Temperature variability of European lakes under changed climatic conditions and its impact on plankton development

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- Introduction
- Simulations and model validation
- Geographical dependence
- Summary
Introduction

- Increase of *Daphnia* abundance in spring
- leads to „clearwater phase“ with high transparency (Secchi depth)
- Occurrence of maximum abundance at $T_{\text{epi}} = 15 – 20 \, ^\circ\text{C}$
  mean 18.5 °C – lakes of North America (Gillooly & Dodson, 2000)
  mean 15°C – European lakes
North Atlantic Oscillation

high                                    low

warmer                                  colder

www.ldeo.columbia.edu/NAO/
Linkage between global climate and plankton succession

**NAO**

- Mean Air Temperature (Dec.-March) [°C]:
  - $r = 0.62$, $p < 0.01$

- Water Temperature in May [°C]:
  - $r = 0.73$, $p < 0.005$

**Local Meteorology**

- Water Temperature

**Daphnia**

- Growth and biomass
  - $r = 0.73$, $p < 0.005$

- Grazing
  - $r = -0.84$, $p < 0.0001$

**Timing of the clear-water phase**

- Start clear-water phase [julian day]:
  - $r = -0.55$, $p < 0.05$
Clear-water Timing in Central European Lakes

136 seasonal courses from 28 lakes

r = -0.5, p < 0.01
after linear detrending: r = -0.45, p < 0.05

Straile (2002)
• Linkage between NAO
  
  water temperature
  timing of clear water-phase

• Succession events can be predicted by characteristic temperature marks

• Simulations for temperature stratification
  - reveal geographical dependence
  - allow for testing climate scenarios
Simulations and model validation

- k-e-turbulence model (LAKEoneD, Joehnk 2000)
- Ice cover model included (degree-day formulation)
- Simulation using a single artificial “test lake“
  \[ H = 30 \text{ m}, \ A = 10 \text{ km}^2 \]
- Assuming knowledge of mean monthly meteorological data only
- Simulation of the response to a change in global temperature
  \[ T + 2 \degree \text{C} \text{ and } T + 4 \degree \text{C} \]
- Meteorological data of 101 European stations used
- Model validation using different European locations („lakes“)

The following examples show simulations for temperature stratification and lake surface temperature (LST)
Model - LAKEoneD

$k-$\textit{ε}-turbulence model

- **Processes:**
  - Wind stress
  - Turbulent mixing
  - Shortwave radiation
    - Absorption and heating of water column
  - Longwave radiation, heat conduction, evaporation
    - Heat flow across water surface

- **Model:**
  - Horizontal flow $u, v$
  - Temperature $T$
  - Turbulent kinetic energy $k$
  - Turbulent dissipation rate $\varepsilon$
Horizontal integration \(\rightarrow\) 1D model

\[
\begin{align*}
\frac{\partial u}{\partial t} + f v &= -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\partial}{\partial z} \left( \nu + \nu_t \right) \frac{\partial u}{\partial z} \\
\frac{\partial v}{\partial t} - f u &= -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + \frac{\partial}{\partial z} \left( \nu + \nu_t \right) \frac{\partial v}{\partial z} \\
\frac{\partial p}{\partial z} &= -\rho g \\
\frac{\partial T}{\partial t} &= \frac{\partial}{\partial z} \left( \chi + \frac{\nu_t}{\sigma_T} \right) \frac{\partial T}{\partial z} + \frac{1}{\rho_0 c_p A(z)} \frac{\partial A(z)}{\partial z} \\
\end{align*}
\]

k-\(\varepsilon\)-Turbulenzmodell

\[
\begin{align*}
\frac{\partial k}{\partial t} &= \frac{\partial}{\partial z} \left( \nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial z} + P + G - \varepsilon \\
\frac{\partial \varepsilon}{\partial t} &= \frac{\partial}{\partial z} \left( \nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial z} + \left( c_1 P + c_3 G - c_2 \varepsilon \right) \frac{\varepsilon}{k} \\
\nu_t &= c_\mu \frac{k^2}{\varepsilon}
\end{align*}
\]

Parameter

\(c_\mu, c_1, c_2, c_3, \sigma_\tau, \sigma_k, \sigma_\varepsilon\)
LAKEoneD – I/O

- **Meteorological input:**
  - Wind speed
  - Air temperature
  - Relative humidity
  - Global irradiance
  - Cloud cover
    - Hourly values or daily mean values

- **Lake morphology:**
  - Hypsographic curve (Area-depth-distribution)

- **Results:**
  - Temperature-depth-distribution \( T(z,t) \)
  - Turbulent diffusivity \( \nu(z,t) \)
  - \( \Delta t = 5 \text{ min} \)
  - \( \Delta x = 1 \text{ m} \)
Comparing Simulations

- Example 1: Ammersee – temperature profiles
  Simulations using meteorological data from
  0) hourly measurements,
  1) constructed from mean monthly data using daily cycles with stochastic component and
  2) constructed from mean monthly data

- Example 2: Lake Constance – lake surface temperature
  Simulations using hourly data
  Simulations using interpolated mean monthly data
Comparison between simulation results for different meteorological inputs

- Simulation 1
- Simulation 2 (mean monthly values)
- Hourly meteorology
- Measurements

Simulation dates:
- 14.5.96
- 11.6.96
- 16.7.96
- 14.8.96

Measurement dates:
- 3.9.96
- 12.9.96
- 15.10.96
- 30.10.96
- 20.11.96

Temperature [°C]

Height [m]
Long term simulation results for LST of Lake Constance

Measurements
LST (monthly)
Simulation

- Measurements
- LST (monthly)
- Simulation
Comparison between simulated LST using mean monthly meteorological data and measurements

![Graph comparing simulated LST with measurements](image)

- Measurements 1979-1995
- mean LST 1901-1990 (monthly)
- Simulation
Characteristic values for geographical analysis

- Timing of $T = 6^\circ C$ - Measure for onset of stratification
- Timing of $T = 15^\circ C$ - Measure for clear-water timing
- Maximum surface temperature
- Duration of stagnation period
- Onset of ice cover
- Duration of ice cover
Simulations using
- mean monthly meteorology
- air temperature + 4°C
- hourly meteorology (1995)
Geographical dependence

- **Length of stratification period**
- **Duration of ice cover**
- **Maximum temperature**
- **Date LST = 6 °C**
  as a measure for the onset of stratification and enhanced biological activity
- **Date LST = 15 °C**
  as a measure for maximum abundance of *Daphnia*
  (18.5 °C in American lakes, 15 °C in Lake Constance)
Location of meteorological stations with climate normals including wind speed

Station List
Change in duration of stagnation period in case of increased air temperature

• stagnation period 3 – 4 weeks longer
• Length of stratification period
• **Duration of ice cover**
• Maximum temperature
• Date LST = 6 °C
  as a measure for the onset of stratification and enhanced biological activity
• **Date LST = 15 °C**
  as a measure for maximum abundance of *Daphnia*
  (18.5 °C in American lakes, 15 °C in Lake Constance)
Change in duration of ice cover

Break up starts earlier
T + 2°C : 21 days
T + 4°C : 35 days

Freezing starts later
T + 2°C : 19 days
T + 4°C : 32 days
• Length of stratification period
• Duration of ice cover
• **Maximum temperature**
• Date LST = 6 °C  
as a measure for the onset of stratification and  
enhanced biological activity
• Date LST = 15 °C  
as a measure for maximum abundance of *Daphnia*  
(18.5 °C in American lakes, 15 °C in Lake Constance)
T + 2°C  
T + 4°C

slope = -0.37 °C / deg

slope = -0.32 °C / 100 m
Maximum temperature - Tair + 4 C
• Length of stratification period
• Duration of ice cover
• Maximum temperature
• Date LST = 6 °C
  as a measure for the onset of stratification and enhanced biological activity
• Date LST = 15 °C
  as a measure for maximum abundance of *Daphnia*
  (18.5 °C in American lakes, 15 °C in Lake Constance)
slope = 3 days / deg

slope = 1.4 days / 100 m
• Length of stratification period
• Duration of ice cover
• Maximum temperature
• Date LST = 6 °C
  as a measure for the onset of stratification and enhanced biological activity
• Date LST = 15 °C
  as a measure for maximum abundance of *Daphnia*
  (18.5 °C in American lakes, 15 °C in Lake Constance)
Variation of clear-water phase with geographical location

- Slope: 3.6 days / deg
- Variation: -16 days at T + 2°C, -13 days at T + 4°C

Variation of clear-water phase with elevation:

- Slope: 3.9 days / 100 m
Variation of clear-water phase with geographical location in Central European lakes

- shift in timing of clear-water phase 4 days / 100 m
Summary

• Geographical dependence of lake stratification simulated using climate normals

• Change of lake stratification characteristics due to change in air temperature $+2 \, ^\circ\text{C}$ ( $+4 \, ^\circ\text{C}$ ) quantified

• Stagnation period prolonged $+12 \, \text{days}$ ( $+24 \, \text{days}$ )

• Dates of ice formation and ice break up changed, duration $-1 \, \text{month}$ ( $-2 \, \text{months}$ )

• LST $= 15 \, ^\circ\text{C}$: clear-water phase $16 \, (29) \, \text{days}$ earlier
In progress:

• Better automation of picking of characteristic values
• Using gridded meteorological fields
  New et al. 2002: 10˚ grid -> ca. 15000 points for Europe
• Simulating impact of realistic climate change scenarios
  (gridded fields)
• Show effects for lakes with different depths
• Geographical boundaries for climatic forced occurrence of mixing types (e.g., polymixis, meromixis)