Possible effects of climate change on the mixing regime of Lake Maggiore and implications for its water quality

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Manerba del Garda, 10th May 2018
DEEP SUBALPINE LAKES

NUTRIENT LOADS FROM POINT SOURCES ARE ~ STABLE

WHAT WILL HAPPEN IN THE FUTURE?

Under nutrient limitation, evolution of lake ecosystems is mainly determined by changes in meteorology and lake thermal structure (Morabito et al., 2012)

CLIMATE CHANGE

LAKE HYDRODYNAMICS

DSL (Salmaso et al., 2003):

• Climate
• Morphology
• Hydrodynamics
• Ecology
In the Alpine region, air temperature is rising twice as fast than the global average (Dokulil et al., 2010) \( \Delta T_w \approx 0.04 \, ^\circ C/\text{year} \)
LAKE HYDRODYNAMICS

**OLIGOMICTIC REGIME**

**COMPLETE-MIXING:** cold and windy winters

- $O_2$ ↓
- $PO_4$, $NO_3$, $NH_4$, $SiO_2$ ↑

**COMPLETE-MIXING EVENTS 1990-2018:**
- Lake Maggiore: 4
- Lake Iseo: 2
- Lake Lugano: 1

**Chemical gradients**

**1960s → more frequent full turnovers** (Ambrosetti and Barbanti, 1999)

**AIR TEMPERATURE WARMING**

**EPILOMNION: follows air temperature increase**

**HYPOLOMNION: warms at a much slower rate**

**STABILITY**

**MIXING**
REASONS FOR OUR STUDY

1) **How will the oligomictic behaviour of the DSL evolve?**

2) **Could a future decrease in GHG emissions revert the transition towards meromixis?**

3) **How will the chemistry and ecosystems of the DSL be influenced?**

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**NUMERICAL SIMULATIONS**

**CASE STUDY: LAKE MAGGIORE**

**FUTURE EVOLUTION**

- **Extensible to other DSL**
- **since 1950s**
- **since 1981**

**MIXING REGIME**
- Calibration/validation ✓
- Application ✓

**BASIC ECOSYSTEM**
- Calibration/validation ✓
- Application IN PROGRESS
HYDRODYNAMIC MODEL

**GLM** (General Lake Model; Hipsey et al., 2014) → 1D horizontally averaged model

LaKE MAGGIORE → 33 inflows (12 main ones) → Uncertainties in modelling future advective fluxes

ENCLOSED LAKE MODEL

Adective fluxes mimicked by a fictitiously low light extinction coefficient

CALIBRATION OVER 1998-2014 → EXTENDED PERIOD

<table>
<thead>
<tr>
<th>MAE [°C]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall (0 ÷ 360 m)</td>
<td>0.523</td>
</tr>
<tr>
<td>Epilimnion (0 ÷ 10 m)</td>
<td>1.124</td>
</tr>
<tr>
<td>Metalimnion (20 ÷ 50 m)</td>
<td>0.710</td>
</tr>
<tr>
<td>Hypolimnion (100 ÷ 360 m)</td>
<td>0.129</td>
</tr>
</tbody>
</table>

AIR TEMPERATURE WARMING FORECASTS

CH2011 → 20 (GCM + RCM) ensemble → 3 IPCC scenarios

- \textbf{"lower"}: 2.5%
- \textbf{"medium"}: 50%
- \textbf{"upper"}: 97.5%

\textbf{A2}: boundless growth of GHG

\textbf{A1B}: renewables ≈ fossils from ~2050

\textbf{RCP3PD}: drop of GHG from ~2020

\textbf{2016-2085 HYDRODYNAMIC SIMULATIONS:}
- 9 CH2011 SCENARIOS
- \text{STAT_2016 SCENARIO} → \( T_a \) at 2016 levels

\textbf{CH2011 (2011)}
ADOPTED FUTURE METEOROLOGICAL SERIES

RADIATIVE FLUXES

• AIR TEMPERATURE
• SOLAR RADIATION
• RELATIVE HUMIDITY
• WIND SPEED

HYPOLIMNETIC TEMPERATURES

"SAWTOOTH TREND"
(Livingstone, 1997)

Lake Maggiore, $T_w$ at 360 m depth:

Hypolimnion thermal evolution depends on the NUMBER and POSITION of full turnovers

MULTIPLE RANDOM REALISATIONS

MONTE CARLO APPROACH

VG (Vector-Autoregressive Weather Generator; Schlabing et al., 2014) Generates random meteorological series

INPUT:
1) 1998-2015 meteorological observations DEPENDENCE STRUCTURE
2) Alteration of $T_a$ CH2011

200
SIMULATED WATER WARMING

Evolution of $T_w$ averaged over the 200 realisations:

- **Depth = 0 m**
  - **EPIPLIMNION**
  - Maximum $\Delta T_w = +0.065 ^\circ$C/year

- **Depth = 70 m**
  - **LOWER METALIMNION**
  - Stabilisation achieved later

- **Depth = 100 m**
  - **UPPER HYPOLIMNION**
  - Stabilisation not yet achieved

- **Depth = 370 m**
  - **LOWER METALIMNION**
  - Common trend: $\Delta T_w = +0.010 \div +0.012 ^\circ$C/year

(→ → Observed bottom warming 1956-2016: $\Delta T_w = +0.013 ^\circ$C/year)
SIMULATED DECREASE OF COMPLETE-MIXING

Statistical distributions of minimum annual surface $T_w$ and simultaneous bottom $T_w$ over the 200 realisations:

- Higher complete-mixing probability than today
- Collapse of complete-mixing probability
EFFECTS OF GLOBAL WARMING ON THE THERMAL STRUCTURE

Evolution of the return period for complete-mixing over the 200 realisations:

COMPLETE-MIXING: \( \Delta T_{\text{surf-bott}} \leq 0.1 \, ^\circ\text{C} \)

NON-MITIGATION SCENARIOS:
- frequency of complete-mixing events
- duration
- depth of partial-mixing events
- wind speed

MITIGATION SCENARIOS: The current behaviour is recovered (or improved)

DROP OF EXCHANGES BETWEEN EPILIMNION AND HYPOLIMNION

INCREASES

DECREASE
RECOVERY OF COMPLETE-MIXING FREQUENCY

Let’s suppose that $T_a$ stabilises in 2085…

How long would it take to recover the "natural" complete-mixing frequency?
EFFECTS OF GLOBAL WARMING ON THE DSL

Lake Maggiore and the other DSL are ALREADY warming

Global GHG emissions dropped from ~2020 (RCP3PD):
1) Restricted water warming (maximum mean annual $\Delta T_w \approx +0.9 \, ^\circ C$ for Lake Maggiore)
2) Recovery of oligomixis by the end of 21st century

Global GHG not addressed (A2) / reduced from ~2050 (A1B):
1) Significant water warming (maximum mean annual $\Delta T_w \approx +4.6 \, ^\circ C$ for Lake Maggiore)
2) Pseudo-tropical meromixis for the coming centuries

ECOLOGICAL EFFECTS OF TEMPERATURE AND STABILITY INCREASE:

Earlier, more prominent phytoplankton blooms (Peeters et al., 2007) vs. Productivity decrease due to stratification (Yankova et al., 2017)

Rise of cyanophytes (Jöhnk et al., 2008)

Deep-water oxygen depletion (Jankowski et al., 2006)

What would happen to Lake Maggiore and how? COUPLED ECOLOGICAL-HYDRODYNAMIC MODEL
ECOLOGICAL MODEL

GLM-AED2 (Aquatic EcoDynamics; Hipsey et al., 2013)

Modular approach

Loads from 12 main tributaries

NUTRIENTS → PHYTOPLANKTON → DETRITUS

1) Diatoms
2) Cyanophytes
3) Dinophytes
4) "C3phytes" = Chlorophytes + Chrysophytes + Cryptophytes

POM / DOM

1998-2014 SIMULATION

1998: SPIN-UP
1999-2006: CALIBRATION
2007-2014: VALIDATION

EXTENDED PERIODS

1) DEEP-WATER CHEMICAL EVOLUTION (200 ÷ 370 m)
2) EVOLUTION OF PHYTOPLANKTON SUCCESSION (0 ÷ 20 m)

FOCUS

MULTIPLE:
- Variables
- Depths
- Model levels

MANUAL CALIBRATION

SIMULATED DEEP-WATER CHEMISTRY

**O₂**
- R: 0.83, 0.79, 0.88 ± 0.05
- NMAE: 5%, 7%, 19% ± 10%

**PO₄**
- R: 0.61, 0.70, 0.60 ± 0.26
- NMAE: 19%, 12%, 78% ± 27%

Full turnovers
Partial turnovers
SIMULATED PHYTOPLANKTON SUCCESSION

Bloom of Mougeotia spp. not reproduced as not parameterised individually

<table>
<thead>
<tr>
<th>Component</th>
<th>R</th>
<th>NMAE</th>
<th>CAL</th>
<th>VAL</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Chl-α</td>
<td>0.69</td>
<td>38%</td>
<td>0.19 (0.41)</td>
<td>0.36 ± 0.26</td>
<td></td>
</tr>
<tr>
<td>Cyanophytes</td>
<td>0.65</td>
<td>69%</td>
<td>0.44</td>
<td>0.50 ± 0.29</td>
<td></td>
</tr>
<tr>
<td>Diatoms</td>
<td>0.70</td>
<td>63%</td>
<td>0.40</td>
<td>0.29 ± 0.19</td>
<td></td>
</tr>
</tbody>
</table>

PERFORMANCES

- CYCLING
- SUCCESSION AMONG GROUPS
- BIOMASSES

APPLICATION to 2016-2085 climate and nutrient load change simulations IN PROGRESS

COMPOSITIONAL SHIFTS CANNOT BE SIMULATED

Well reproduced

Larger errors
Thank you for your attention

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Manerba del Garda, 10th May 2018
AIR TEMPERATURE WARMING

Observations at Verbania Pallanza:

\[ \nabla T_a = +0.0397 \, ^\circ \text{C/} \text{year} \rightarrow \Delta T_a = +0.71 \, ^\circ \text{C} \]

CH2011 mean annual gradients 1995-2025:
SIMULATED TRENDS OF METEOROLOGICAL VARIABLES

Statistical distributions of the 200 meteorological realisations from VG:

- Trends expected for Southern and Central Europe (Christensen and Christensen, 2003; Brunetti et al., 2009; Ruostenoja and Räisänen, 2013)

- Observed trend on Lake Maggiore (Ambrosetti and Barbanti, 1999)
Hypolimnion evolution is almost identical between mitigation and non-mitigation scenarios!
SIMULATED SURFACE WATER WARMING

Statistical distributions of surface $T_w$ over the 200 realisations:

Mean annual temperatures

Maximum annual temperatures
SIMULATED PHYTOPLANKTON SUCCESSION

<table>
<thead>
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<th></th>
<th>CAL</th>
<th>VAL</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dinophytes</strong></td>
<td>R =</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMAE</td>
<td>0.59</td>
<td>0.48</td>
<td>0.30 ± 0.01</td>
</tr>
<tr>
<td><strong>C3phytes</strong></td>
<td>R =</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NMAE</td>
<td>0.49</td>
<td>-0.08 (0.37)</td>
<td>-</td>
</tr>
</tbody>
</table>

Bloom of *Mougeotia* spp.

Full turnovers
Partial turnovers

(no 2011)
COUPLED MODEL APPLICATION

200 \div 370 \text{ m PHOSPHORUS ACCUMULATION}

e.g.: SAMPLE SIMULATION WITH \text{A2_UPPER CLIMATE CHANGE AND CURRENT NUTRIENT LOAD LEVELS}

\textbf{WARNING: PROVISIONAL RESULTS!}

0 \div 20 \text{ m RISE OF CYANOPHYTES}

\textbf{Work in Progress}
TROPHIC STATUS

• As an effect of **decreasing nutrient loads**, Lake Maggiore underwent **oligotrophication** starting from the **1980s**

• **TP values at winter turnover decreased** from $30 \div 35 \, \mu g \, P \, L^{-1}$ in the **late 1970s** to $9 \div 10 \, \mu g \, P \, L^{-1}$

• A slight tendency towards **increasing TP values** has been observed in **recent years** (since 2010)
NITROGEN COMPOUNDS

• Concentrations of N compounds **steadily increased** since the 1950s

• Total N is mainly in the form of NO$_3$ (about 90%)

• There is a **high imbalance** of N levels with respect to P (N:P molar ratio $\approx$ 150).

• The main source of N to the lake is **atmospheric deposition** (60 ÷ 70%)
The lack of complete turnover is causing oxygen decrease in the deep waters of the lake.

Hypolimnetic oxygen concentrations measured in late winter 2016 were the lowest since 1999.