The Influence of Climate Change, Solar Brightening, and Water Clarity on Thermal Structure in Lake Hallwil, Switzerland

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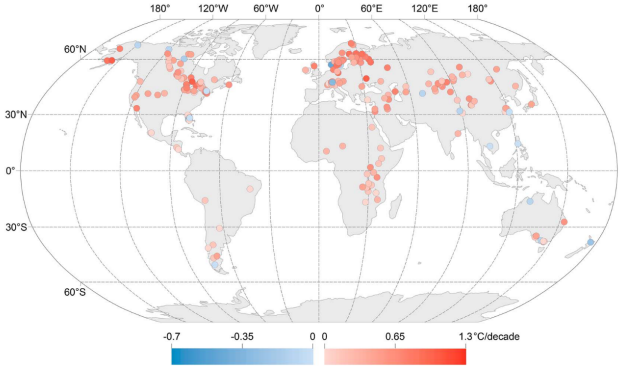
Department F.-A. Forel for environmental and aquatic sciences

Introduction

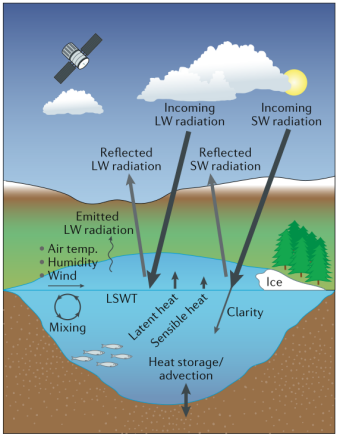


O'Reilly et al. (2015)

- Lake surface water are warming at 0.34 °C per decade.
- Longer stratification periods.
- Shifts in stratification regimes.
- Longer ice-free periods.
- Implications on oxygen concentrations, greenhouse gas emissions, redox cascade, etc.

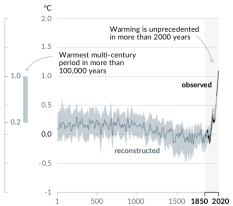
Woolway et al. (2020)

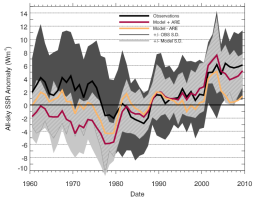
- Solar radiation.
- Air temperature.
- Humidity.
- Wind speed.
- Ice coverage.
- Water clarity and lake color.
- Lake morphology.



Woolway et al. (2020)

- Re-oligotrophication in European lakes ⇒ Increase of water clarity.
- Increase of air temperatures.
- Increase of incoming shortwave solar radiation (solar brightening).





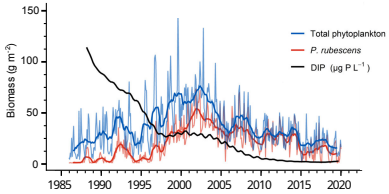
IPCC (2021) and Turnock et al. (2015)

Lake Hallwil

- Mesotrophic.
- Surf. Area: 10.2 km^2
- Max. Depth: 46 m

Data from 1985 to 2023

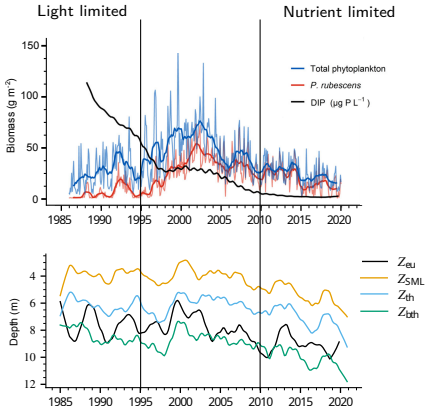
- Water column temperature profiles.
- Secchi disk depth.



Suarez et al. (2023)

Study Site

Methods



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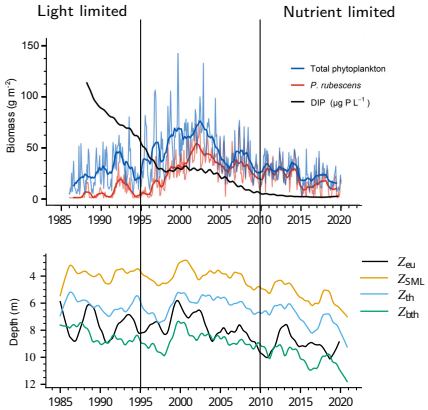

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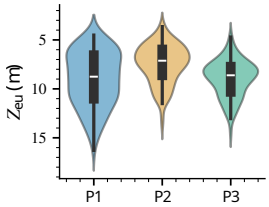
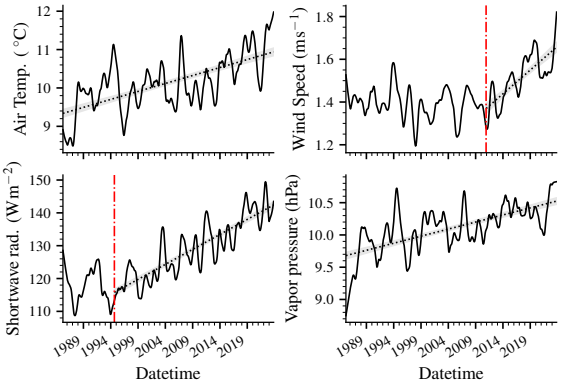


- Turbid face (P2) from 1995 to 2010 with average $Z_{eu} = 7.4$ m
- Clear face (P3) from 2010 to today with average $Z_{eu} = 8.9$ m

Lake and forcing trends

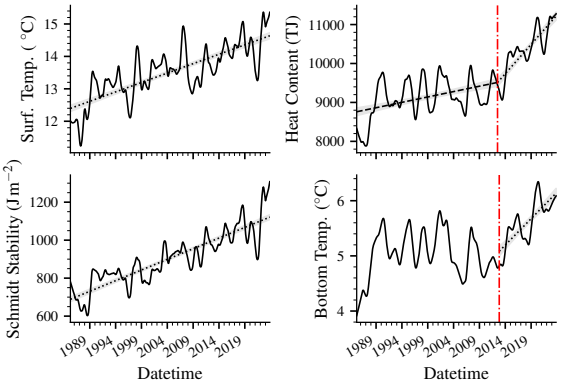
Results

- Constant increase in air temperature.
- Increase in solar radiation from 1995 to today.
- Increase in wind speed from 2011 to today.
- Constant increase in vapor pressure.



Lake and forcing trends

Results

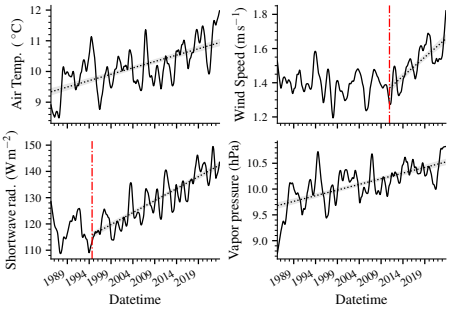


- Constant increase in surface temperature.
- Constant increase in Schmidt Stability.
- Increase in heat content with higher increasing rate from 2013.
- Increase in bottom temperature with a higher increasing rate from 2013.

Model

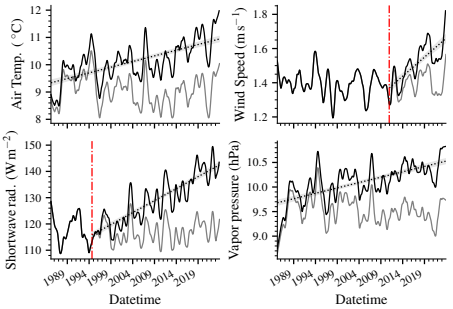
- Simstrat 3.0
- Lake Calibration: EAWAG
- Simulation from 1981 to 2023
- Weather Forcing: Lucerne

	R^2	RMSE	BIAS
Surf. Temp (°C)	0.99	0.78	-0.1
Temp. Profile (°C)	0.97	0.78	0.2
Schmidt St. ($J\,m^{-2}$)	0.98	117	-44
Heat Content (TJ)	0.97	465	167



Scenarios

- Air Temp.: Only consider air temperature increase.
- SW Rad: Only consider the increase of solar radiation from 1995.
- Wind: Only consider the increase of wind speed from 2011.
- Vap. pres.: Only consider the increase of vapor pressure.



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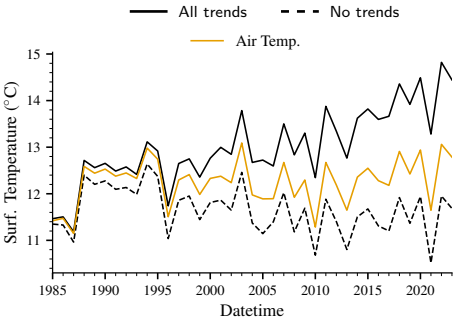
Contributions Atmospheric Forcing

Results



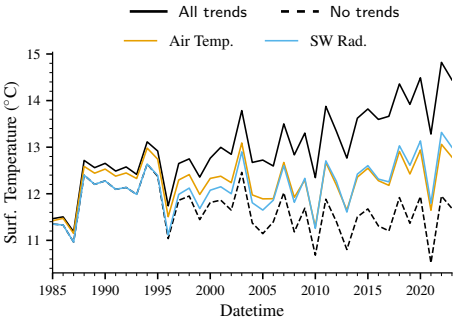
$$\text{Cont}_{\text{m,i}}\ [\%] = 100\frac{\int_{t_c}^{t_f}(y_{\text{m,i}} - y_{\text{none,i}})dt}{\int_{t_c}^{t_f}(y_{\text{all,i}} - y_{\text{none, i}})dt}$$

Percentage of the total change from the "no trend".

	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45		
SW Rad.			
Vapor Pres.			
Wind Speed			

Contributions Atmospheric Forcing

Results



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Vapor Pres.			
Wind Speed			

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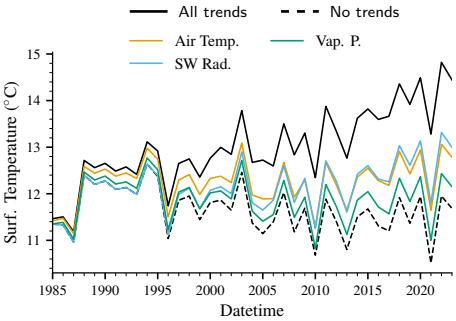

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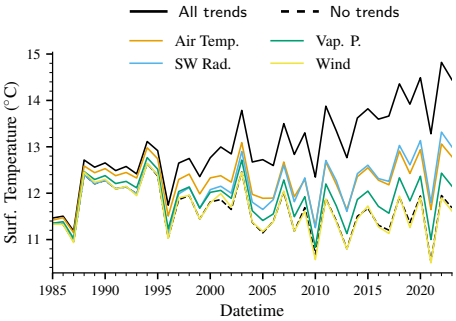
Percentage of the total change from the "no trend".

	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45		
SW Rad.	45		
Vapor Pres.	18		
Wind Speed			

Contributions Atmospheric Forcing

Results



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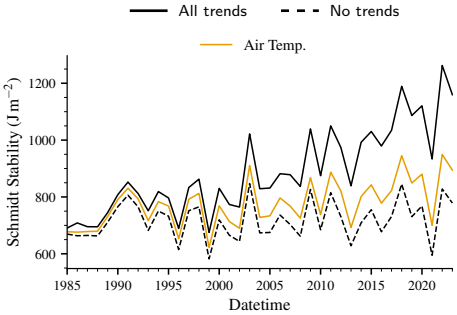
	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45		
SW Rad.	45		
Vapor Pres.	18		
Wind Speed	-0.7		

Contributions Atmospheric Forcing

Results



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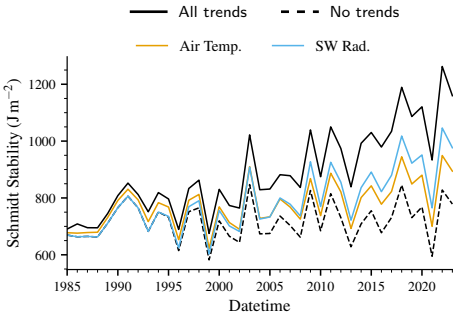
Percentage of the total change from the "no trend".

	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45	34	
SW Rad.	45		
Vapor Pres.	18		
Wind Speed	-0.7		

Contributions Atmospheric Forcing

Results



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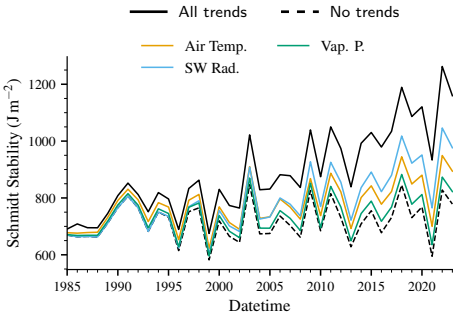
Percentage of the total change from the "no trend".

	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45	34	
SW Rad.	45	50	
Vapor Pres.	18		
Wind Speed	-0.7		

Contributions Atmospheric Forcing

Results



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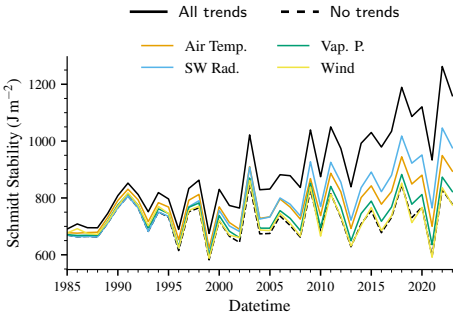

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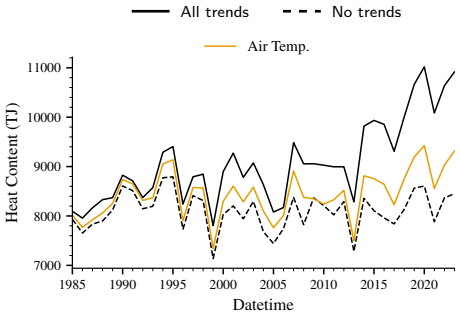
Percentage of the total change from the "no trend".

	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45	34	
SW Rad.	45	50	
Vapor Pres.	18	13	
Wind Speed	-0.7	2.3	

Contributions Atmospheric Forcing

Results



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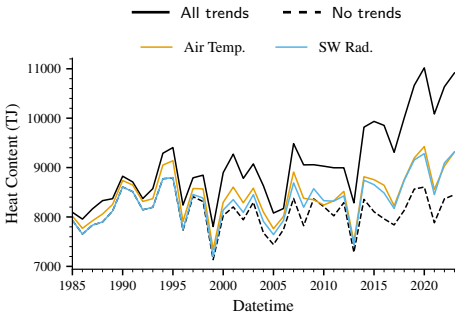

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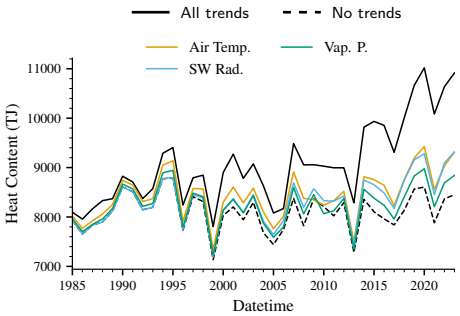
Percentage of the total change from the "no trend".

	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45	34	35
SW Rad.	45	50	28
Vapor Pres.	18	13	
Wind Speed	-0.7	2.3	

Contributions Atmospheric Forcing

Results



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SW Rad.	45	50	28
Vapor Pres.	18	13	14
Wind Speed	-0.7	2.3	

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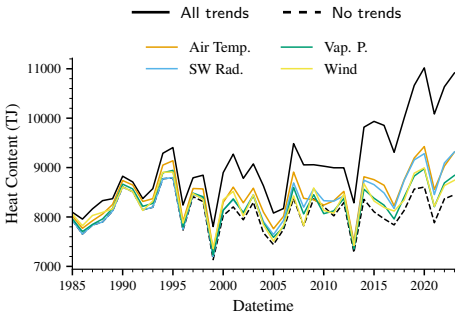
Results



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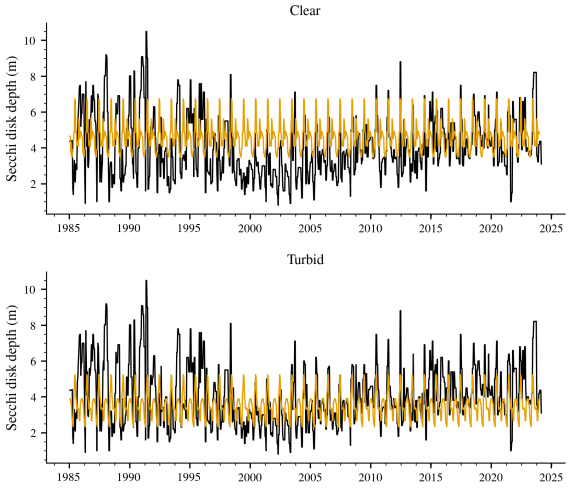
Percentage of the total change from the "no trend".

	Surf. Temp.	Schmidt Stability	Heat Content
Air Temp.	45	34	35
SW Rad.	45	50	28
Vapor Pres.	18	13	14
Wind Speed	-0.7	2.3	15

Changes on Water Clarity

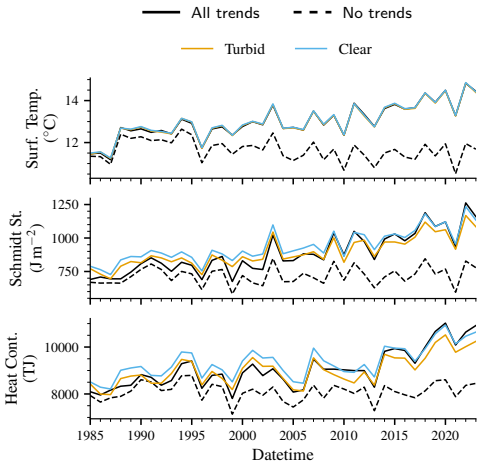
Results



- Case clear - Average Secchi depth $= 4.7 \pm 0.8$ m
- Case turbid - Average Secchi depth $= 3.7 \pm 0.7$ m

Changes on Water Clarity

Results



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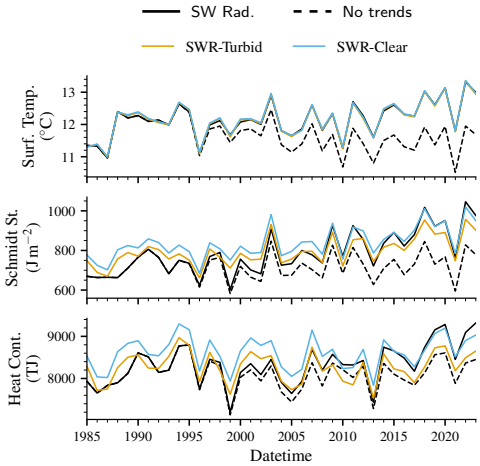
Percentage of change from measured-light scenario if the lake was turbid from 2010 until 2023.

	Surf. Temp.	Schmidt Stability	Heat Content
Turbid	0	-14	-22
SWR-Turbid			
AirT-Turbid			

Changes on Water Clarity

Results



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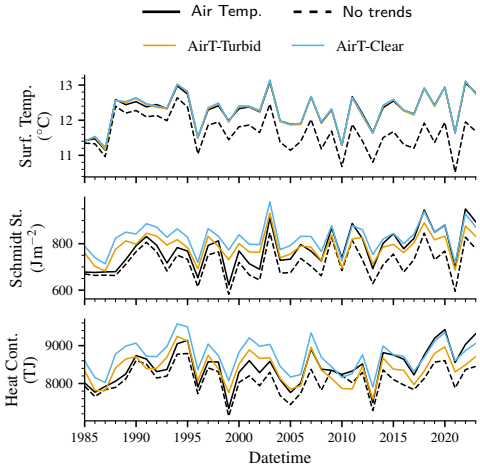
Percentage of change from measured-light scenario if the lake was turbid from 2010 until 2023.

	Surf. Temp.	Schmidt Stability	Heat Content
Turbid	0	-14	-22
SWR-Turbid	2	-15	-70
AirT-Turbid			

Changes on Water Clarity

Results



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Percentage of change from measured-light scenario if the lake was turbid from 2010 until 2023.

	Surf. Temp.	Schmidt Stability	Heat Content
Turbid	0	-14	-22
SWR-Turbid	2	-15	-70
AirT-Turbid	1	-35	-63

Conclusions

Atmospheric Forcing

- The increase of air temperature and solar radiation are the most important drivers controlling the heat budget in Lake Hallwil.
- Whereas the increase of wind speed seems to transfer heat to deep waters, have not affected the surface temperature of Lake Hallwil.

Water Clarity

- It does not produce any clear effect on surface temperature.
- Increase of water clarity enhance the effect of the increase of solar radiation and air temperature.

Implications

- It is necessary to include changes on water transparency for future projections.
- Changes on water clarity due to re-oligotrophication or invasive species (e.g. Quagga mussels) could increase the heat content in lakes.
- Understand heat distribution in lakes, and not only surface temperatures.
- Increase of water temperature could enhance reactions rates.

Lake Hallwil

Acknowledgment

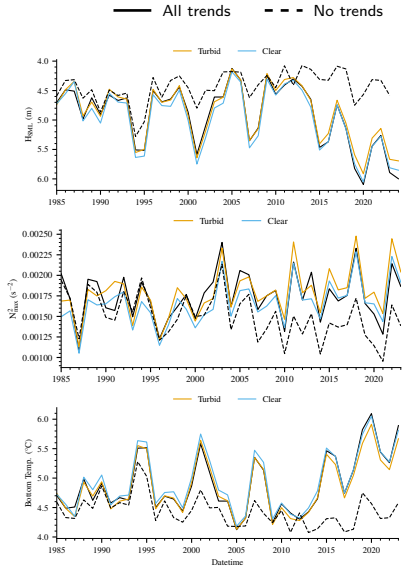
KANTON AARGAU

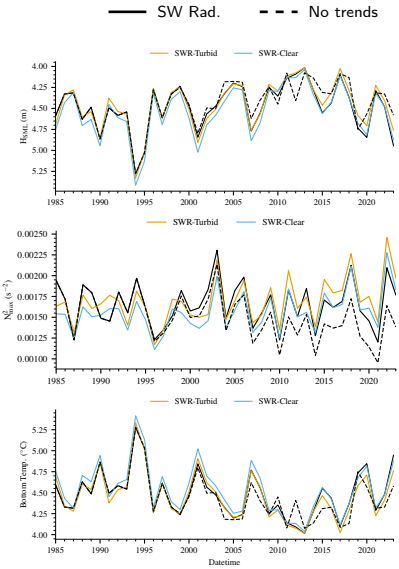
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

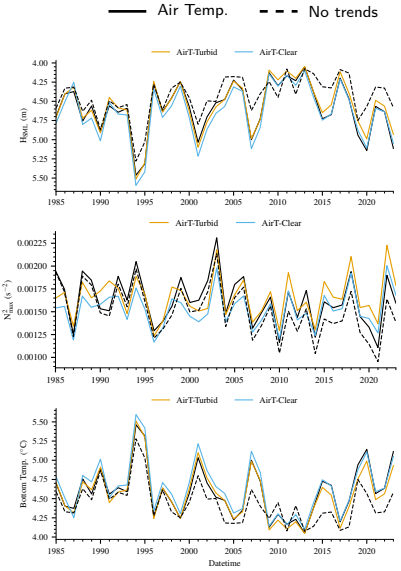
Federal Office of Meteorology and Climatology MeteoSwiss

UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE
Department F.-A. Forel for environmental and aquatic sciences

eawag aquatic research


All trends
No trends
Turbid
Clear
$H_{bot.}$ (m)
$N^2_{Min.}$ (s^{-2})
Bottom Temp. (°C)
Datetime


SW Rad.
No trends
SWR-Turbid
SWR-Clear
H_{SML} (m)
N^2_{SML} (s^{-2})
Bottom Temp. (°C)
Datetime


Air Temp.
No trends
AirT-Turbid
AirT-Clear
$H_{Strt.}$ (m)
$N^2_{Bot.}$ (s^{-2})
Bottom Temp. (°C)
Datetime