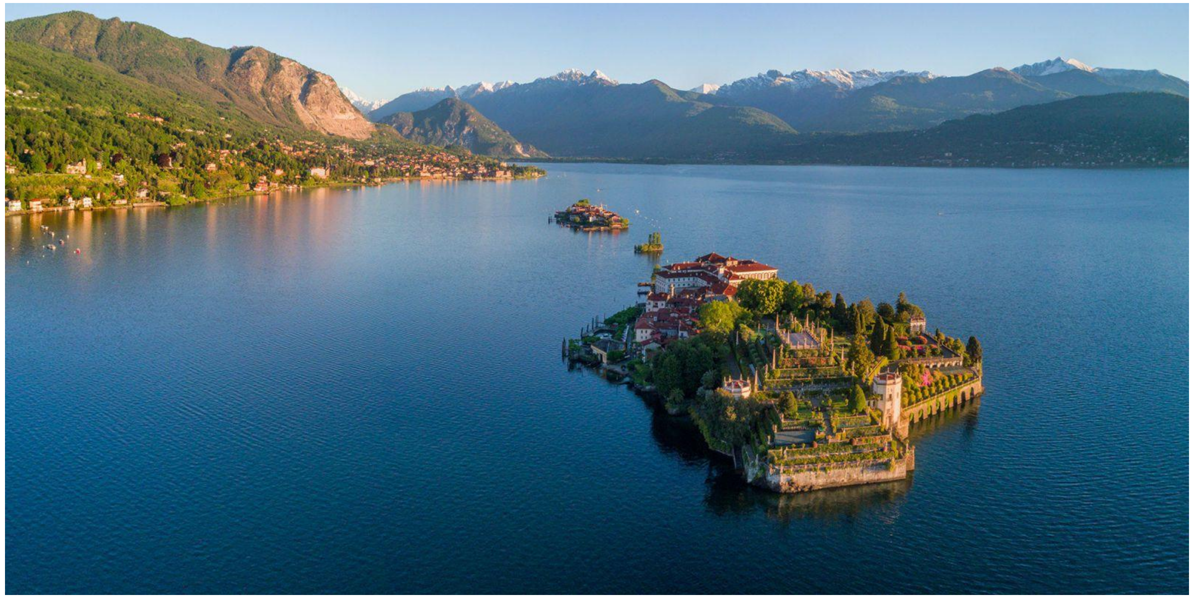
2^{nd} GARDEN International Scientific Workshop



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

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UNIVERSITÀ DI PAVIA DICAr

Manerba del Garda, 10th May 2018

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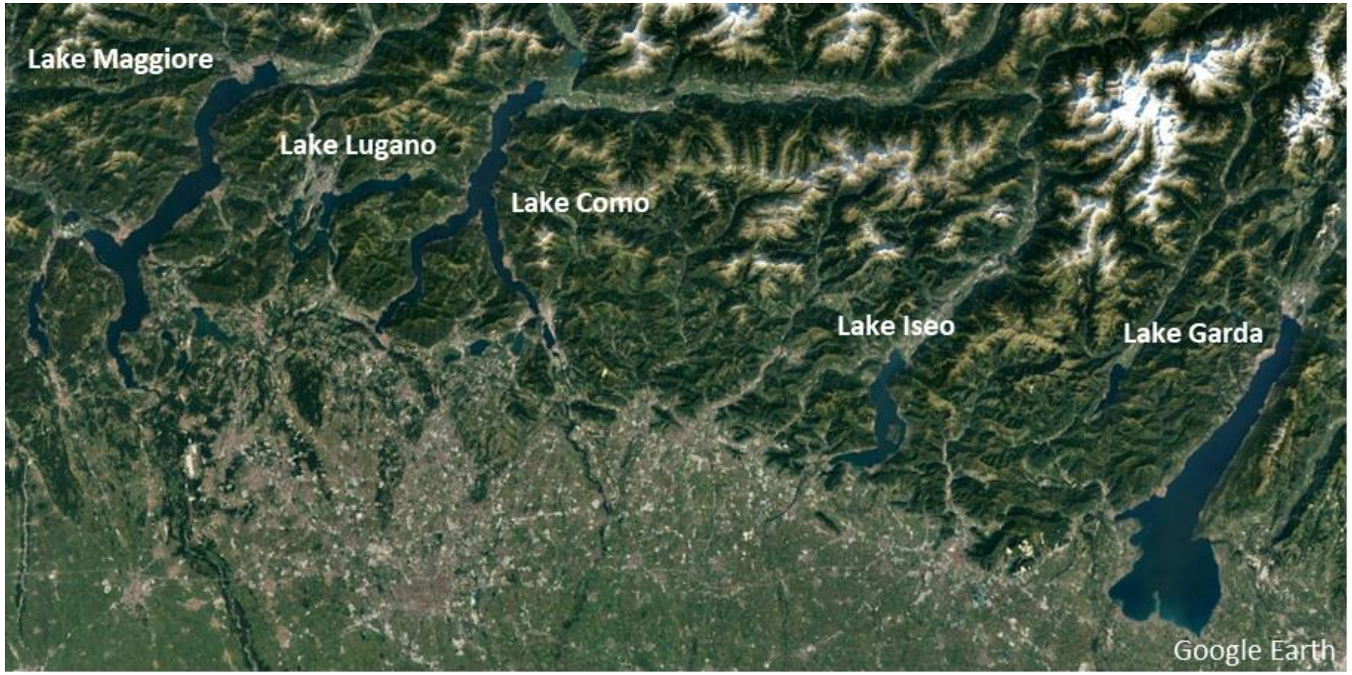
DEEP SUBALPINE LAKES



DSL (Salmaso et al., 2003):

SIMILAR

- *Climate*
- *Morphology*
- *Hydrodynamics*
- *Ecology*

EUTROPHICATION → RECOVERY

NUTRIENT LOADS FROM POINT SOURCES ARE ~ STABLE → **WHAT WILL HAPPEN IN THE FUTURE?**

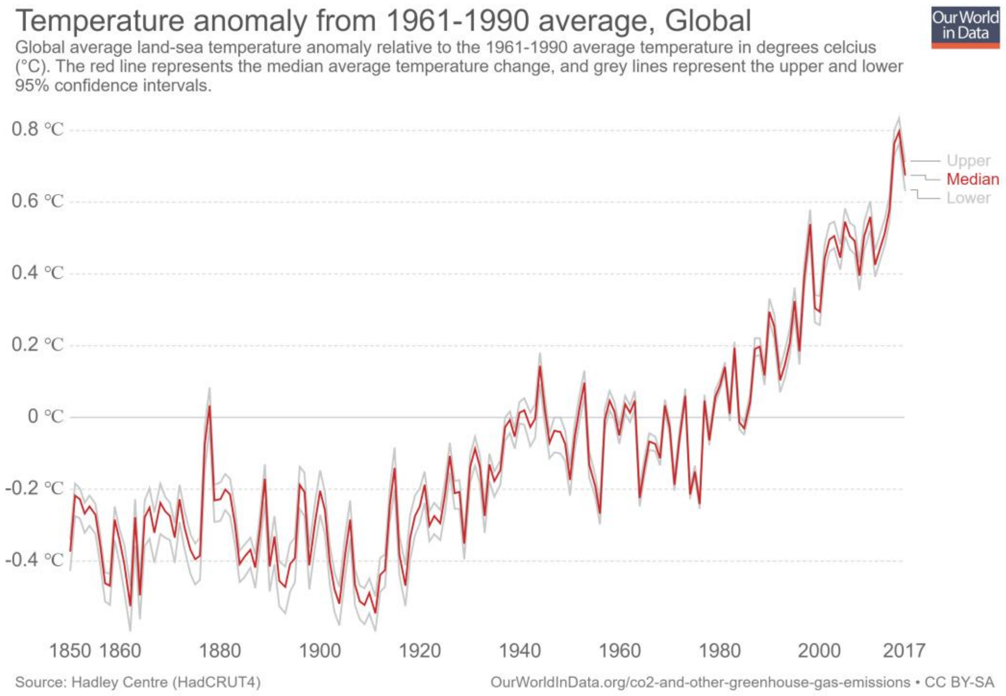
Under nutrient limitation, evolution of lake ecosystems is mainly determined by changes in meteorology and lake thermal structure (Morabito et al., 2012)

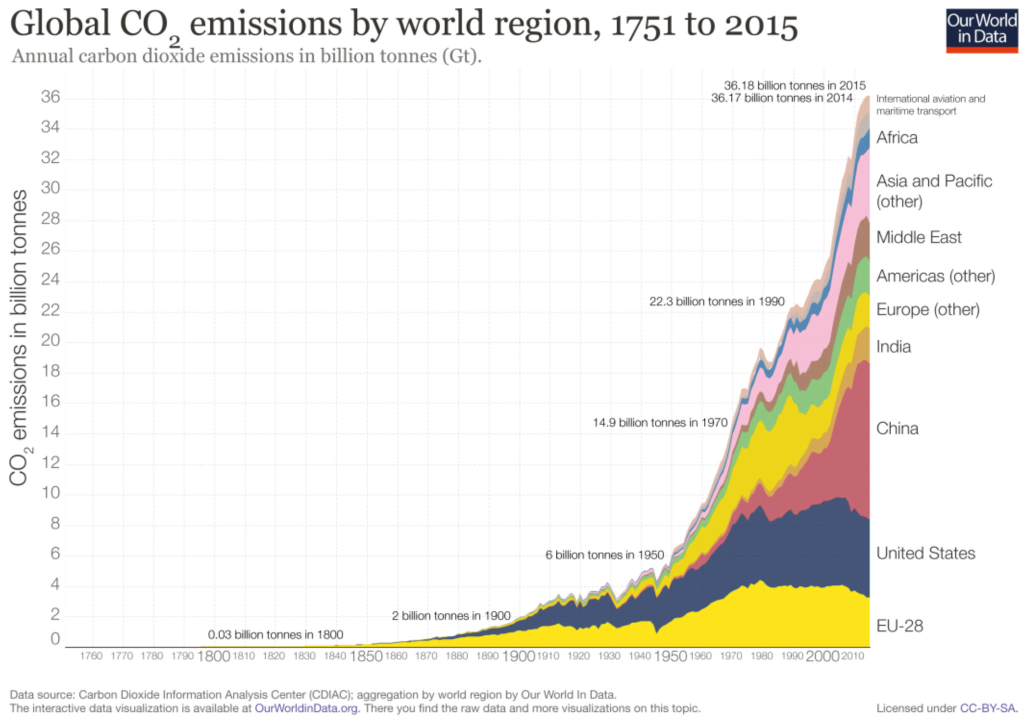
- CLIMATE CHANGE
- LAKE HYDRODYNAMICS

CLIMATE CHANGE

GLOBAL WARMING

- **NATURAL** → ***NAO – North Atlantic Oscillation***
- **ANTHROPOGENIC** → ***GHG EMISSIONS***





In the Alpine region, air temperature is rising <u>twice as fast than the global average</u> (Dokulil et al., 2010)

→ $\nabla T_w \approx 0.04$ °C/year

LAKE HYDRODYNAMICS

DSL → 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

EPILIMNION: ***follows air*** *temperature increase*

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

STABILITY +

MIXING -

REASONS FOR OUR STUDY

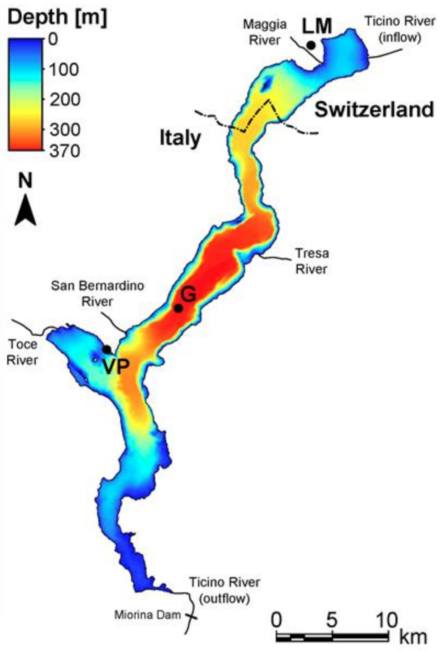
1) ***<u>How</u> will the oligomictic behaviour of the DSL evolve?***

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

3) ***How will the <u>chemistry and ecosystems</u> of the DSL be influenced?***

Extensible to other DSL

<u>NUMERICAL SIMULATIONS</u> → **CASE STUDY: <u>LAKE MAGGIORE</u>** → **FUTURE EVOLUTION**



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since 1950s

CIPAIS
Commissione Internazionale per la Protezione delle Acque Italo-Svizzere

since 1981

<u>MIXING REGIME</u>
Calibration/validation ✓
Application ✓

<u>BASIC ECOSYSTEM</u>
Calibration/validation ✓
Application **IN PROGRESS**

HYDRODYNAMIC MODEL

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

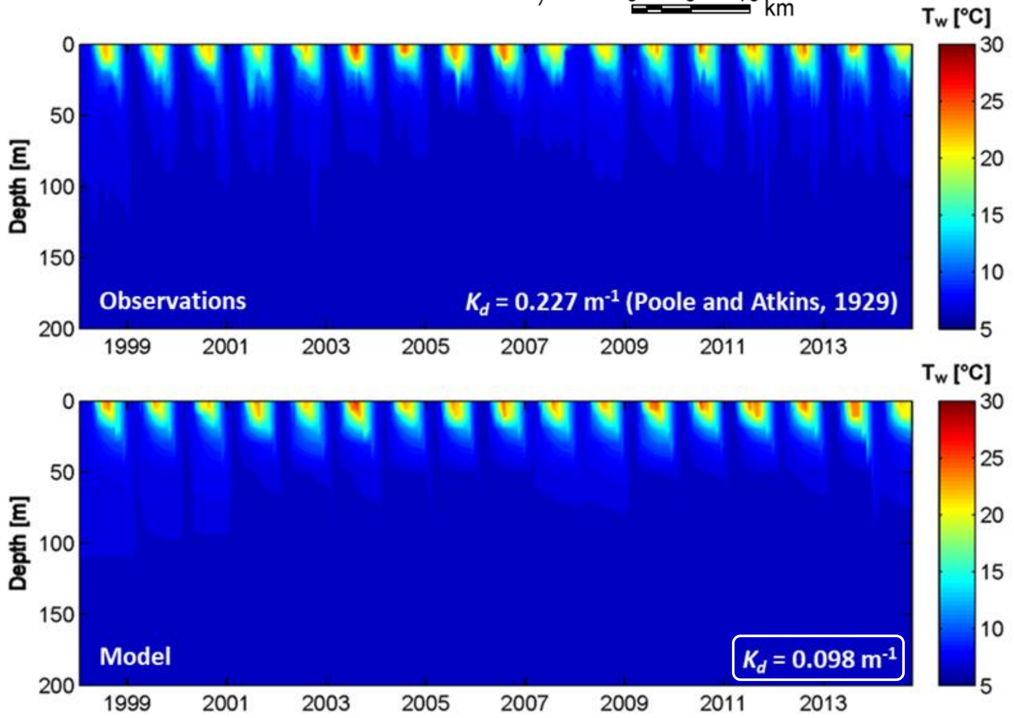
LAKE MAGGIORE → **33 inflows (12 main ones)** → ***Uncertainties in modelling future advective fluxes***

↓

ENCLOSED LAKE MODEL → ***Advective fluxes mimicked by a fictitiously low light extinction coefficient***

CALIBRATION OVER 1998-2014
→ ***EXTENDED PERIOD***

MAE [°C]	
Overall (0 ÷ 360 m)	0.523
Epilimnion (0 ÷ 10 m)	1.124
Metalimnion (20 ÷ 50 m)	0.710
Hypolimnion (100 ÷ 360 m)	0.129



Fenocchi A., Rogora M., Sibilla S., Dresti C. (2017). Relevance of inflows on the thermodynamic structure and on the modeling of a deep subalpine lake (Lake Maggiore, Northern Italy/Southern Switzerland). Limnologica 63:42-56. DOI: 10.1016/j.limno.2017.01.006

AIR TEMPERATURE WARMING FORECASTS

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

- **A2**: *boundless growth of GHG*
- **A1B**: *renewables ≈ fossils from ~2050*
- **RCP3PD**: *drop of GHG from ~2020*

20 (GCM + RCM) ensemble → **3 levels**

- **"lower"**: *2.5%*
- **"medium"**: *50%*
- **"upper"**: *97.5%*

C2SM Center for Climate Systems Modeling

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

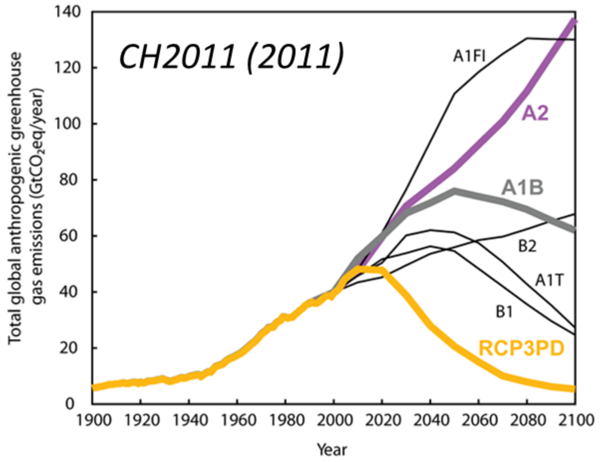
Swiss Confederation

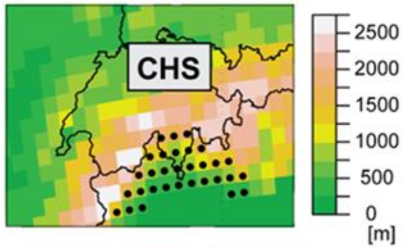
Federal Department of Home Affairs FDHA
Federal Office of Meteorology and Climatology
MeteoSwiss

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

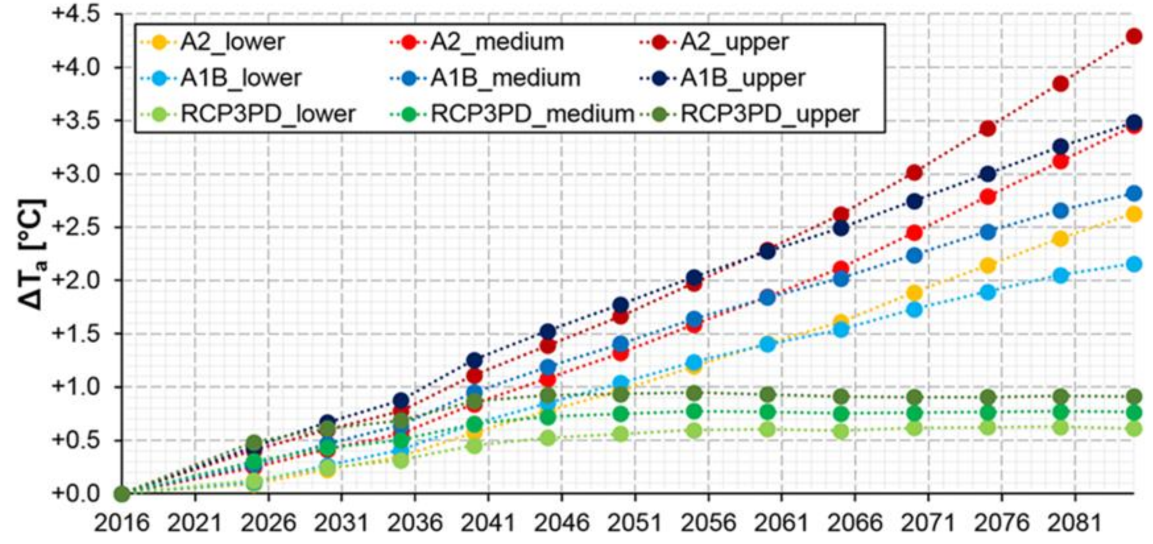
NCCR CLIMATE
Swiss Climate Research

OcCC
Organe consultatif sur les changements climatiques
Beratendes Organ für Fragen der Klimaänderung





CH2011 mean annual variations:



2016-2085 HYDRODYNAMIC SIMULATIONS:

- **9 CH2011 SCENARIOS**
- **STAT_2016 SCENARIO** ⟶ *T_a at 2016 levels*

Fenocchi A., Rogora M., Sibilla S., Ciampittiello M., Dresti C. (2018). Forecasting the evolution in the mixing regime of a deep subalpine lake under climate change scenarios through numerical modelling (Lake Maggiore, Northern Italy/Southern Switzerland). Climate Dynamics (*available online*). DOI: 10.1007/s00382-018-4094-6

ADOPTED FUTURE METEOROLOGICAL SERIES

RADIATIVE FLUXES

- **AIR TEMPERATURE**
- **SOLAR RADIATION**
- **RELATIVE HUMIDITY**
- **WIND SPEED**

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

MULTIPLE RANDOM REALISATIONS → **MONTE CARLO APPROACH**

HYPOLIMNETIC TEMPERATURES → **"SAWTOOTH TREND" (Livingstone, 1997)**

Lake Maggiore, T_w at 360 m depth:

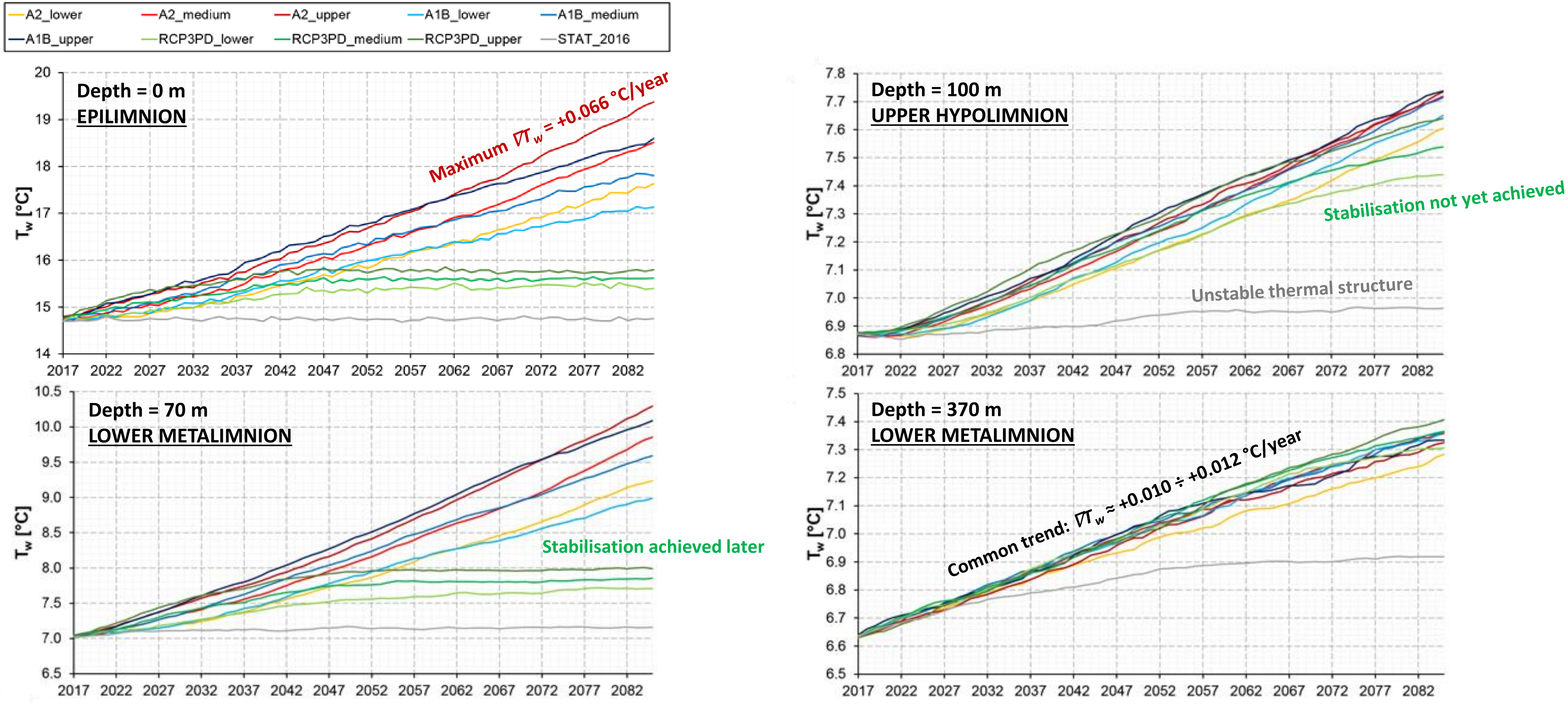
VG (*Vector-Autoregressive Weather Generator*; Schlabing et al., 2014) → *Generates* ***random meteorological series*** → **200**

INPUT:

1) 1998-2015 meteorological observations → ***DEPENDENCE STRUCTURE***
2) Alteration of T_a → ***CH2011***

SIMULATED WATER WARMING

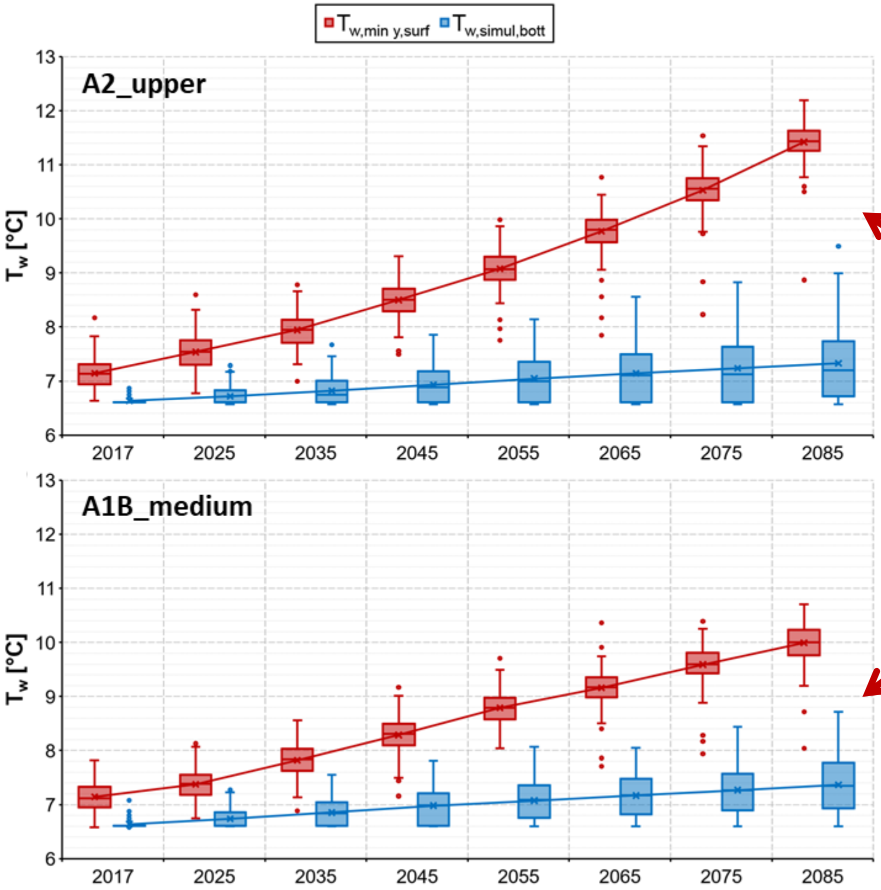
Evolution of T_w averaged over the 200 realisations:



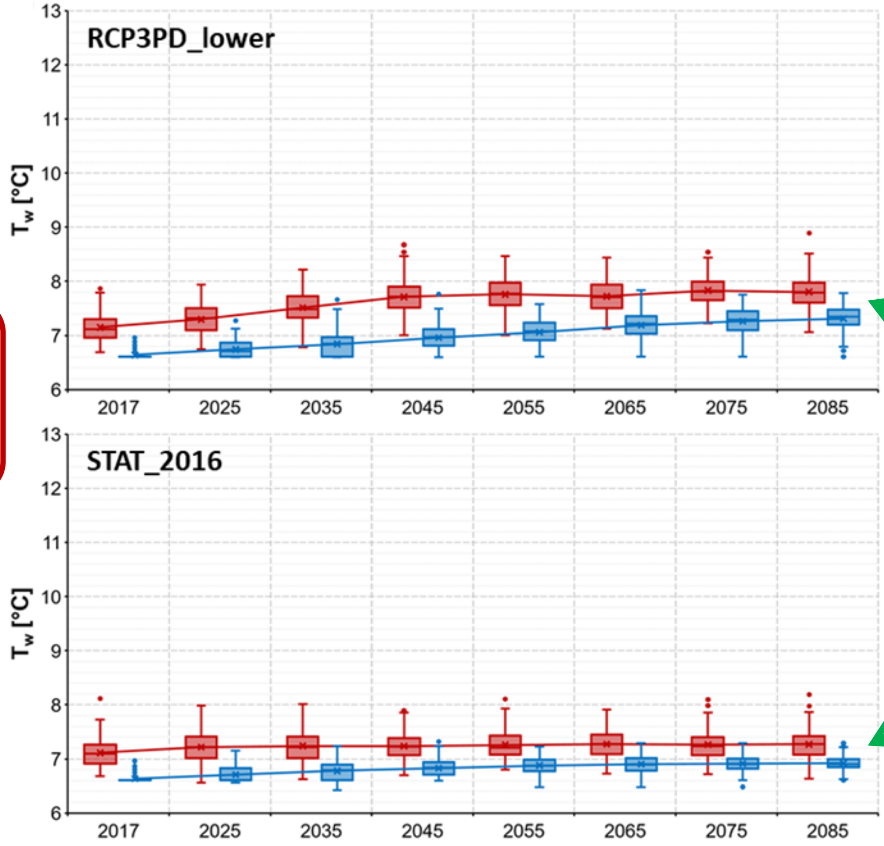
(⟶ Observed bottom warming 1956-2016: ∇T_w = +0.013 °C/year)

SIMULATED DECREASE OF COMPLETE-MIXING

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



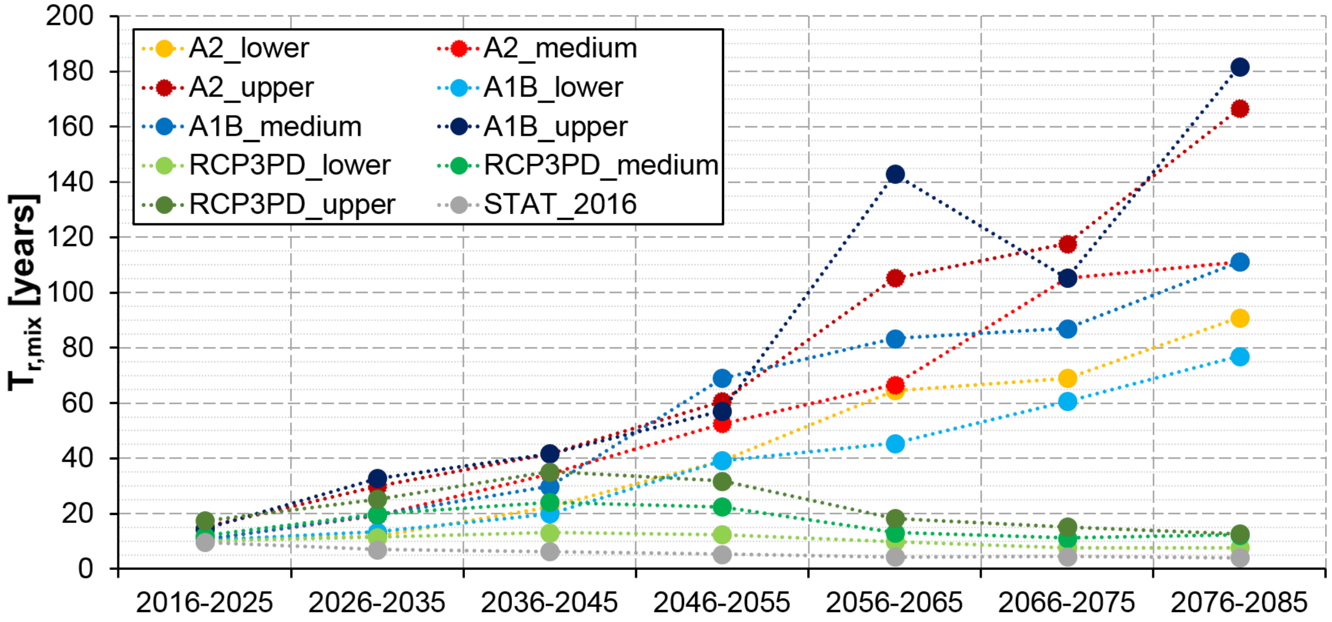
Collapse of complete-mixing probability



Higher complete-mixing probability than today

EFFECTS OF GLOBAL WARMING ON THE THERMAL STRUCTURE

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



COMPLETE-MIXING:
$\Delta T_{surf\text{-}bott} \leq 0.1$ °C

NON-MITIGATION SCENARIOS:

- ***frequency*** } *of* ***complete-mixing*** *events*
- ***duration***
- ***depth*** *of* ***partial-mixing*** *events*
- ***wind speed***

} **DECREASE**

- ***duration*** *of* ***annual stratification*** → **INCREASES**

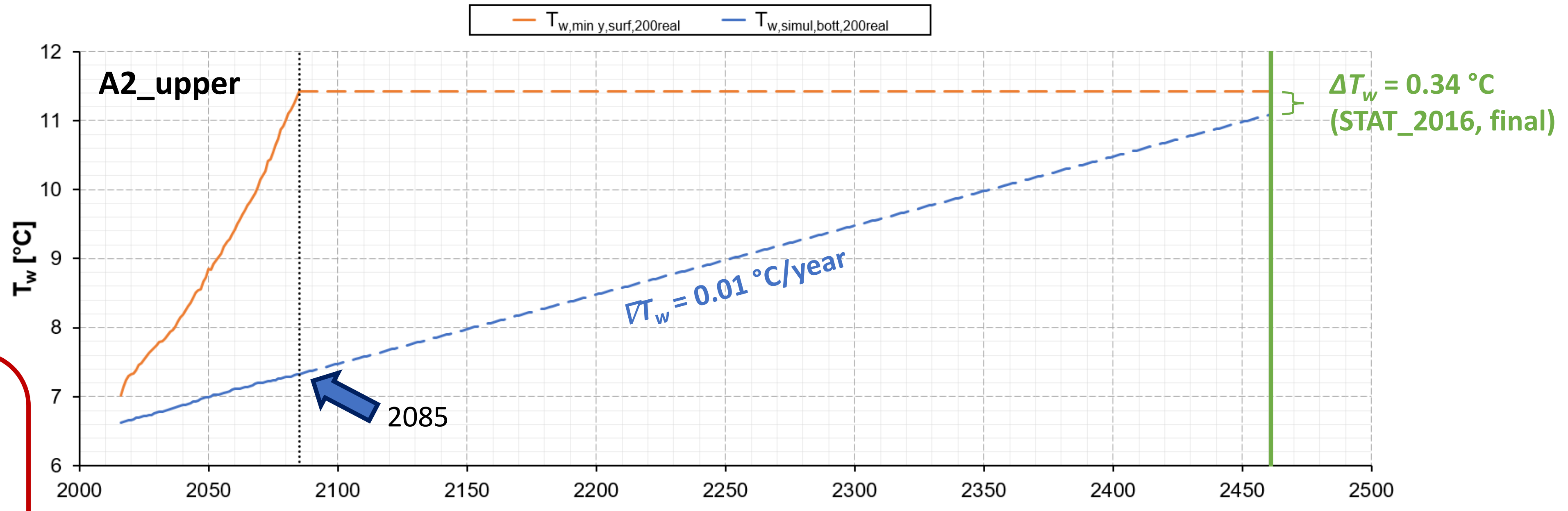
} **DROP OF EXCHANGES BETWEEN EPILIMNION AND HYPOLIMNION**

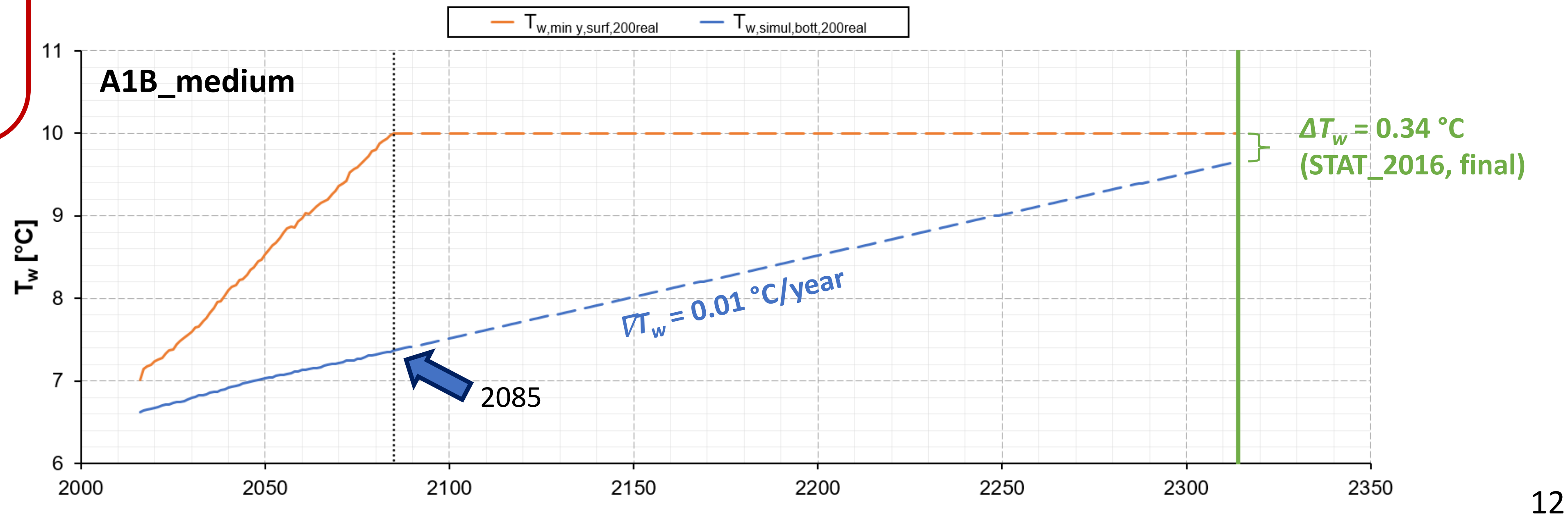
MITIGATION SCENARIOS:
The current behaviour is ***recovered*** *(or* ***improved****)*

RECOVERY OF COMPLETE-MIXING FREQUENCY

Let's suppose that T_a stabilises in 2085…

<u>How long would it take to recover the "natural" complete-mixing frequency?</u>





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 $\Delta T_w \approx +0.9$ °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 $\Delta T_w \approx +4.6$ °C for Lake Maggiore)
2) **Pseudo-tropical meromixis for the coming centuries**

ECOLOGICAL EFFECTS OF TEMPERATURE AND STABILITY INCREASE:

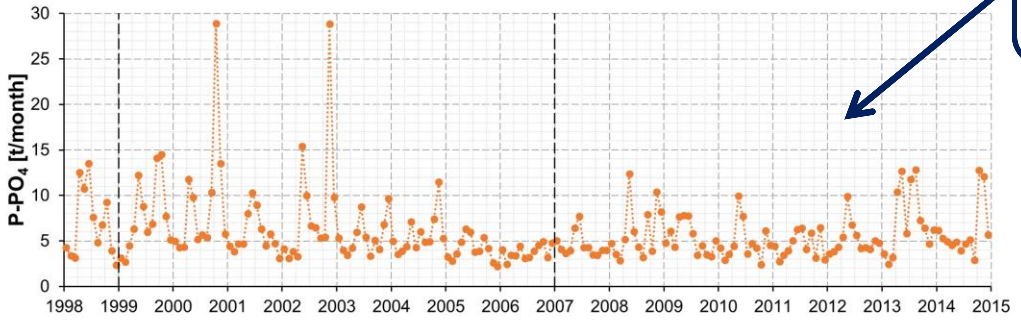
- **Earlier, more prominent phytoplankton blooms (Peeters et al., 2007)**
- *vs.*
- **Productivity decrease due to stratification (Yankova et al., 2017)**
- **Rise of cyanophytes (Jöhnk et al., 2008)**
- **Deep-water oxygen depletion (Jankowski et al., 2006)**

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

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

POM / DOM

NUTRIENTS → **PHYTOPLANKTON** → **DETRITUS**

1998-2014 SIMULATION

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

EXTENDED PERIODS

MULTIPLE:

- **Variables**
- **Depths**
- **Model levels**

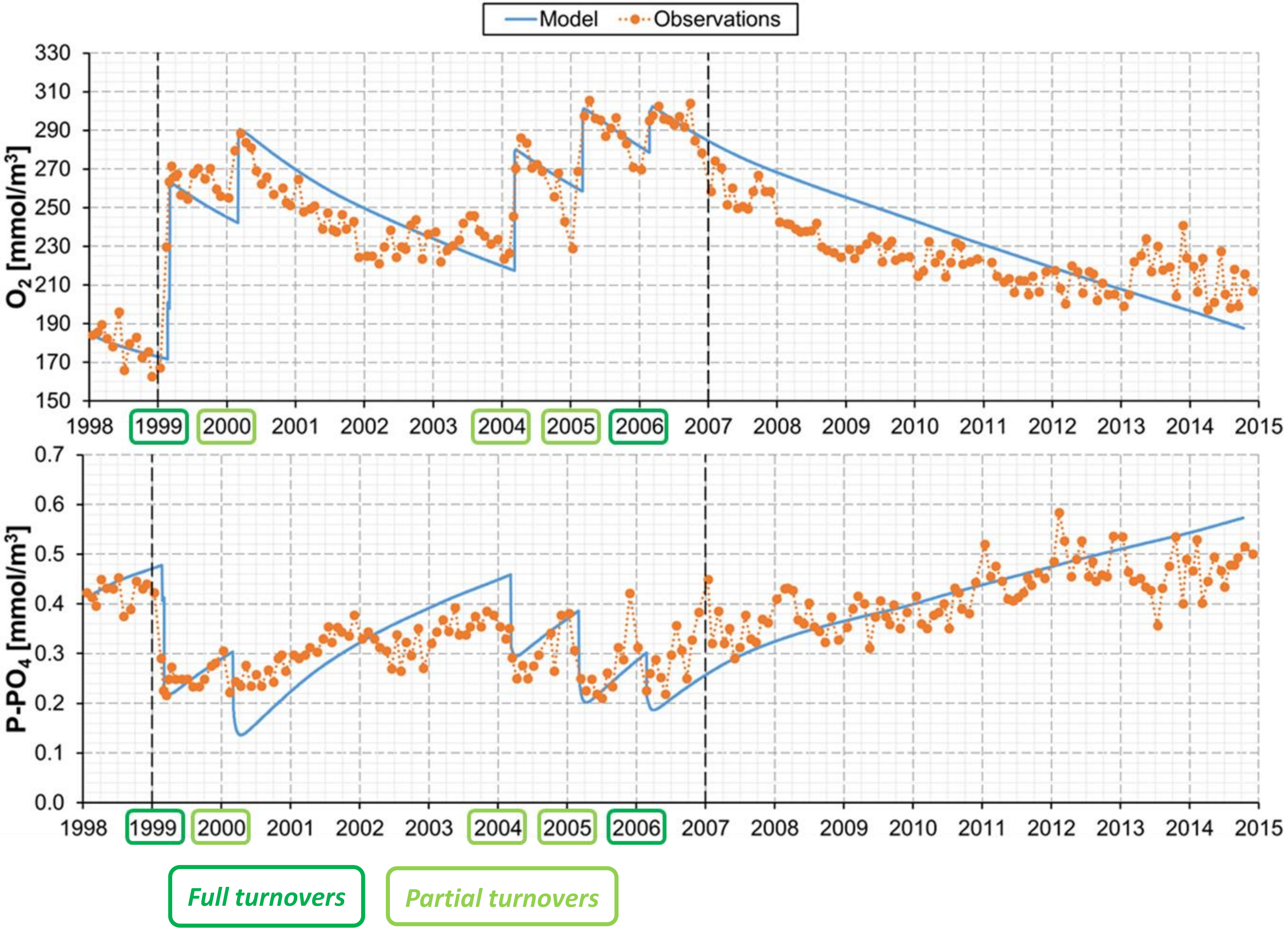
→ **MANUAL CALIBRATION**

FOCUS

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

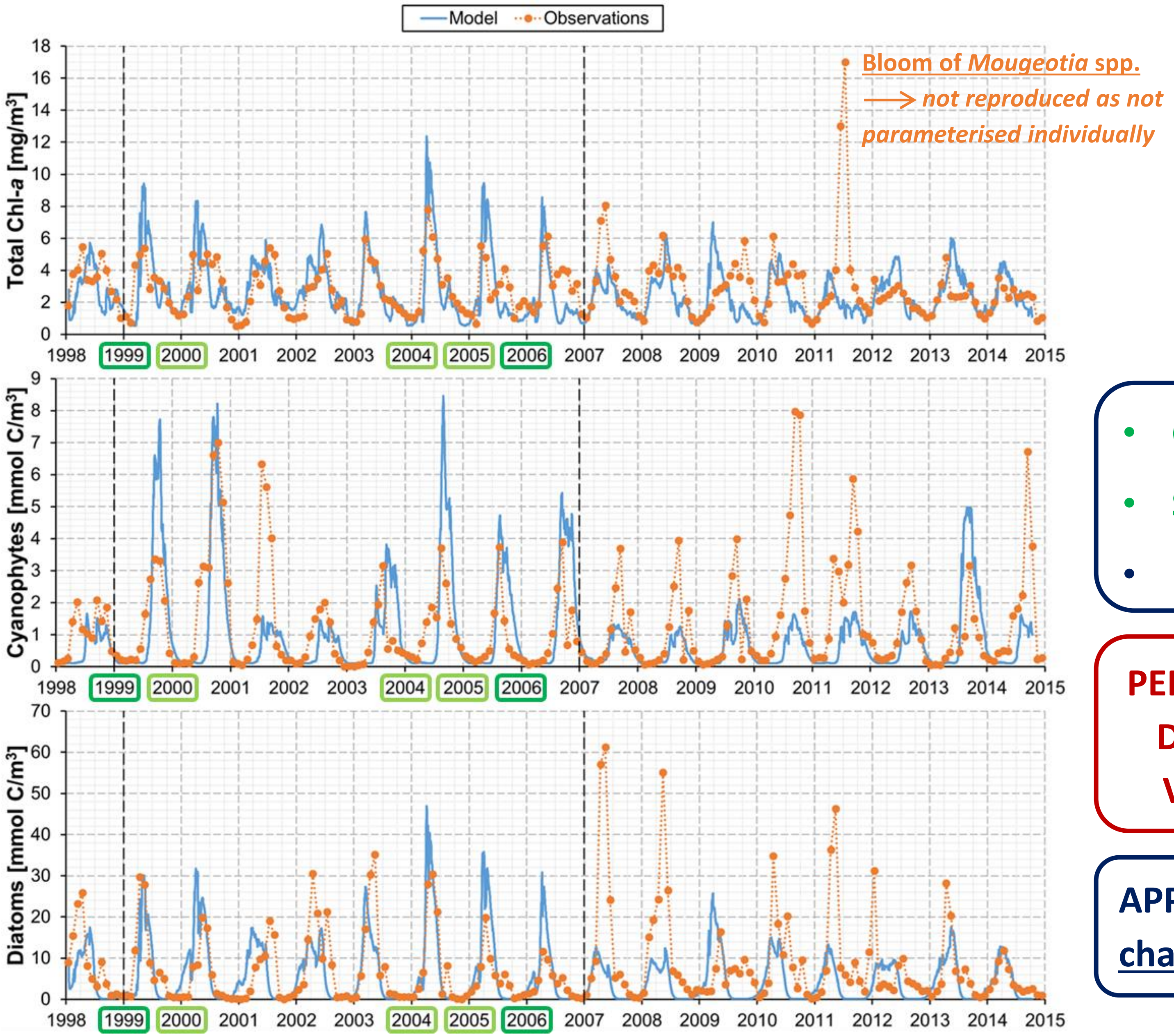
Fenocchi A., Rogora M., Morabito G., Marchetto A., Sibilla S., Dresti C. (2018). Applicability of one-dimensional coupled ecological-hydrodynamic numerical models to future projections in very deep large lakes: extended calibration and validation on Lake Maggiore (Northern Italy/Southern Switzerland). Ecological Modelling (*under review*).

SIMULATED DEEP-WATER CHEMISTRY



200 ÷ 370 m		CAL	VAL	Literature
O_2	R	0.83	0.79	0.88 ± 0.05
	NMAE	5%	7%	19% ± 10%
PO_4	R	0.61	0.70	0.60 ± 0.26
	NMAE	19%	12%	78% ± 27%

SIMULATED PHYTOPLANKTON SUCCESSION



(no 2011)

0 ÷ 20 m		CAL	VAL	Literature
Total Chl-*a*	R	0.69	0.19 (0.41)	0.36 ± 0.26
	NMAE	38%	44% (39%)	56% ± 24%
Cyanophytes	R	0.65	0.44	0.50 ± 0.29
	NMAE	69%	72%	69% ± 26%
Diatoms	R	0.70	0.40	0.29 ± 0.19
	NMAE	63%	78%	85% ± 34%

- CYCLING
- SUCCESSION AMONG GROUPS

Well reproduced

- BIOMASSES ⟶ *Larger errors*

PERFORMANCES DECREASE IN VALIDATION ➡ ***COMPOSITIONAL SHIFTS CANNOT BE SIMULATED***

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

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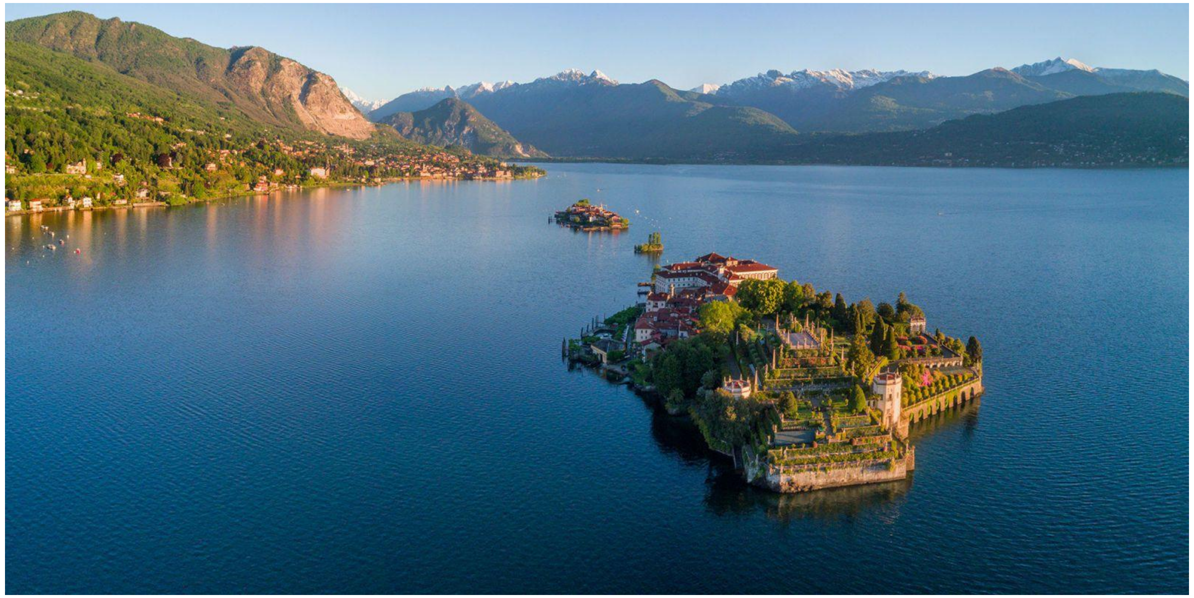

Thank you for your attention

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Verbania Pallanza

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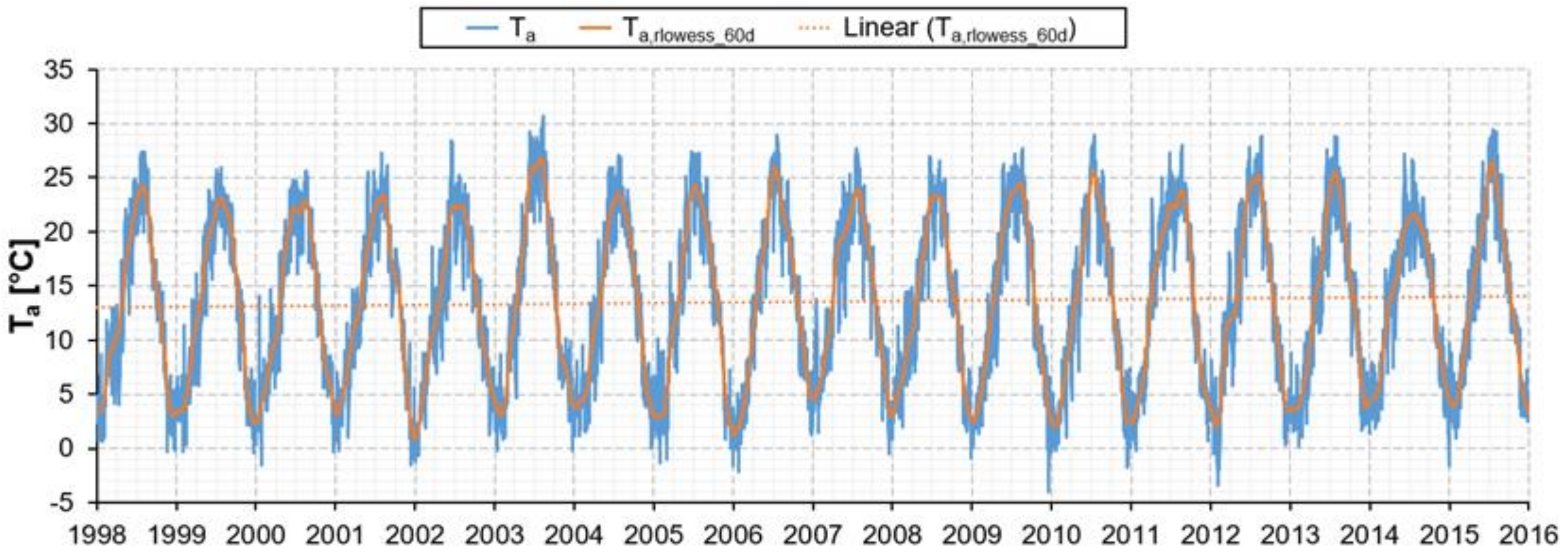
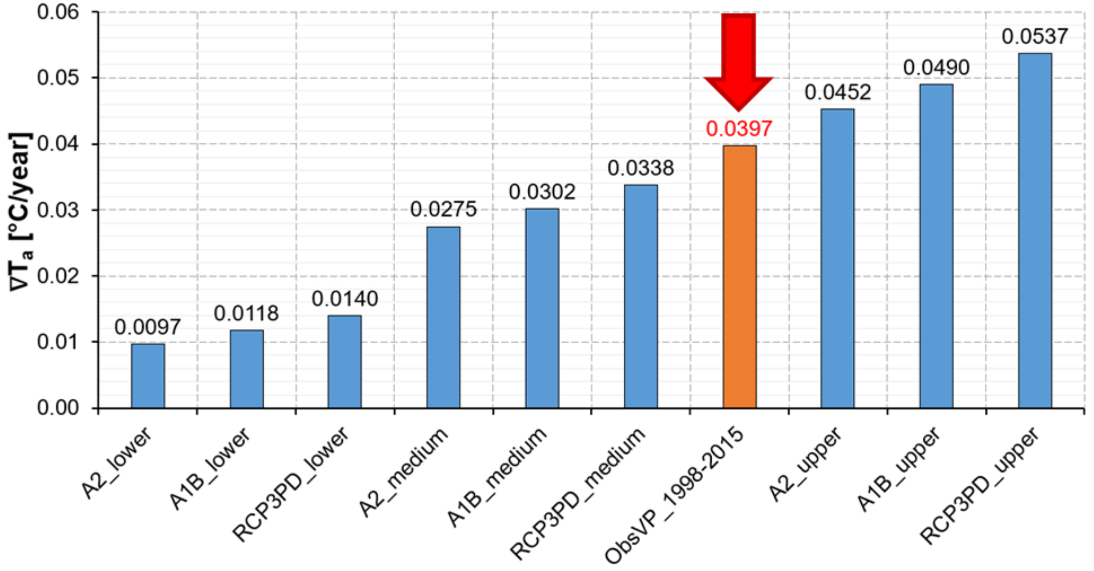
AIR TEMPERATURE WARMING

Observations at Verbania Pallanza:



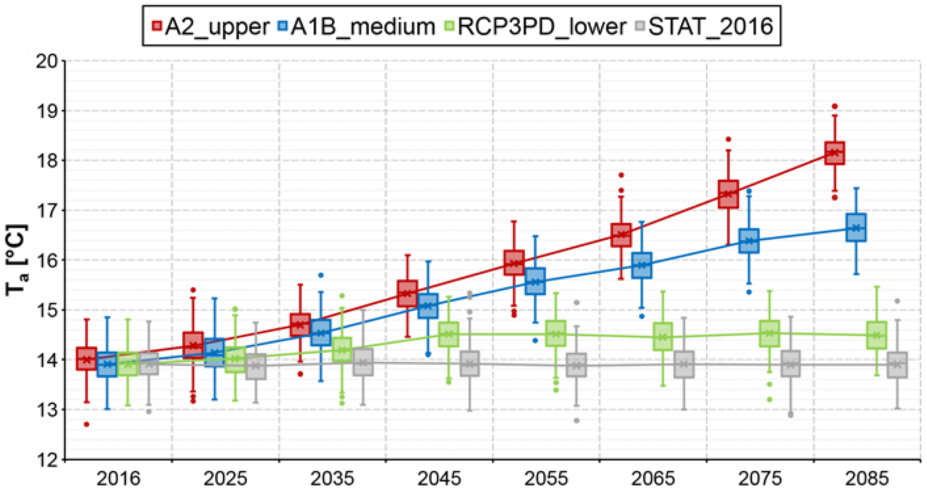
∇T_a = +0.0397 °C/year ⟶ ΔT_a = +0.71 °C

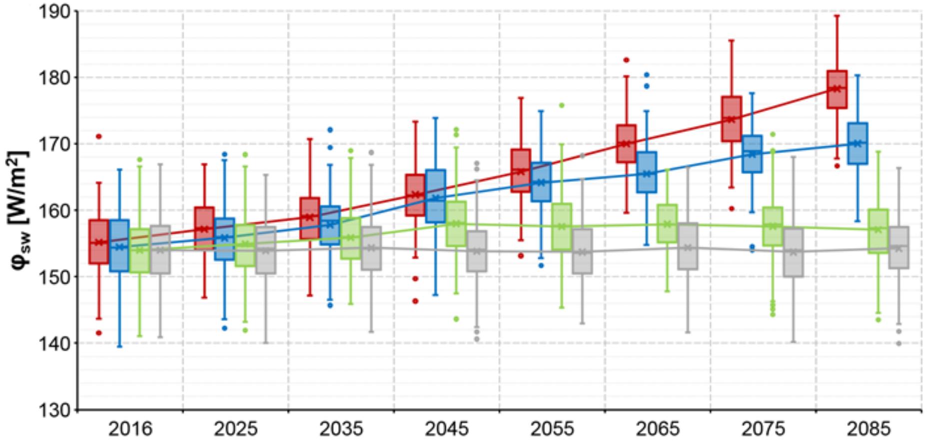
CH2011 mean annual gradients 1995-2025:



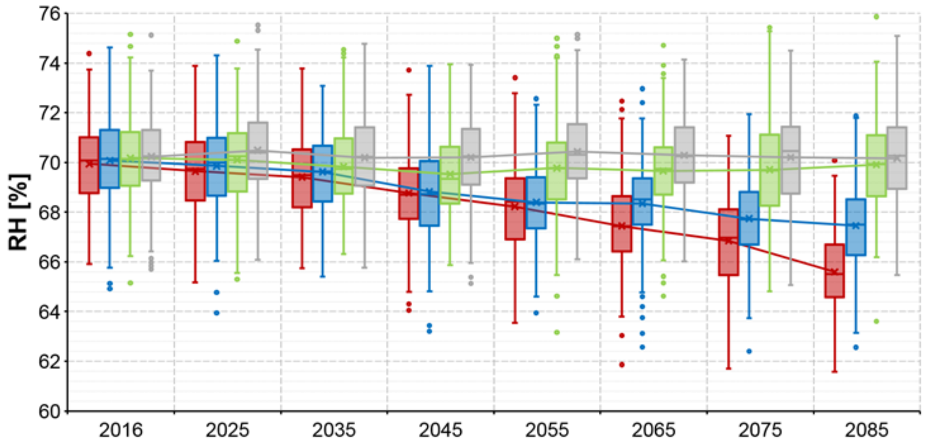
SIMULATED TRENDS OF METEOROLOGICAL VARIABLES

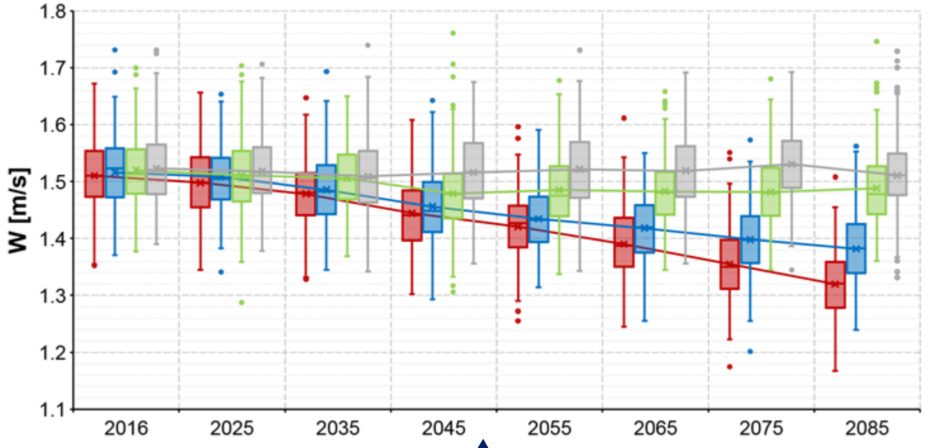
Statistical distributions of the 200 meteorological realisations from VG:





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

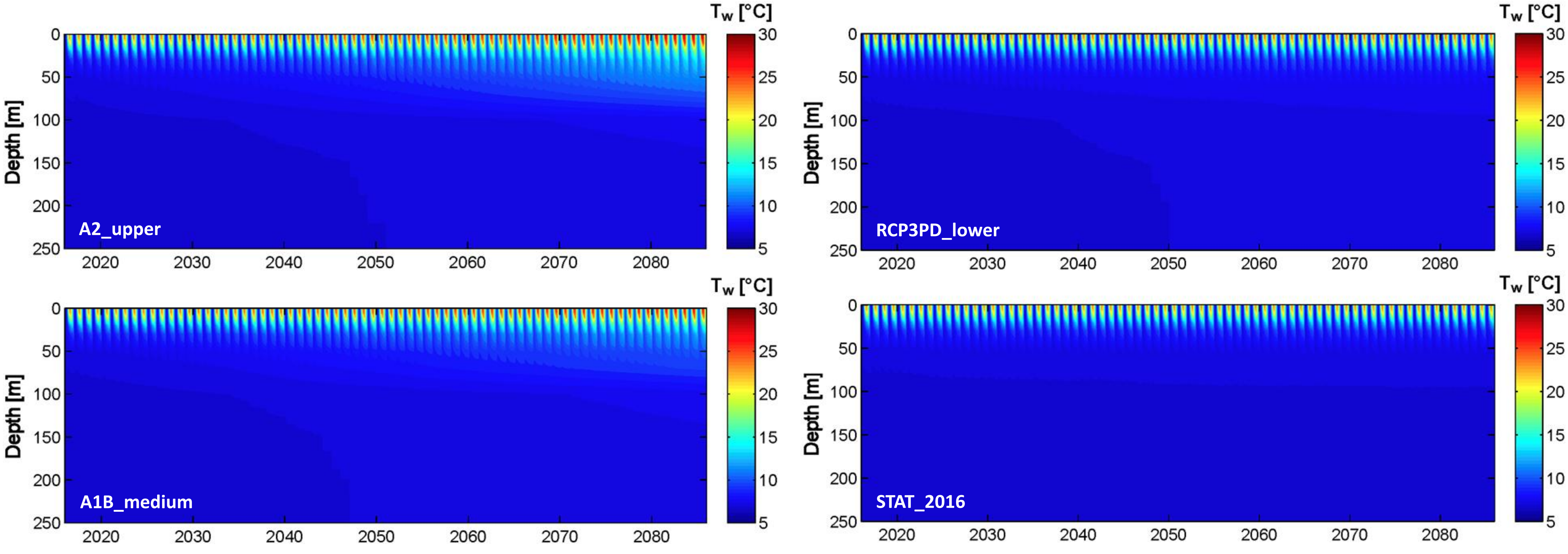




Observed trend on Lake Maggiore (Ambrosetti and Barbanti, 1999)

SIMULATED INCREASE OF STABILITY

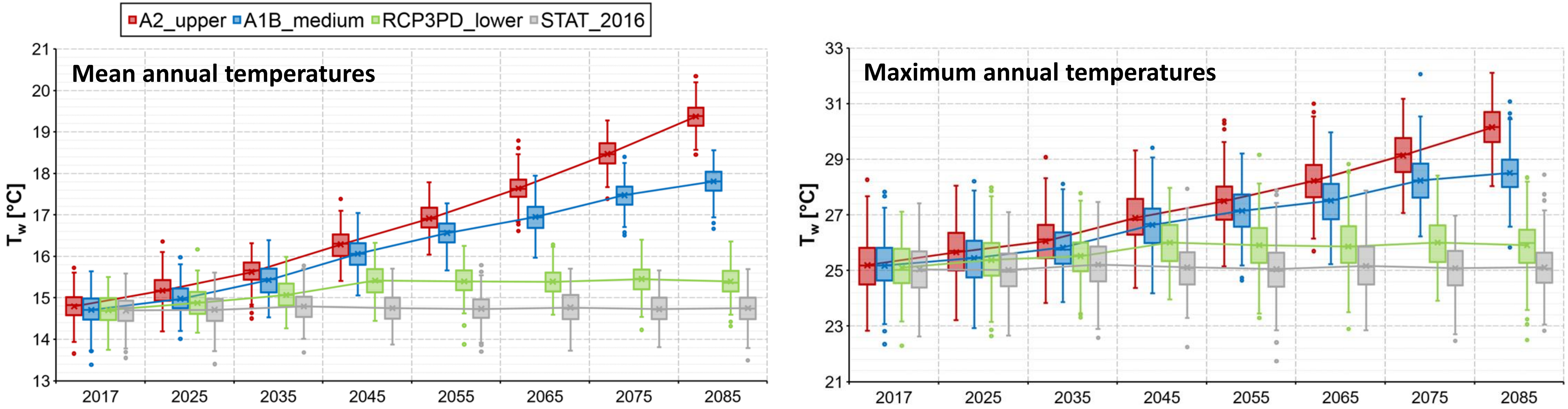
Evolution of the thermal structure averaged over the 200 realisations:



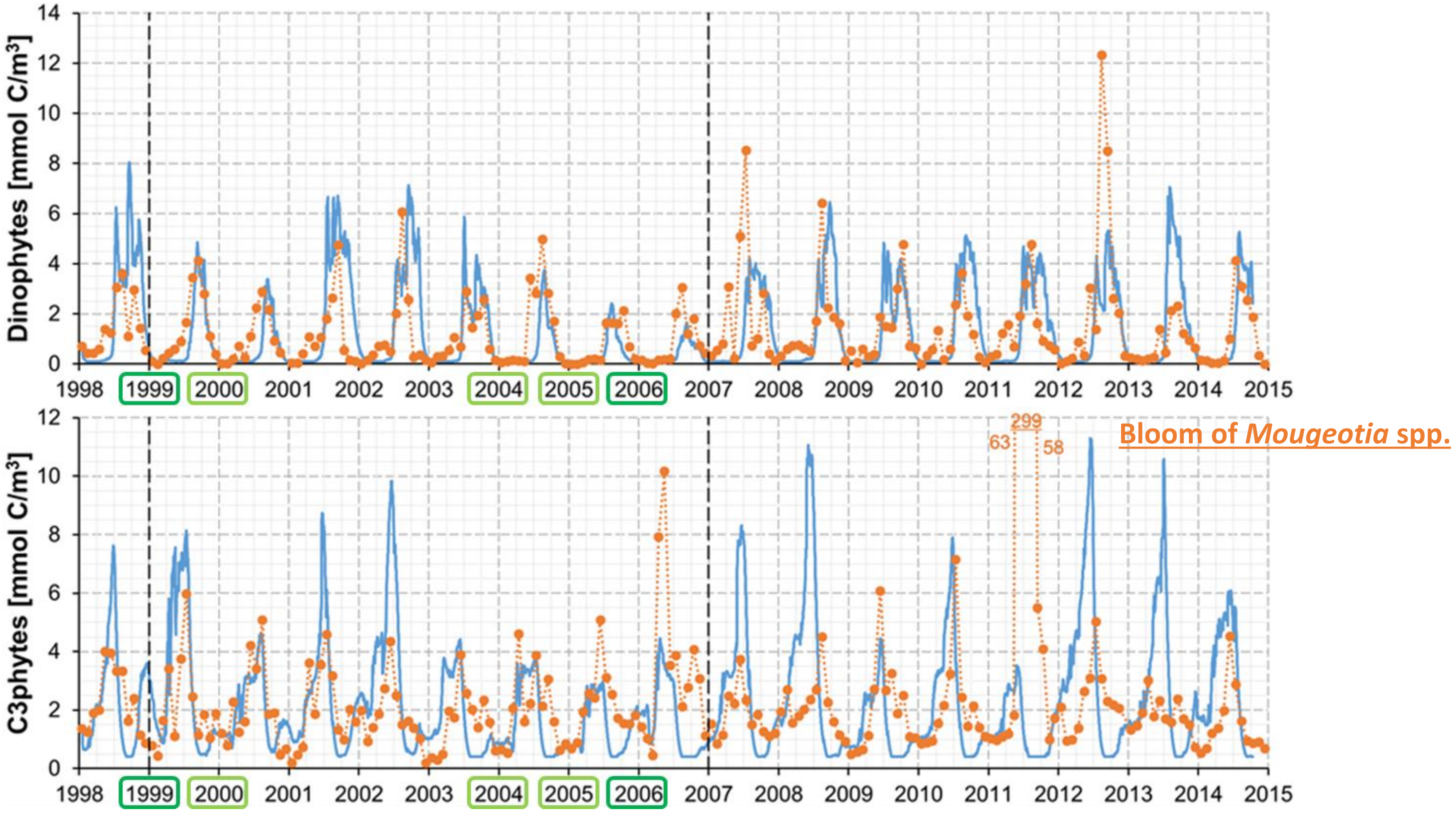
<u>Hypolimnion evolution is almost identical between mitigation and non-mitigation scenarios!</u>

SIMULATED SURFACE WATER WARMING

Statistical distributions of surface T_w over the 200 realisations:



SIMULATED PHYTOPLANKTON SUCCESSION

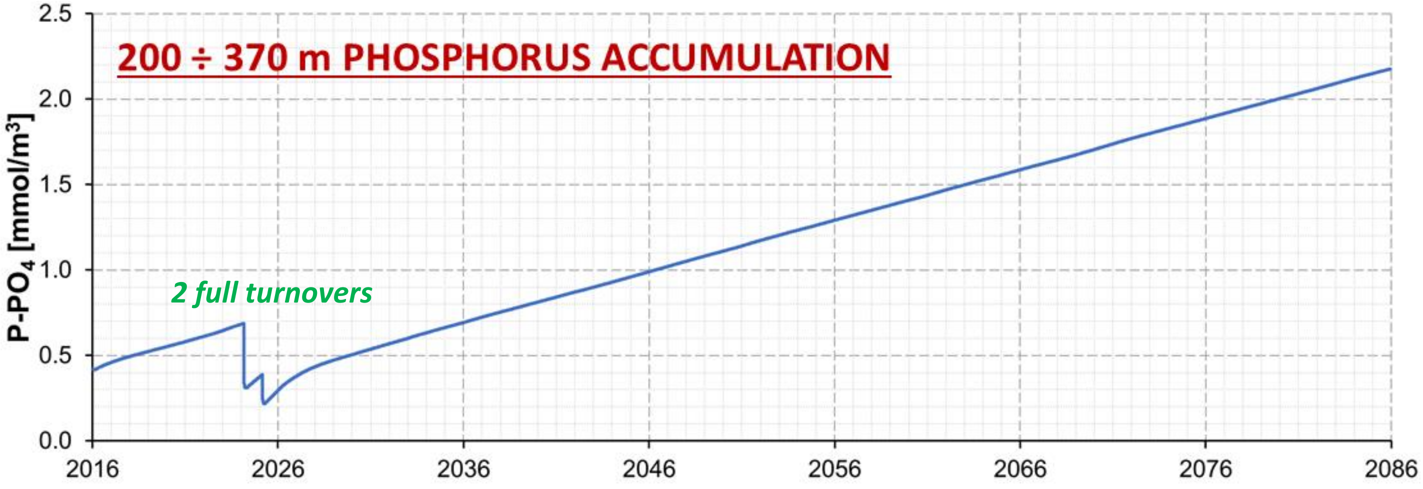


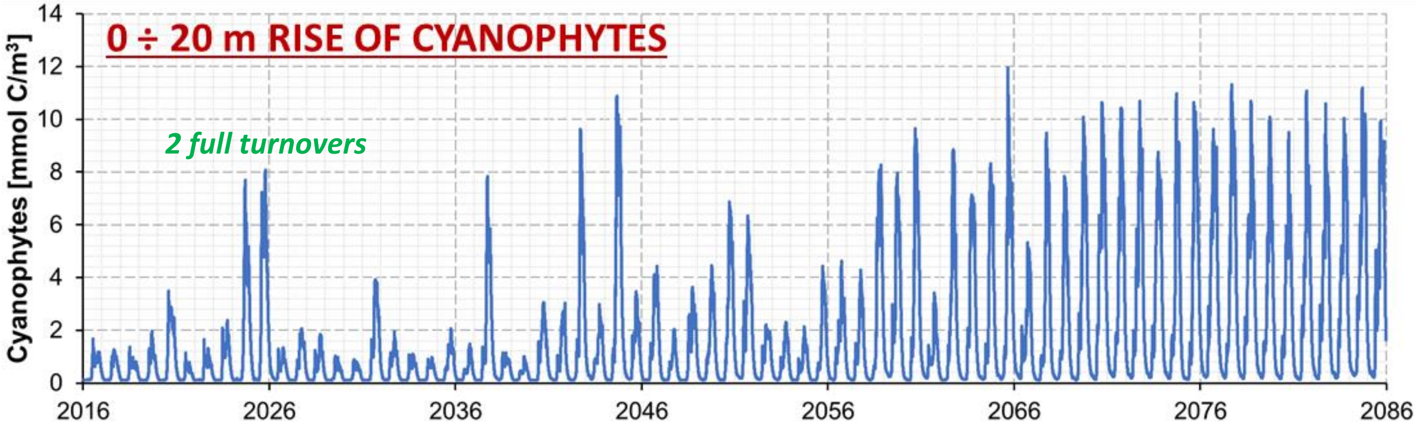
Full turnovers **Partial turnovers**

0 ÷ 20 m		CAL	VAL	Literature
Dinophytes	**R**	0.59	0.48	0.30 ± 0.01
	NMAE	72%	76%	64% ± 26%
C3phytes	**R**	0.49	-0.08 (0.37)	-
	NMAE	58%	94% (85%)	-

(no 2011)

COUPLED MODEL APPLICATION





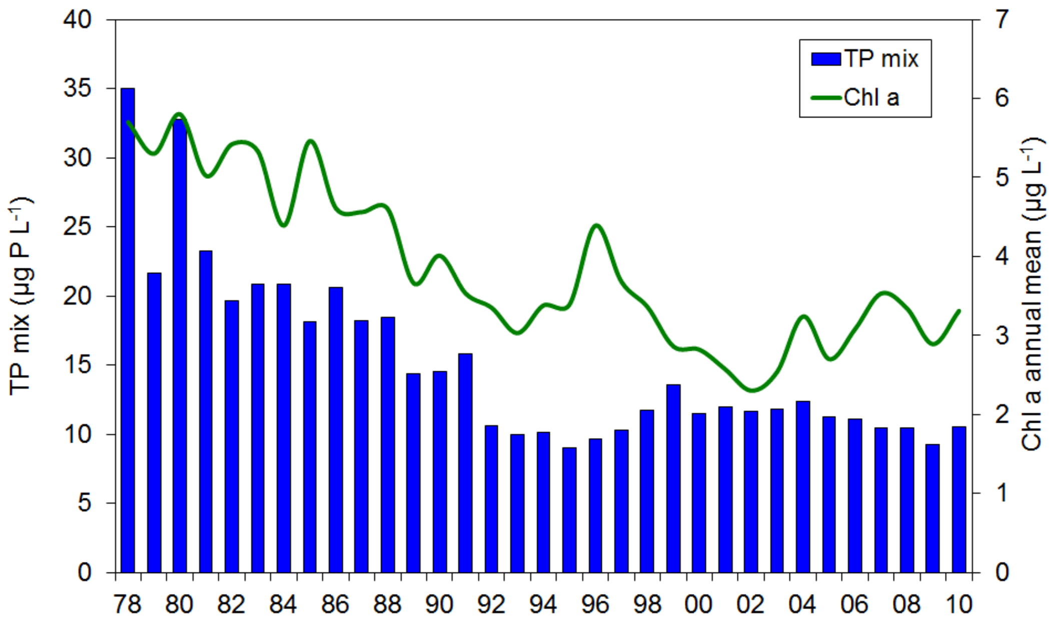
e.g.: SAMPLE SIMULATION WITH A2_UPPER CLIMATE CHANGE AND CURRENT NUTRIENT LOAD LEVELS

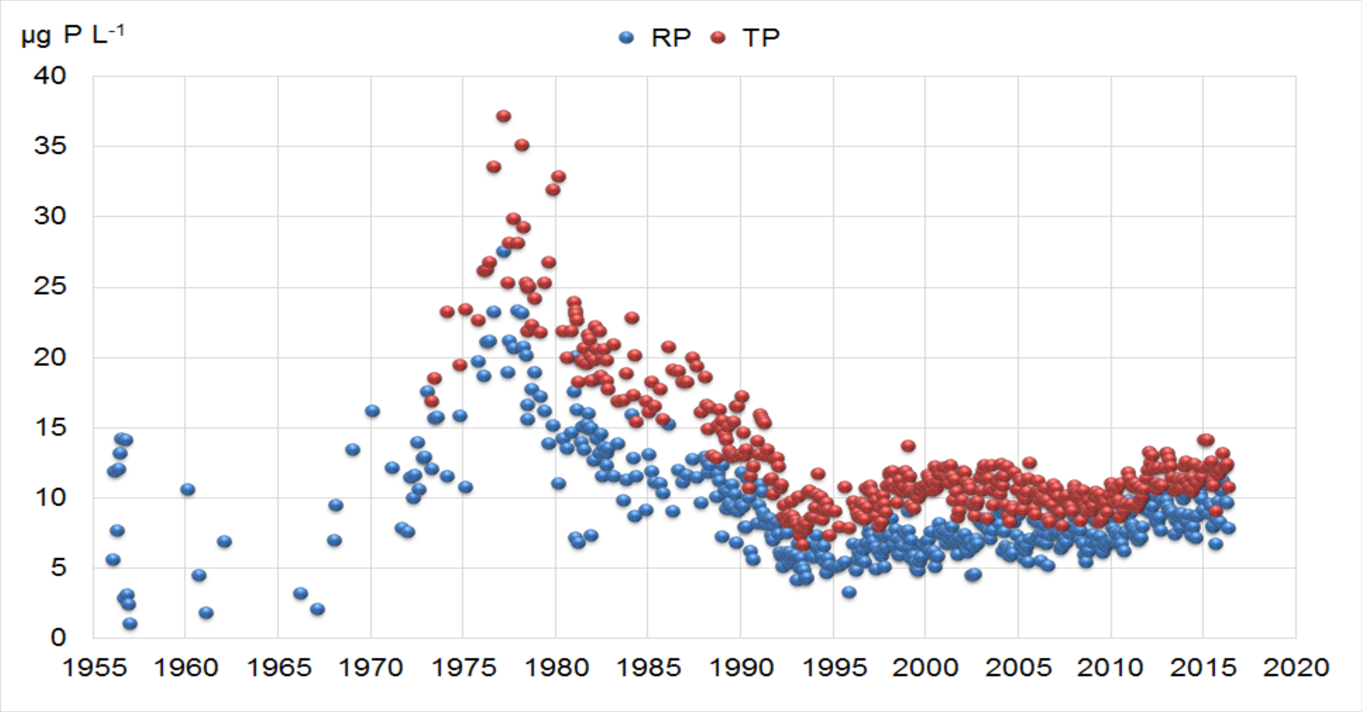
WARNING: PROVISIONAL RESULTS!

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 ÷ 35 µg P L^{-1}** in the **late 1970s** to **9 ÷ 10 µg P L^{-1}**





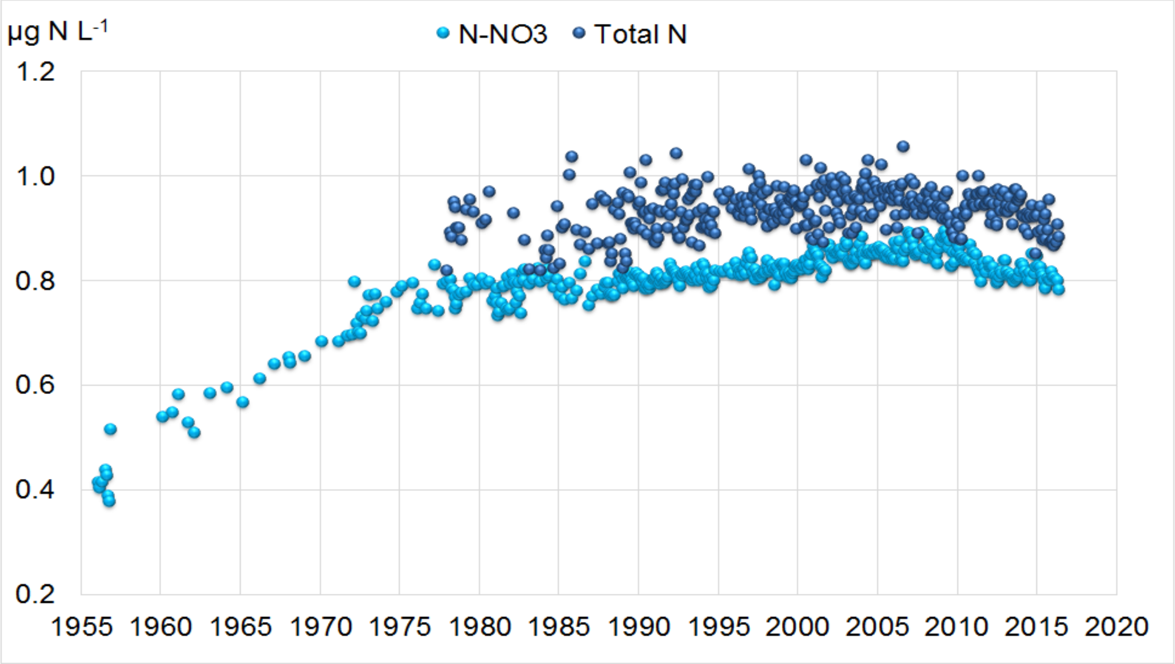
- A slight tendency towards **increasing TP values** has been observed in **recent years** (since 2010)

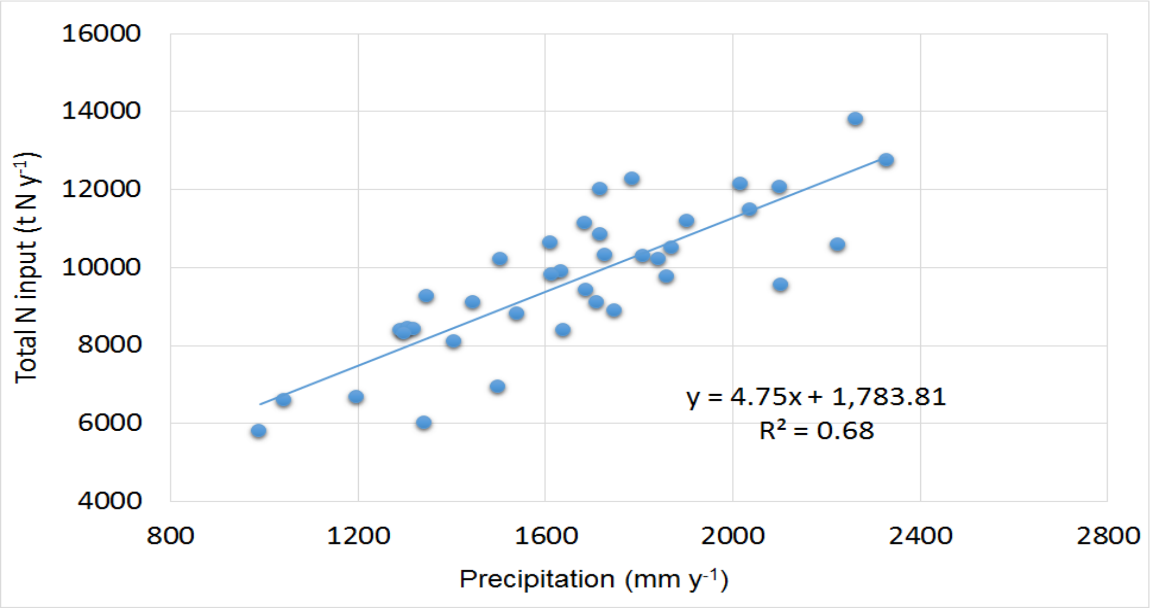
NITROGEN COMPOUNDS

- 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 ≈ 150**).

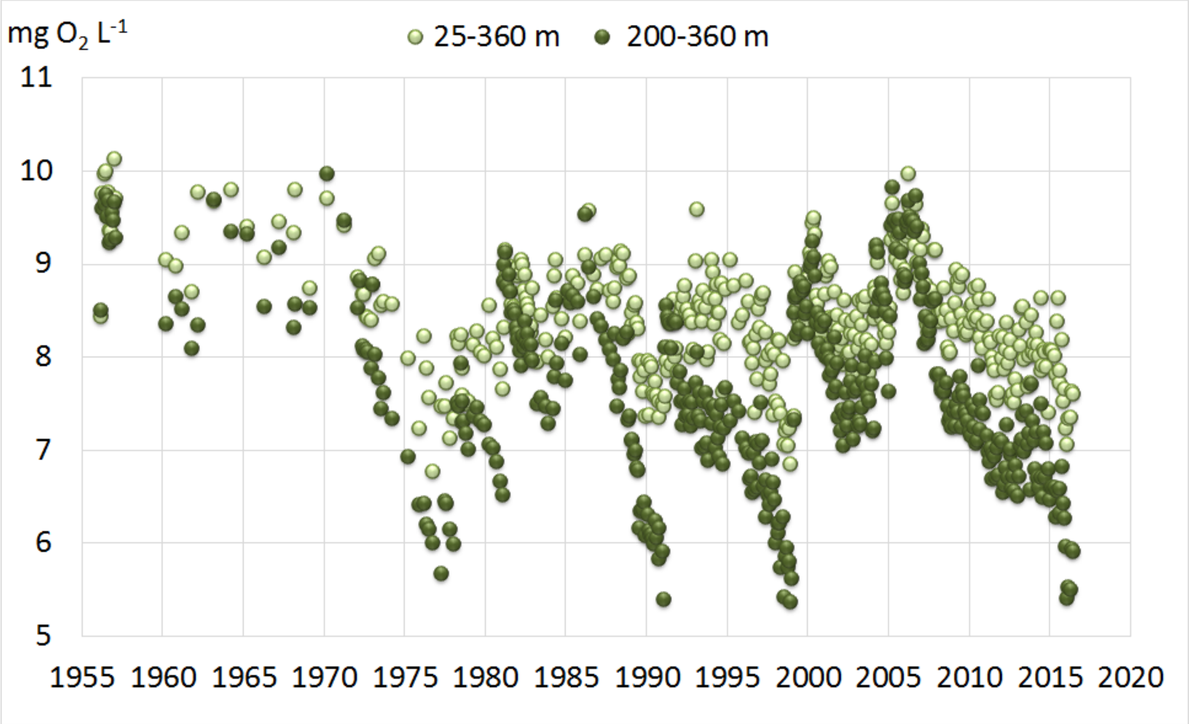




- The **main source of N** to the lake is **atmospheric deposition (60 ÷ 70%)**

OXYGEN TREND

- 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**