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
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
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)
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 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) for four different seasons.
Climate
Local very large impact.

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

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?

- Turbulent diffusion
- Molecular diffusion
- Molecular diffusion
- Turbulent diffusion

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?

Turbulent diffusion

Molecular diffusion

Molecular diffusion (parallel to a circuit)
Flux = \((X_1 - X_2)/r = (X_1 - X_2)v\)

\(r = \text{resistance}\)
\(v = \text{transfer velocity}\)
\(X_1 - X_2 = \text{difference in layer}\)
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

\[ \frac{1}{r_{D1}} + \frac{1}{r_{D2}} = \frac{1}{r_D} \rightarrow r_D \leq r_H \]
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…

\[ \tau = \rho_a u_*^2 = \rho_a C_D U_{10} (U_{10} - U_0) \approx \rho_a C_D U_{10}^2 \]
Drag coefficient, $C_D$:

$C_D$ depends on:

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

Calculate the neutral counterpart $C_{DN}$

\[
C_D = \frac{\kappa^2}{\left( \ln\left( \frac{z}{z_0} \right) - \Psi_m \right)^2} \quad \text{or} \quad C_D = \left( C_{DN}^{-1/2} - \frac{\Psi_m}{\kappa} \right)
\]
Wind speed:

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

\[ C_{DN} \cdot 10^3 = 1.2 \quad 4 \leq U_{10} \leq 11 \text{ m/s} \]

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

\[ C_{DN} \cdot 10^3 = (0.07U_{10} + 0.95) \quad \text{(Donelan et al, 1997)} \]

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 Larsen 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…
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
2. Carbon dioxide and many other scalars – molecular sublayer in the ocean is limiting. The thickness of the molecular diffusion layer determines the resistance. Processes controlling the thickness of this layer control the transfer.
What controls the air-water exchange of CO$_2$?

Turbulent diffusion

\[ p_{\text{CO}_2-\text{atm}} \]

Molecular diffusion

\[ k= \text{transf. vel} \]

Molecular diffusion

\[ p_{\text{CO}_2-\text{ocean}} \]

Turbulent diffusion

Difference in concentration

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

\( \alpha = \text{solubility coefficient} \)

Difference in partial pressure

\[ F = kK_0(p_{\text{CO}_2\text{ocean}} - p_{\text{CO}_2\text{atm}}) \]

\( K_0 = \text{solubility} \)

\[ K_0 = \frac{\alpha}{RT} \]

\( K_0 \) is salinity and temperature dependent

Transfer velocity (piston velocity), efficiency of transfer

rtco 
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
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.
Measurement site

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

Very shallow, maximum depth < 2m
Fast response instrumentation
5m height
LI-7700 – CH₄, open path
LI-7500 – H₂O, CO₂ open path
Sonic anemometer (R3, Gill)

Additional instrumentation:
Wind speed and temperature at three levels
RH, Global radiation, airpressure, precipitation
Float instrumentation

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

Profiles of pCO₂ and temperature at five levels down to ~1.7 m depth.

Prototype CH₄ sensor since 2011-05-11

SAMI-CO₂ sensor (Sunburst) since 2011-08-15
LI-7700 Open Path CH₄ Analyzer Specifications

Resolution (RMS noise): 5 ppb @ 10 Hz and 2000 ppb CH₄

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

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

Stable stratification

Unstable stratification

Land breeze

Waterside convection

Night
Day

Unstable stratification

Lake breeze

stable stratification

Lake breeze
Stable cases, daytime

Unstable cases, nighttime

q- spectra
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

\[ C_D = \frac{u'w'}{U_{10}^2} \]

\[ C_H = \frac{w'\theta'}{U_{10}(\theta_s - \theta_{10})} \]

\[ C_E = \frac{w'q'}{U_{10}(q_s - q_{10})} \]
Exchange coefficients

COARE 3.0 (Fairall et al. 2003)
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

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!

All four periods from 2011
Results from the entire measuring period

What causes the daily cycle?
Night

Stable stratification

Unstable stratification

Land breeze

Waterside convection

Increased chance of bubble formation?
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 $\text{FCH}_4$ during night and also for longer periods.
Factor influencing air-sea CO$_2$ flux (Garbe, Rutgersson et al. 2013)
Problems with diffusive flux

• Large variability in surface water concentration

• Forcing mechanisms of piston velocity highly unknown (convection, surface films…).
Float instrumentation, CO2

Profile system, CO₂ at 5 levels

**SAMI2-CO₂**
- Measures: partial pressure of CO₂ in water \( (pCO₂) \)
- Precision: < 1 ppm
- Accuracy: ± 3 ppm based on lab calibration*
- Long-term drift: < 1 ppm over 6 months
Lake aquatic ecosystems, air water exchange aspects

Open questions:

• Footprint/internal boundary layer impact.

• Variation in time and space.

• Exchange forcing mechanisms.