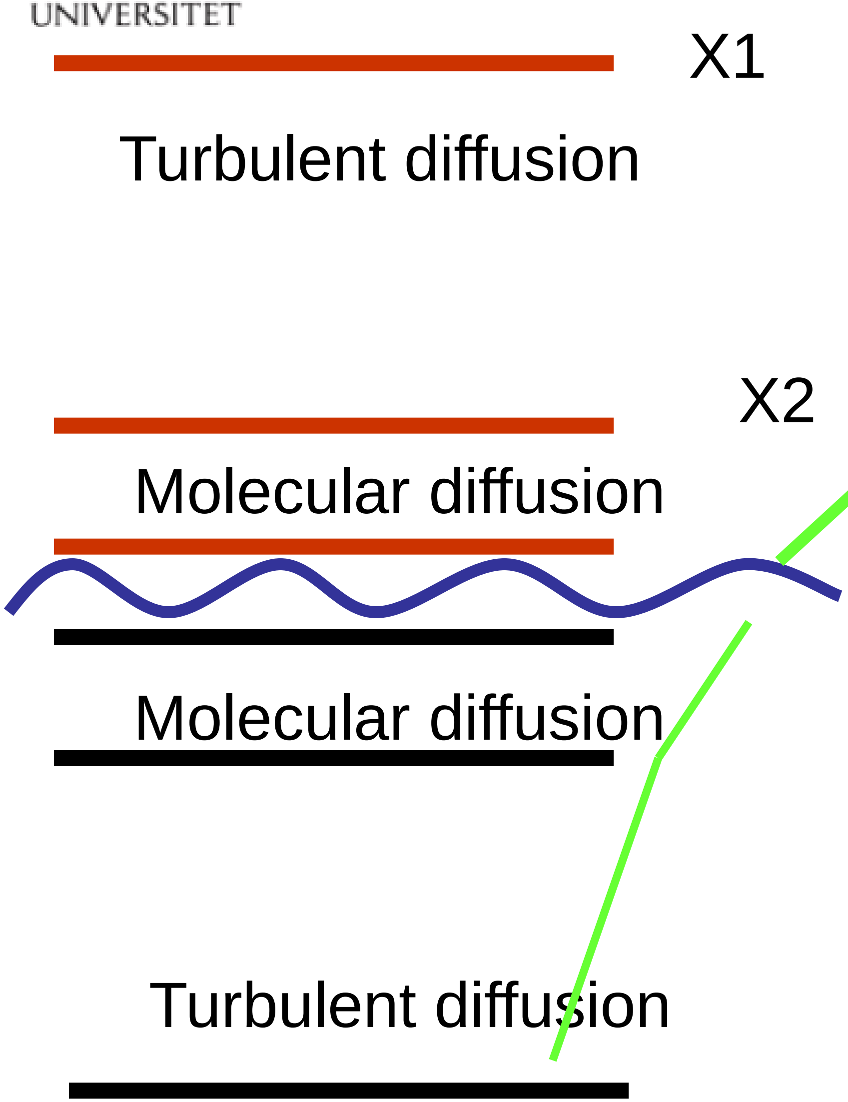
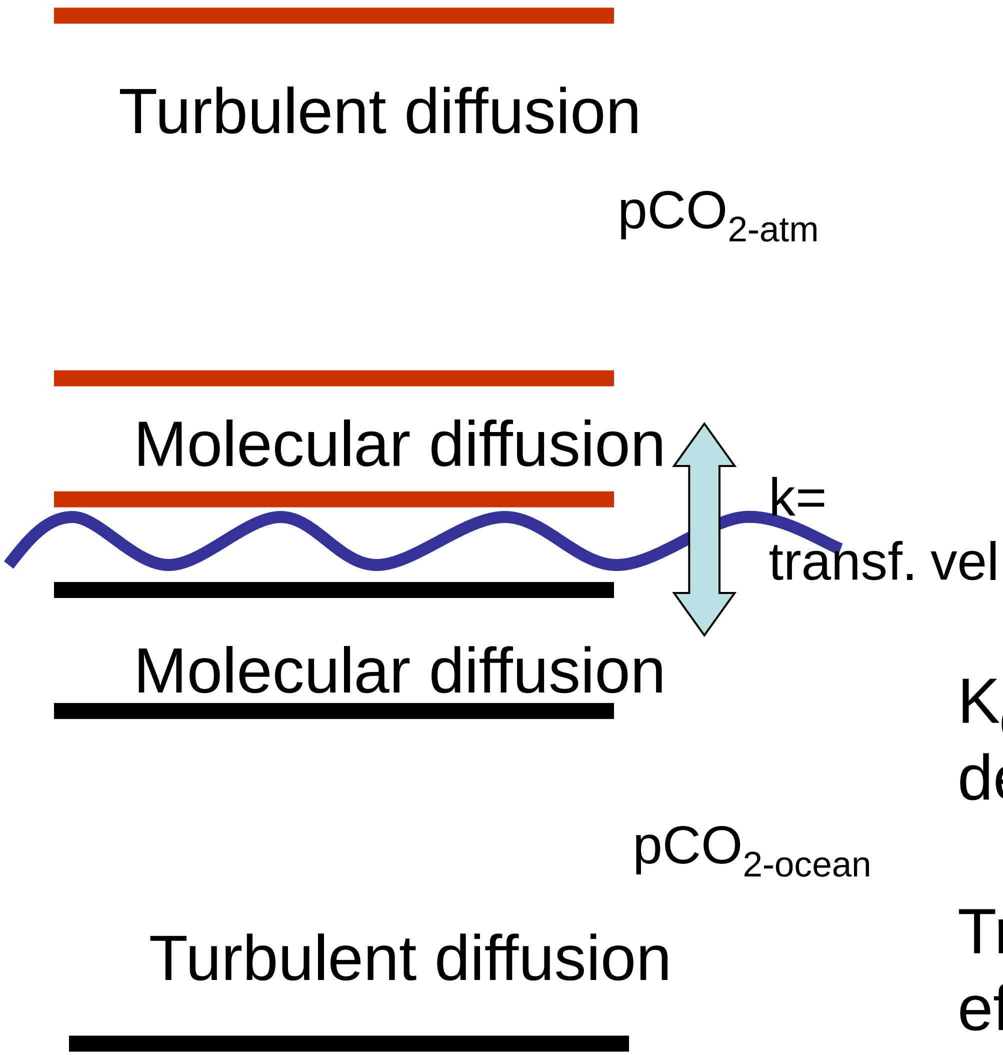


2. Carbon dioxide and many other scalars – molecular sublayer in the ocean is limiting

The thickness of the molecular diffusion layer determine the resistance. Processes controlling the thickness of this layer controlls the transfer

What controls the air-water exchange of CO_2 ?



Difference in concentration

$$F = k\Delta C = K(C_w - \alpha C_a)$$

$$\alpha = \text{solubility coefficient}$$

Difference in partial pressure

$$F = kK_0(pCO_{2ocean} - pCO_{2atm})$$

$$K_0 = \text{solubility}$$

$$K_0 = \frac{\alpha}{RT}$$

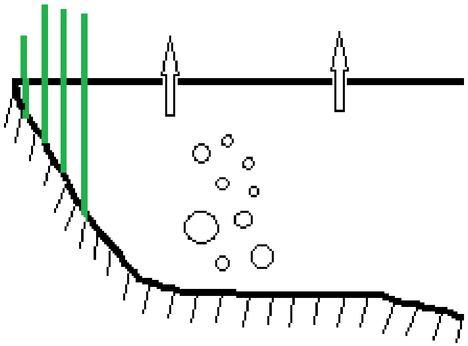
K_0 is salinity and temperature dependent

Transfer velocity (piston velocity), efficiency of transfer

Other transport mechanisms for methane

- Formation of methane in sediment
  - Oxygen
  - Temperature
  - Organic matter

- Transport pathways of methane from sediment to atmosphere:
  - Diffusive transport
  - Ebullition
  - Vegetation



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Problems

Large gradients between lake and surrounding areas (advection of turbulence)

Small lakes, footprint

Compared to land areas – different response to surface forcing (another timescale of response due to lake processes).

Large variation of processes.

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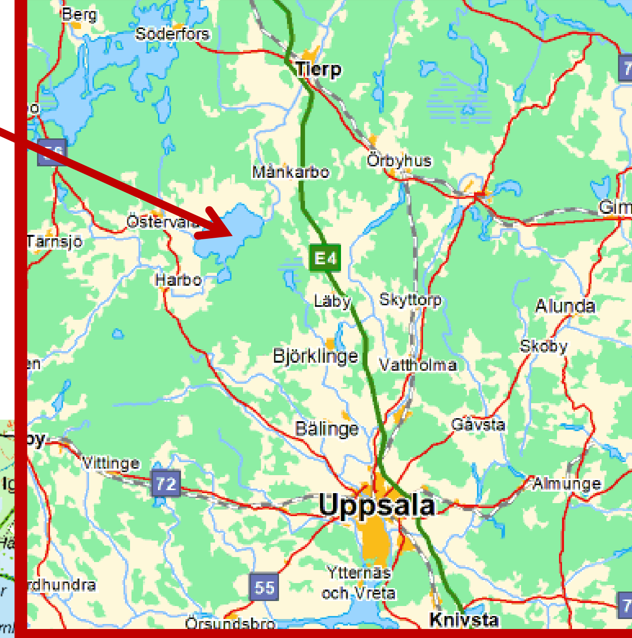
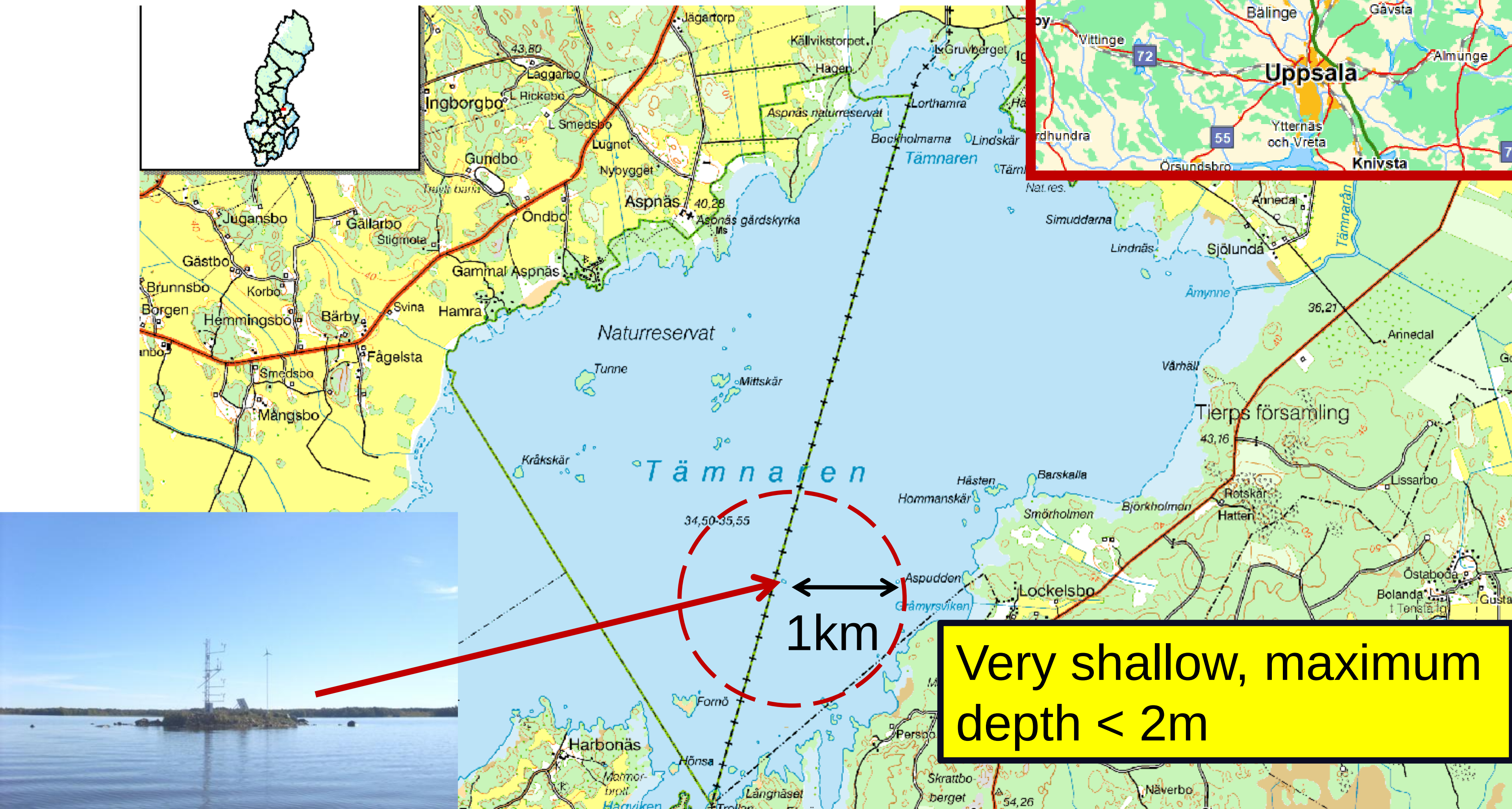
Measurement site

Lake Tämnaren
2010-09-14 to 2012-08-31





Very shallow, maximum depth < 2m

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Tower instrumentation

<u>Fast response instrumentation</u>

5m height

LI-7700 – CH_4, open path

LI-7500 – H_2O, CO_2 open path

Sonic anemometer (R3, Gill)

<u>Additional instrumentation:</u>

Wind speed and temperature at three levels

RH, Global radiation, airpressure, precipitation

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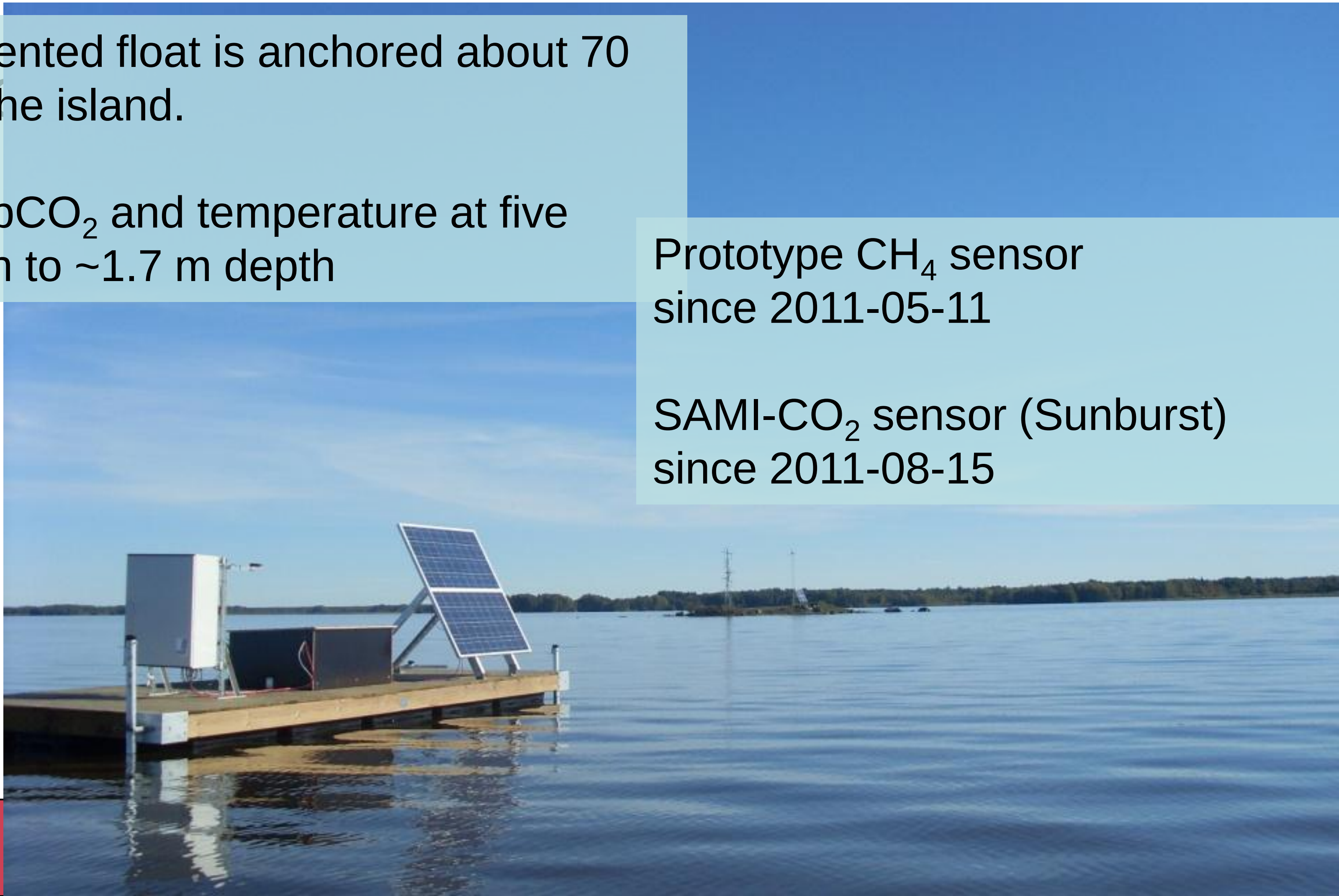
Float instrumentation

An instrumented float is anchored about 70 m west of the island.

Profiles of pCO_2 and temperature at five levels down to ~1.7 m depth

Prototype CH_4 sensor since 2011-05-11

SAMI-CO_2 sensor (Sunburst) since 2011-08-15



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LI-7700 Open Path CH_4 Analyzer Specifications

Resolution (RMS noise): 5 ppb @ 10 Hz and 2000 ppb CH_4

Measurement Range:
0 to 25 ppm @ -25 °C, 0 to 40 ppm @ 50 °C

Accuracy at constant temperature:
typically < 1%, maximum < 2%

Drift from -25 °C to +45 °C: 0.05% per degree C

Bandwidth: 1,2,5,10, or 20 Hz

Operating Pressure Range: 50 to 110 kPa

Operating Relative Humidity Range: 0 to 100%

Operating Temperature Range: -25 to 50 °C

Data Communication: Ethernet (up to 40 Hz)

Detection method:
Wavelength Modulation Spectroscopy 2f detection

Power Requirements: 10.5 to 30 VDC

Power Consumption:
8 W nominal, 16 W during cleaning cycle

Dimensions:

Sensor: 14.33 cm dia (5.64 in), 82.8 cm height (32.6 in.)

Optical Path: 0.5 m physical path (1.65 ft), 30 m measurement path (98.4 ft)

Weight: 5.2 kg (11.5 lbs)

Evaluation of the LI-7700 instrumentation

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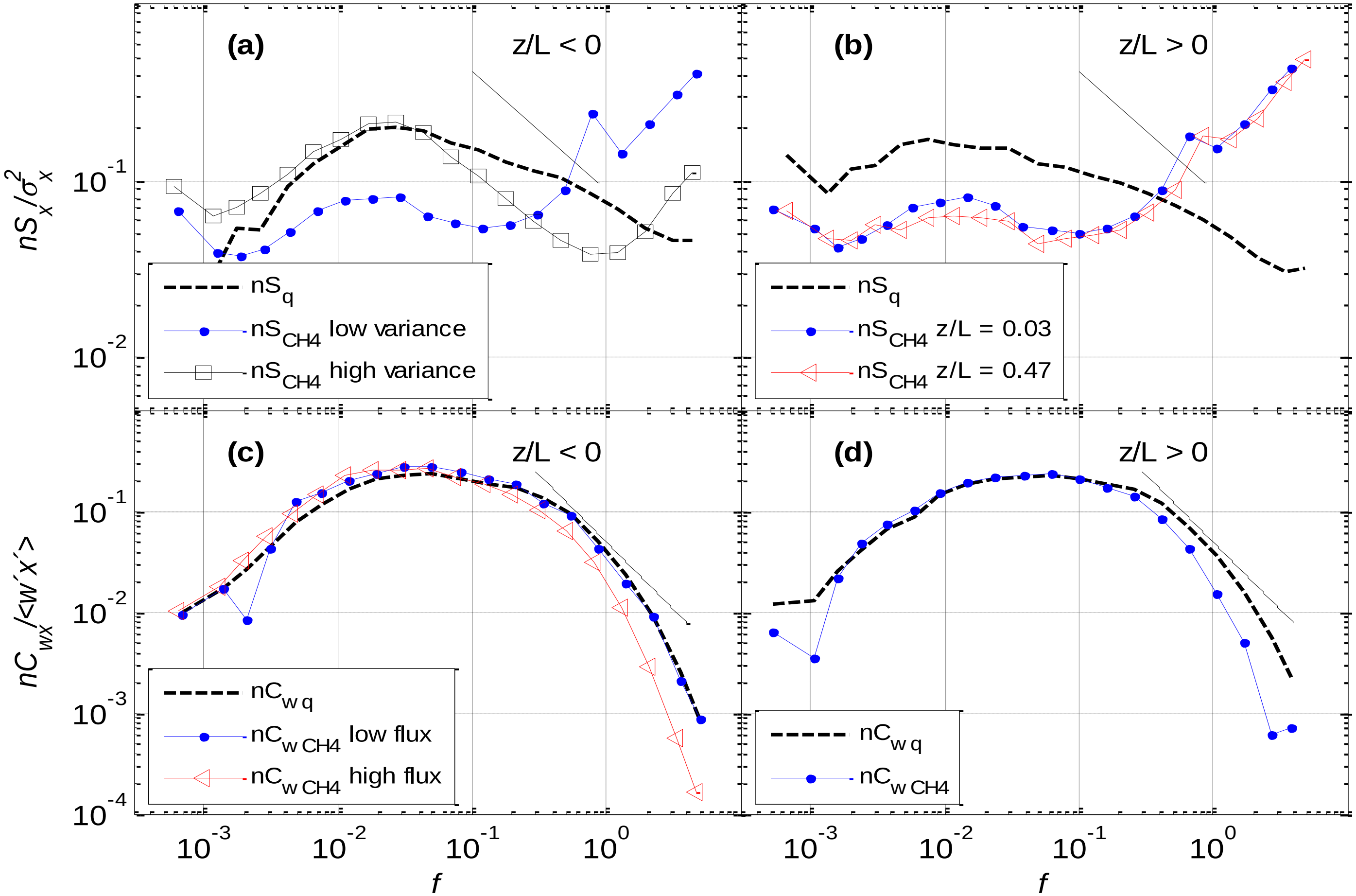
z/L<0

z/L>0



Slightly underestimates fluxes during stable conditions (5-10% flux loss)

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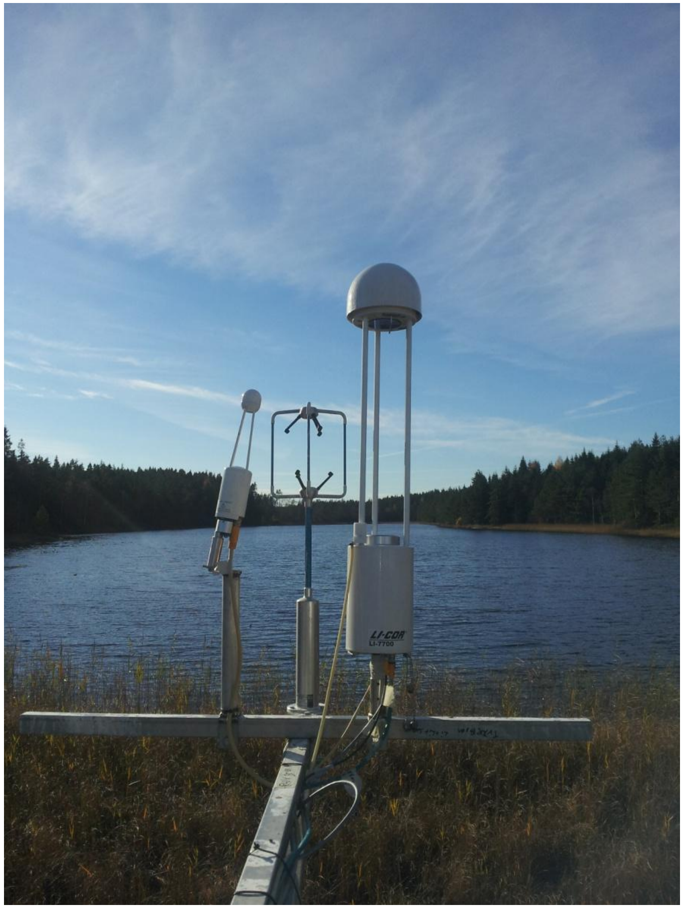
New EC-site, Skogaryd, Swedish west coast

Presently:

Smaller lake

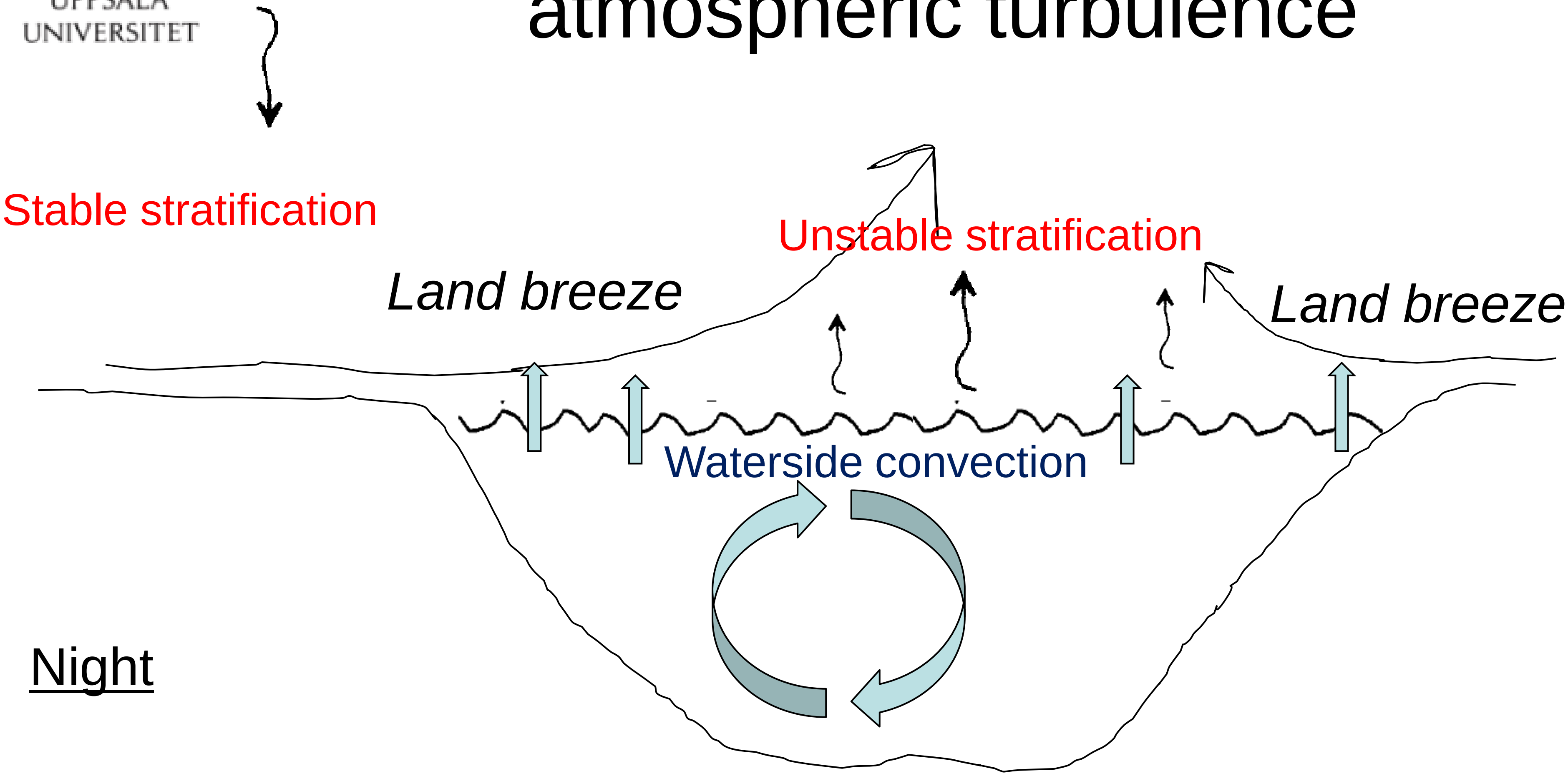
Lower measuring height



Focus on

- Lake impact on turbulence structure.
- Diurnal variation of methane fluxes from a lake.

Land influence on Lake atmospheric turbulence



Night

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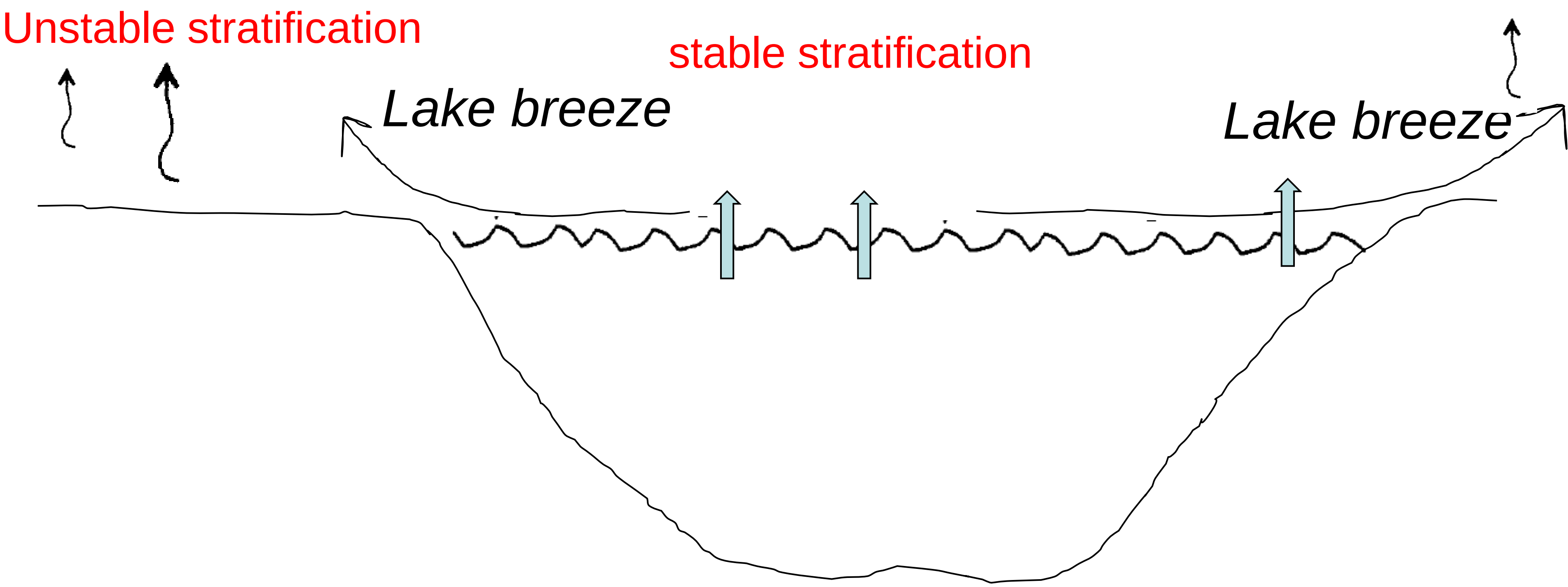
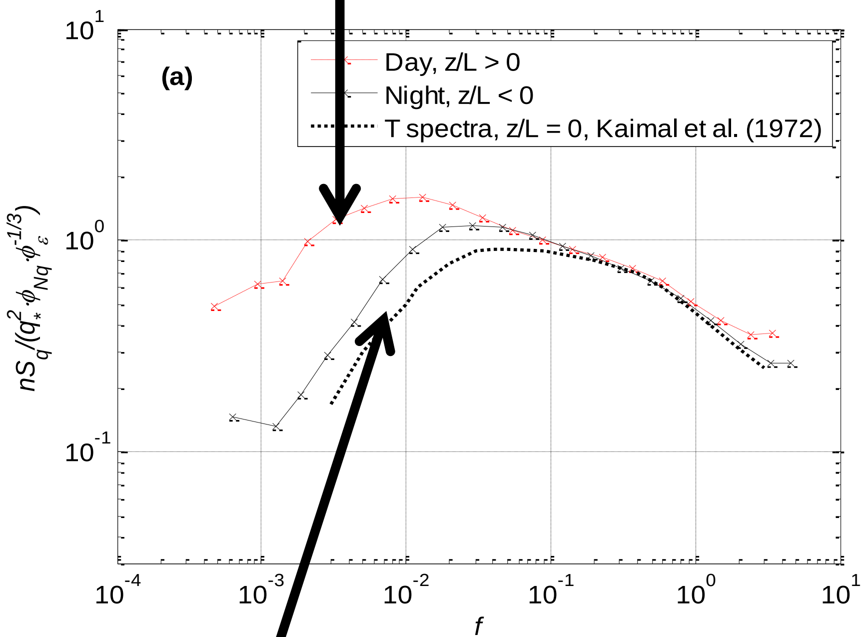
Day

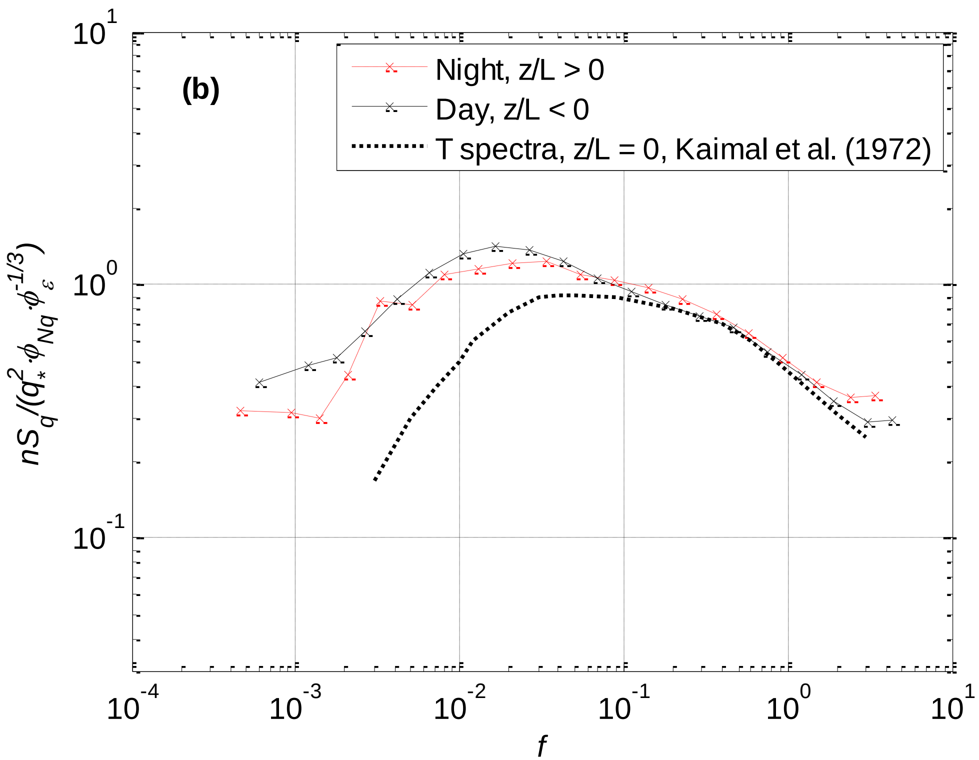


q- spectra

Stable cases, daytime



Unstable cases, nighttime



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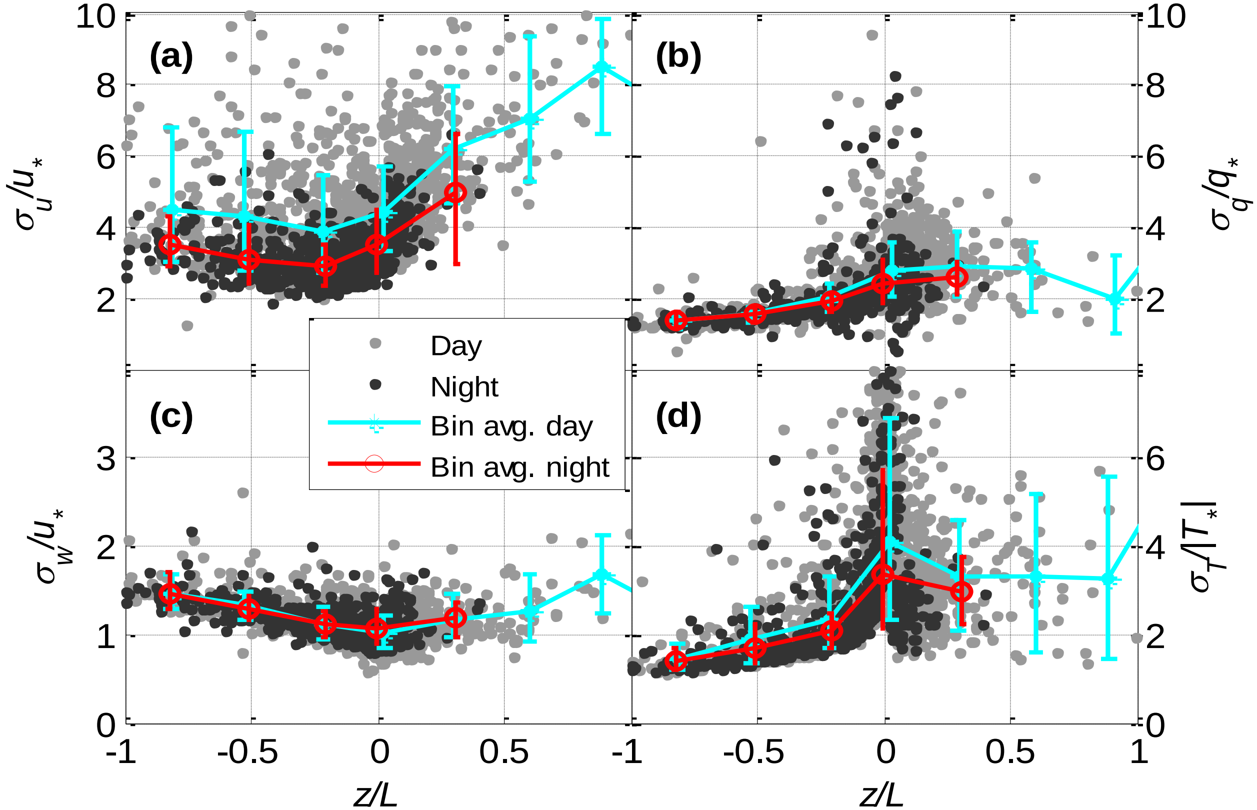
What is going on?

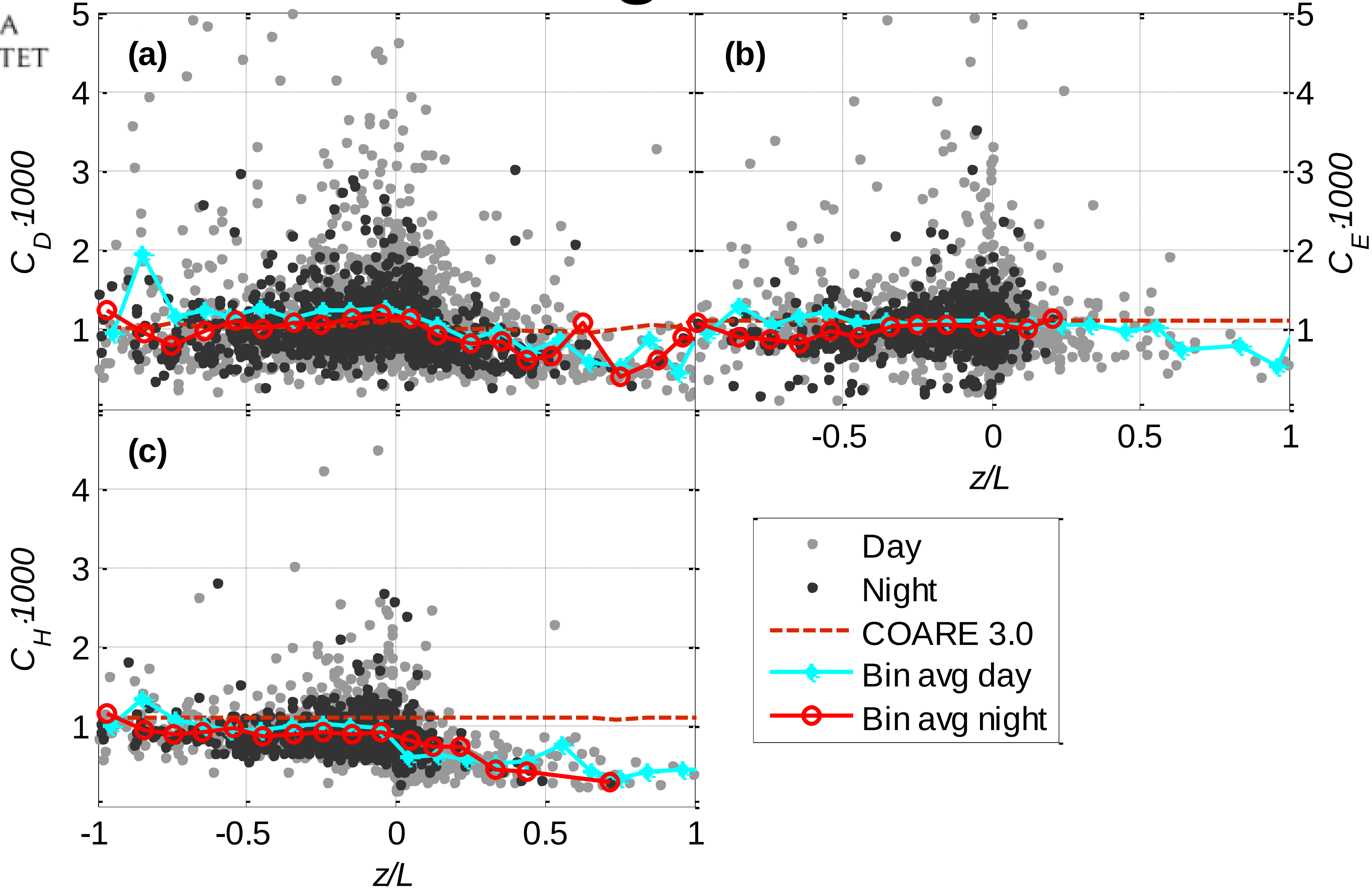
- Effect called spectral lag.
- Atmospheric ”memory” of upstream conditions.
- HF part of spectrum quickly equilibrates to new surface conditions, LF part takes considerably longer time
- Effect visible for horizontal velocity components and scalars but not for vertical velocity.

Any influence on the parameterizations?



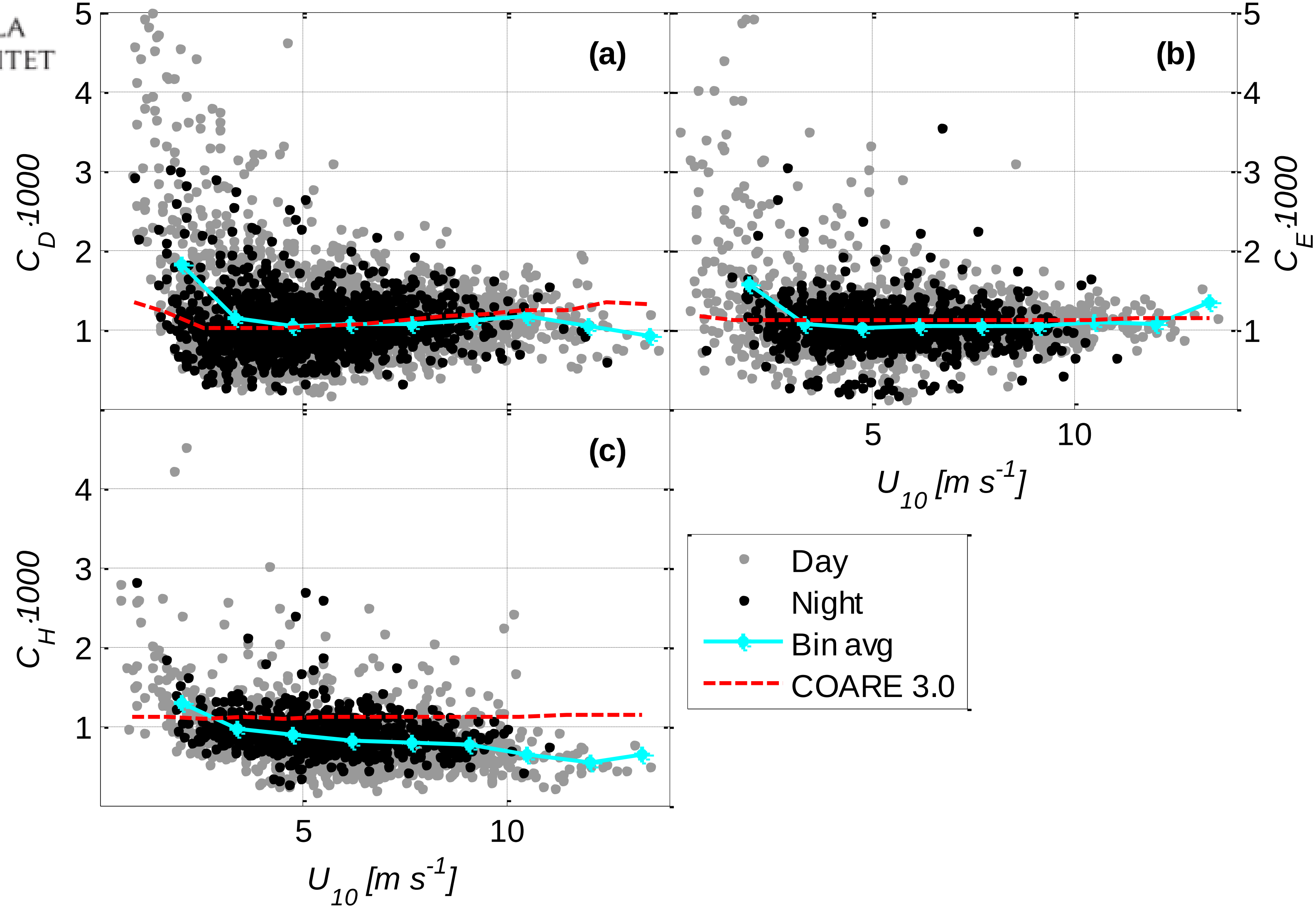
Influence u and scalar variances, but not w.

Exchange coefficients



$$C_D = \frac{\overline{u'w'}}{U_{10}^2} \qquad C_H = \frac{\overline{w'\theta'}}{U_{10}(\theta_s - \theta_{10})} \qquad C_E = \frac{\overline{w'q'}}{U_{10}(q_s - q_{10})}$$

Exchange coefficients



COARE 3.0 (*Fairall et al. 2003*)

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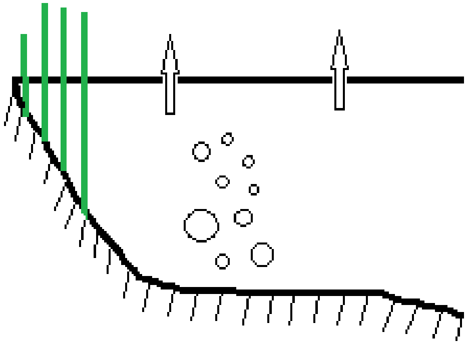
Conclusions

Fluxes appear relatively unaffected: exchange coefficients close to traditional parameterizations. However, for $z/L>0$ C_H only 50% of what COARE predicts (also seen for marine conditions).

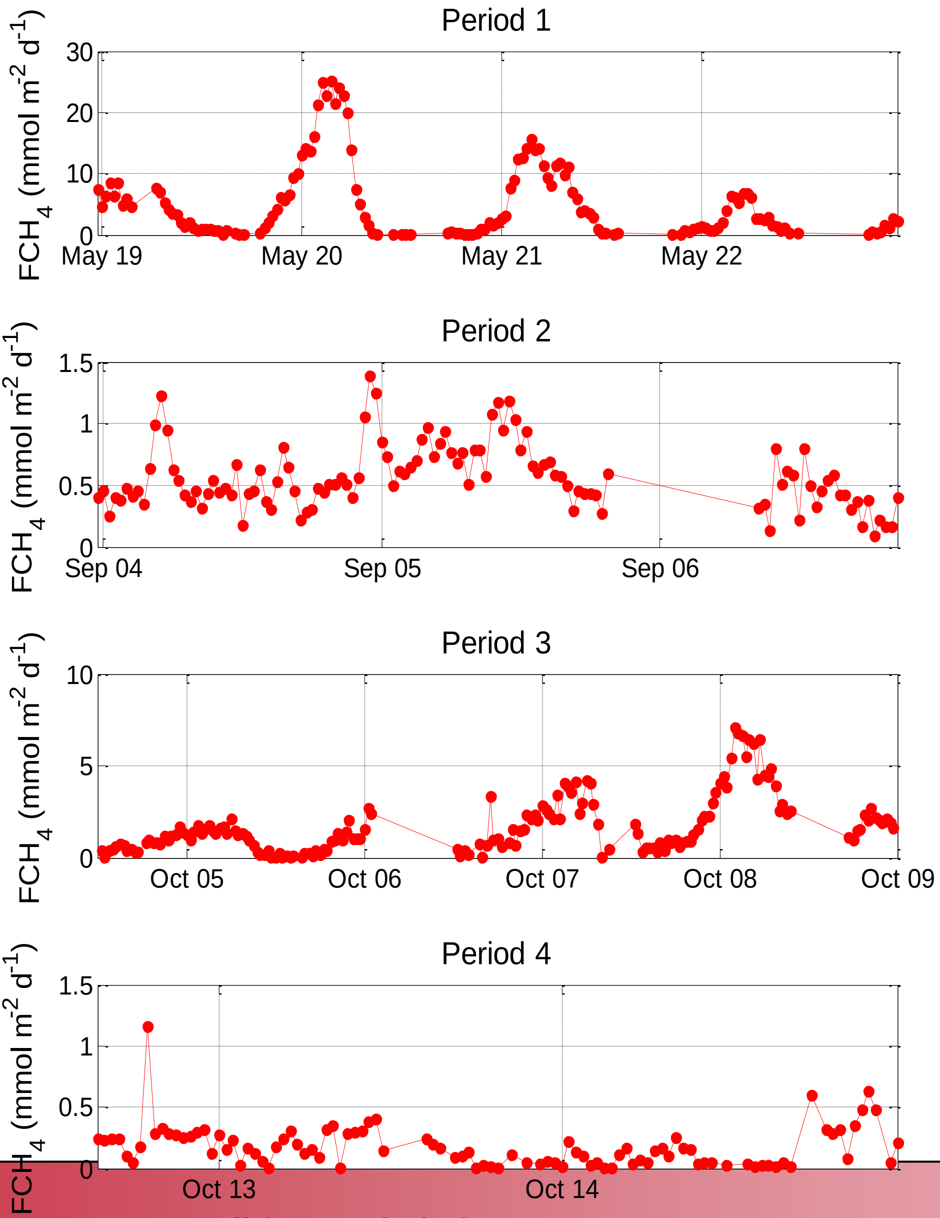
Methane fluxes

- Formation of methane in sediment
  - Oxygen
  - Temperature
  - Organic matter

- Transport pathways of methane from sediment to atmosphere:
  - Diffusive transport
  - Ebullition
  - Vegetation



Results from four periods



All four periods from 2011

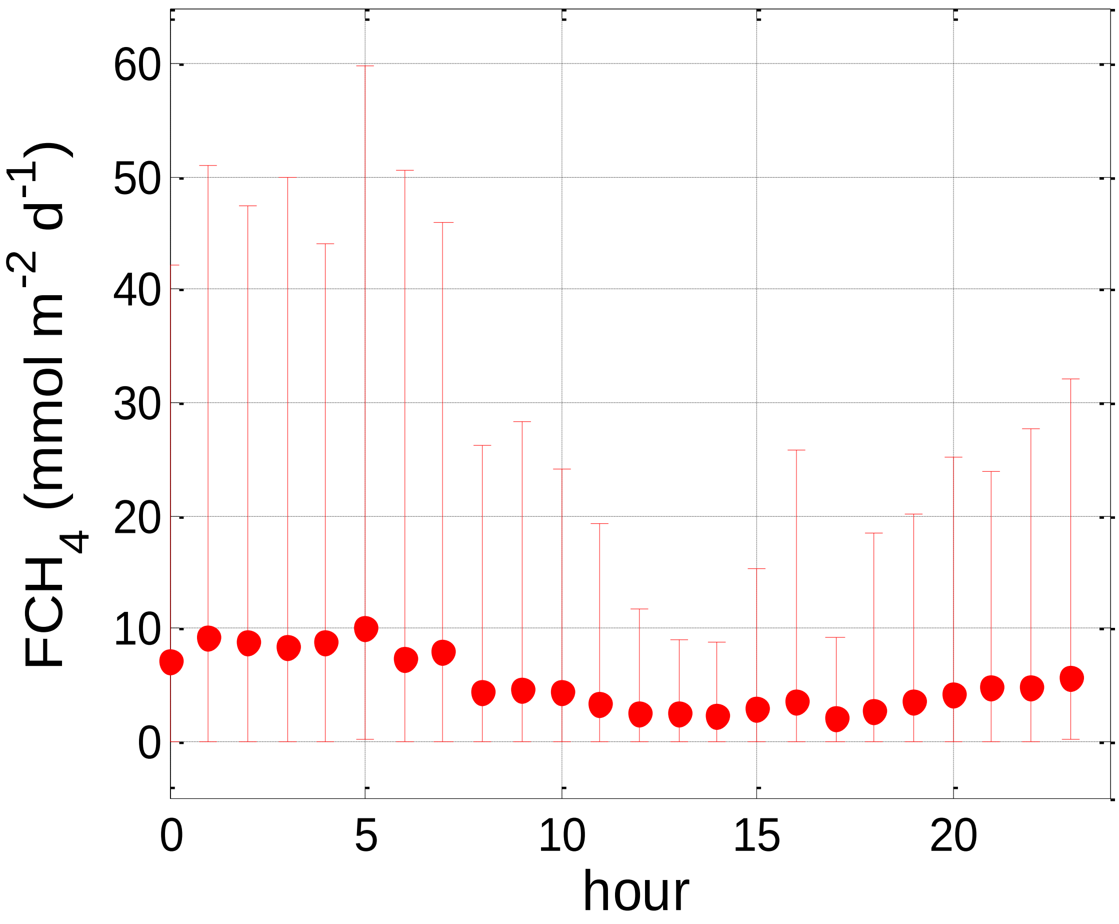
Period 1 and 3; daily cycle of FCH_4.

Period 2 and 4; no pronounced change

Is this daily cycle coincidental for these two periods?

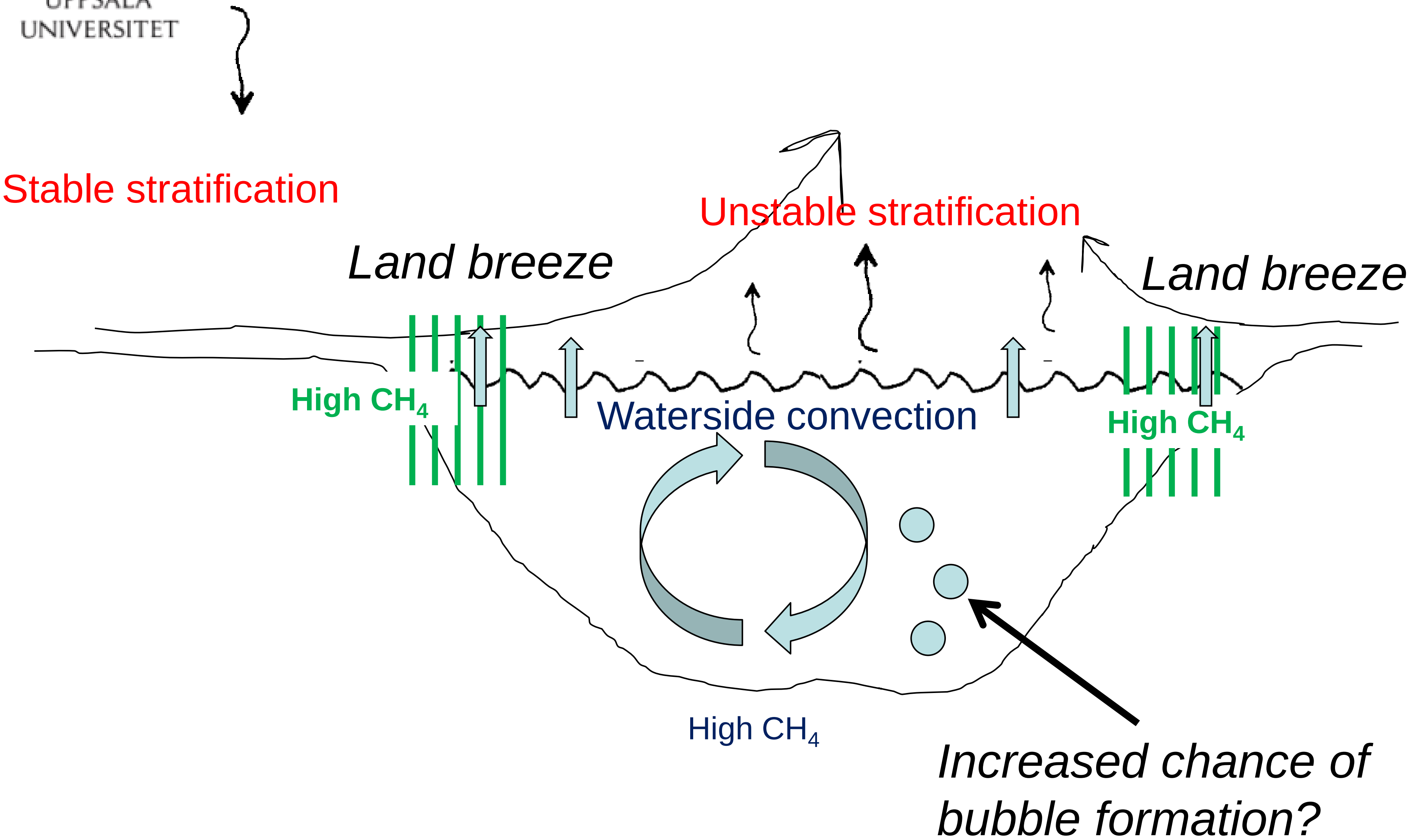
Note the different scales on the y-axes!

Results from the entire measuring period



What causes the daily cycle?

Night


Stable stratification
Unstable stratification
Land breeze
Land breeze
High CH_4
High CH_4
Waterside convection
High CH_4
Increased chance of bubble formation?

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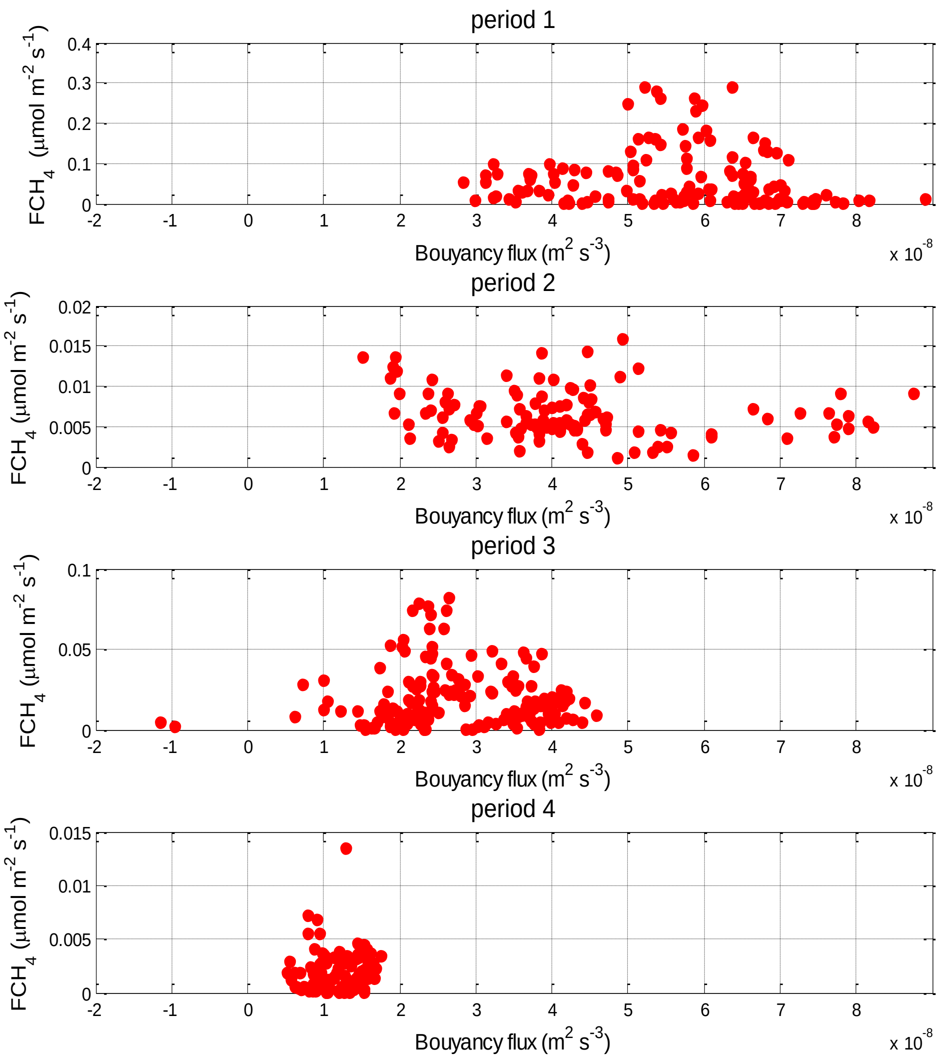
What causes the daily cycle of FCH_4?



Buoyancy flux will enhance the diffusive flux and trigger ebullition!

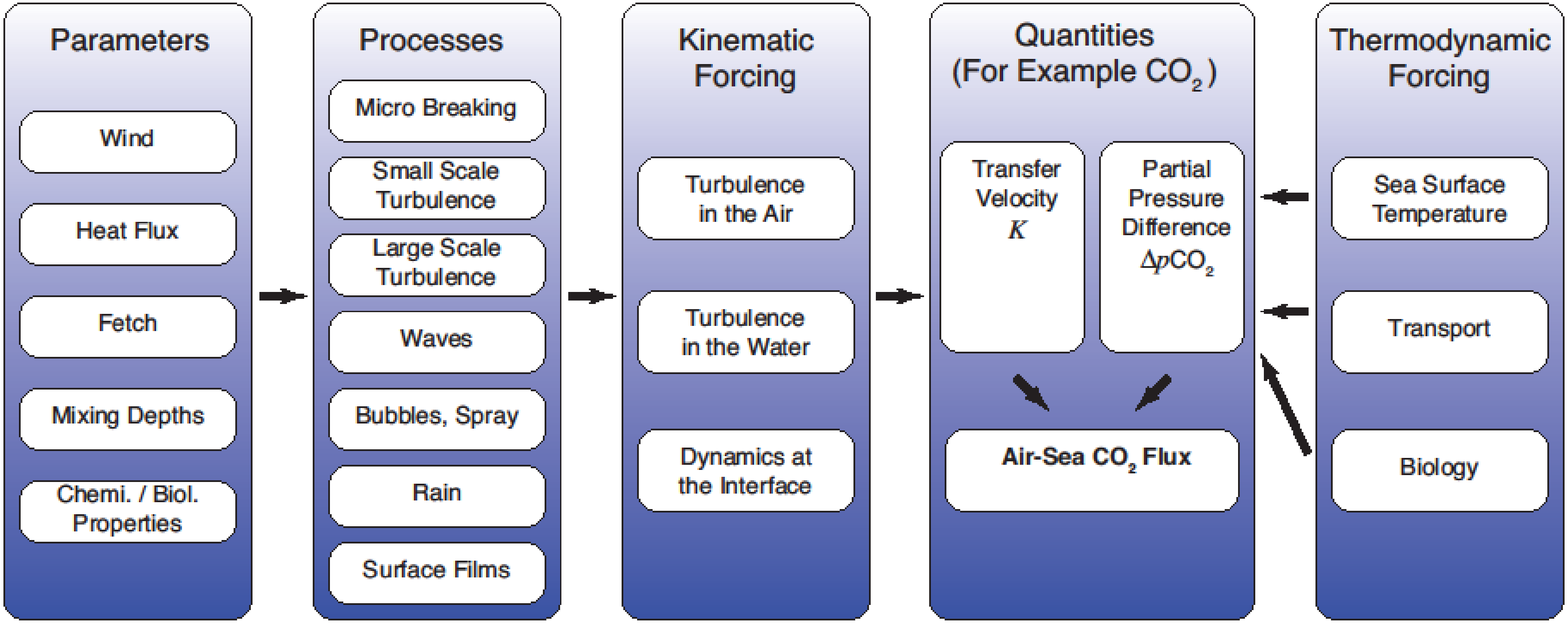
But the production of methane in the sediment is also important.

Note the different scales on the y-axes!

Methane diurnal cycle

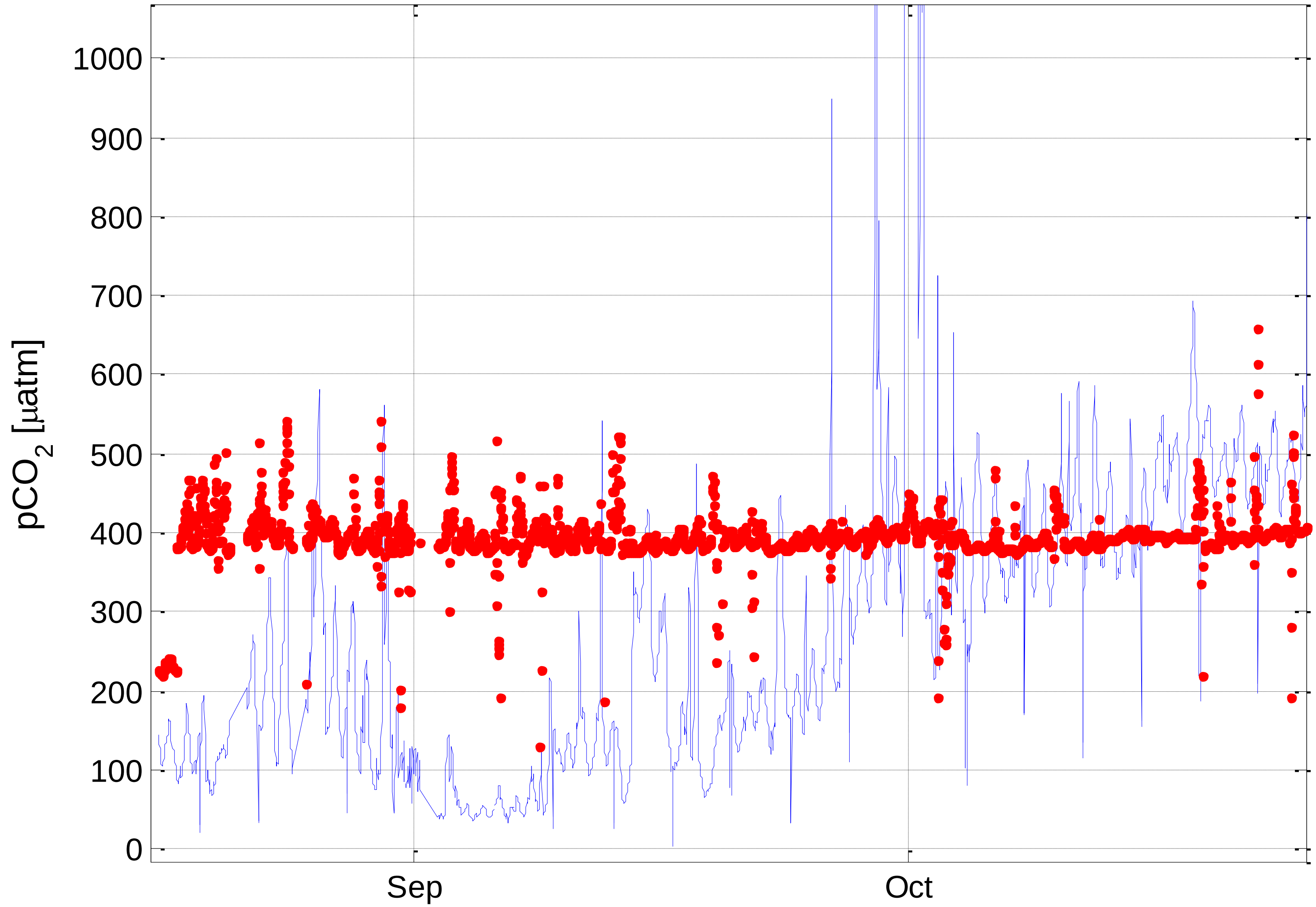
- Convection during night enhance the diffusive flux and triggers flux via ebullition.
- Formation of methane in the sediment will regulate the magnitude of the flux.
- Total methane emissions from lakes can be very different if enhanced nighttime fluxes are not included.
- We want to stress the importance to measure FCH_4 during night and also for longer periods.

Diffusive flux



Factor influencing air-sea CO_2 flux (Garbe, Rutgersson et al. 2013)

2011 SAMI



Problems with diffusive flux

- Large variability in surface water concentration
- Forcing mechanisms of piston velocity highly unknown (convection, surface films…).

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Float instrumentation, CO2

Profile system, CO_2 at 5 levels

SAMI2-CO_2

- *Measures: partial pressure of CO_2 in water (pCO_2)*
- Precision: < 1 ppm
- Accuracy: ± 3 ppm based on lab calibration*
- Long-term drift: < 1 ppm over 6 months

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Lake aquatic ecosystems, air water exchange aspects

Open questions:

- Footprint/internal boundary layer impact.
- Variation in time and space.
- Exchange forcing mechanisms.