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Floating photovoltaics and lake thermal responses: monitoring-based assessment of meteorological drivers across contrasting climates

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Abstract. Floating photovoltaic (FPV) systems influence lake heat budgets by altering radiative input, wind exposure, and air–water heat exchange. However, harmonised field observations describing these processes across contrasting climatic settings and FPV system designs remain scarce, limiting the calibration and validation of hydrodynamic and ecological impact assessments. Here, we present a high-resolution monitoring dataset from three sites: Lake Toules (deep alpine reservoir, elevated open design, Switzerland), Lake Sekdoorn (humid lowland lake, dense east–west design, Netherlands), and Lake Leimersheim (shallow temperate–continental lake, low-profile design, Germany). Water temperature anomalies between FPV-covered and open-water sites (ΔT_w) can be analysed analysed during cold- and warm-period extremes. Water temperature anomalies between FPV-covered and open-water sites (ΔTw) can be analysed during cold- and warm-period extremes. The dataset captures cooler conditions beneath FPV at Toules (–0.12 °C) and Leimersheim (–0.04 °C) but warmer conditions at Sekdoorn (+0.14 °C) during cold periods. Warm-period extremes amplified these contrasts, with alternating cooling and warming at Toules (–0.06 °C mean), negligible differences at Sekdoorn, and strong shading-driven cooling at Leimersheim (–0.55 °C). While mean differences were small, short-term deviations reached –0.75 to +0.5 °C, reflecting variable meteorological forcing. The observations further encompass contrasting meteorological controls and seasonal transitions between lake mixing regimes. Seasonal analysis of the large-scale system at Lake Sekdoorn revealed regime-dependent shifts: air temperature dominated during fully mixed winter conditions, shortwave radiation during stratification onset, and wind speed during stable summer stratification. The ΔT_w–air temperature relationship reversed from positive in winter (heat retention) to negative in summer (shading-driven cooling), dampening the seasonal amplitude of surface water temperatures. All monitoring systems were harmonised across sites and synchronised using a common data acquisition framework. The dataset enables applications ranging from hydrodynamic model calibration and FPV impact parameterisation to comparative assessments across climatic regions and system designs. The underlying monitoring dataset is openly available at https://doi.org/10.5281/zenodo.21156967.

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1 Introduction

Floating photovoltaic (FPV) systems are increasingly deployed on inland water bodies to expand renewable energy production while alleviating land-use conflicts. Beyond their technological and economic potential, FPV installations interact with the underlying aquatic environment, altering heat fluxes, wind fields, and light penetration. These physical changes can influence lake water temperature regimes, with implications for thermal stratification, mixing processes, and associated ecological dynamics (Li et al., 2022; Nobre et al., 2023; Ilgen et al., 2025). Such interactions are of particular relevance in the context of climate change and sustainable water resource management.

Previous studies have reported FPV-induced cooling effects and modifications of stratification stability (de Lima et al., 2021; Ilgen et al., 2023; Nobre et al., 2025); however, the magnitude and direction of these responses vary widely between sites. This variability is likely shaped by a combination of FPV system design characteristics and prevailing meteorological conditions, while the specific role of individual meteorological drivers remains insufficiently quantified. Variations in drivers such as wind speed, incoming solar irradiance, and air temperature across climatic regions may, for example, amplify or mitigate FPV-induced temperature changes. The temporal dynamics of these effects remain poorly understood, with initial studies indicating that, even when the net annual impact of FPV on water temperature is small, pronounced seasonal deviations can occur (Ilgen et al., 2023; Liu et al., 2024; Prandini et al., 2025), while FPV impacts during intra-annual meteorological extremes – expected to become more frequent and intense under climate change (Seneviratne et al., 2012) – remain largely unexplored. A better understanding of these seasonal and extreme-condition responses is critical for accurately predicting FPV impacts under future climate scenarios, guiding system design, and ensuring environmentally sustainable deployment. Furthermore, harmonised observations across multiple climatic regions remain scarce, limiting the development, calibration, and validation of transferable hydrodynamic and ecological impact assessments.

The present study introduces a harmonised high-resolution monitoring dataset from three FPV-covered lakes in contrasting climatic settings and with distinct system designs. The dataset combines meteorological observations with depth-resolved water temperature measurements beneath FPV systems and at adjacent open-water reference locations, complemented by campaign-based water quality observations. The measurements encompass seasonal transitions between lake mixing regimes as well as periods of meteorological extremes, thereby capturing a broad spectrum of FPV–lake interactions. By providing observations across contrasting climatic settings, lake morphologies, and FPV configurations, the dataset supports comparative analyses and improves the empirical basis for understanding FPV–lake interactions. Furthermore, it enables applications such as hydrodynamic model calibration and validation, the development of FPV impact parameterisations, and future assessments of environmentally sustainable FPV deployment.

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2 Materials and Methods

2.1 Study sites and FPV configurations

The dataset was collected at three artificial lakes in Europe hosting FPV systems that differ markedly in morphology, climatic setting, system configuration, and surface coverage (Fig. 1).

Lake Toules (Switzerland) – This high-altitude reservoir (58.5 ha, max. depth 70 m) lies at 1,808 m a.s.l. in the canton of Valais and serves primarily for hydropower generation. Water levels fluctuate seasonally by up to 50 m due to operational drawdown. The oligotrophic lake exhibits persistently high turbidity from sediment-rich inflows of the River Dranse. The regional climate is alpine, characterised by low air temperatures, frequent snowfall, and prolonged winter ice cover. The FPV array has a capacity of 0.45 MWp and covers approximately 1% of the lake surface. It consists of elevated bifacial modules (35° tilt, south-facing) mounted on multiple platforms. During the first half of the year, the structure rests on the lakebed due to hydropower drawdown and refloats following reservoir refilling. Solar irradiance and near-surface wind speed beneath the FPV array are reduced by about 50% and 33%, respectively.

Lake Sekdoorn (Netherlands) – Situated in the province of Overijssel, this mesotrophic sand pit lake (38 ha, max. depth 27 m) lies about 3 m below sea level and is sustained by groundwater exchange without riverine surface inflow or outflow. The temperate oceanic climate is characterised by mild winters, moderate summers, high humidity, and frequent precipitation. The FPV system, with an installed capacity of 14.5 MWp, covers 26% of the lake surface. It employs a rafted-float structure with monofacial modules in a 12° east–west orientation, representing a dense, large-scale deployment. Beneath the array, both irradiance and near-surface wind speed are reduced by approximately 95%.

Lake Leimersheim (Germany) – Located in the Upper Rhine Valley, this groundwater-fed gravel pit lake (19 ha, max. depth 19 m) exhibits oligo- to mesotrophic conditions. The temperate continental climate features warm summers with occasional hot days (>30 °C) and relatively cold winters with limited snowfall. The FPV system has a capacity of 1.5 MWp and covers approximately 8% of the lake surface. It employs a modular pure-float design with monofacial modules tilted 12° south. Beneath the array, solar irradiance and near-surface wind speed are reduced by 88% and 57%, respectively.

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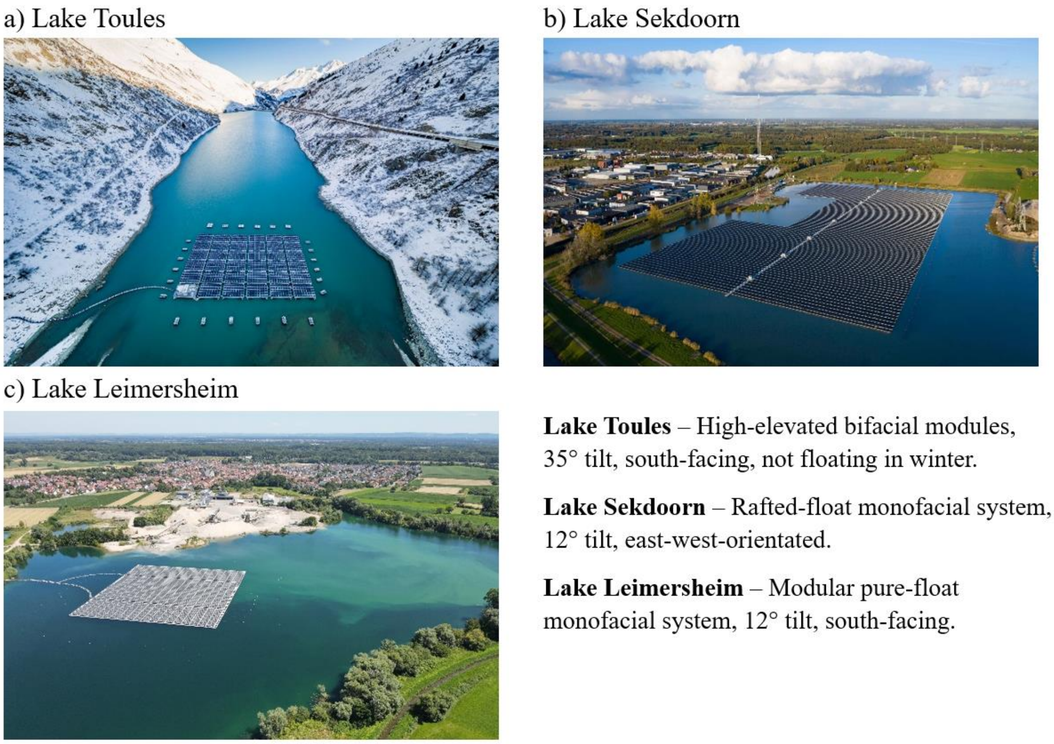

Figure 1: Floating photovoltaic (FPV) power plants at the three study sites (photos: Romande Energie Holding SA, BayWa r.e. AG, Fraunhofer ISE).

2.2 Monitoring approach

A harmonised monitoring setup was implemented at all sites to provide comparable observations of lake microclimate and near-surface conditions beneath FPV systems and at adjacent open-water reference locations (Fig. 2). The monitoring setup was installed during 2023 with varying starting dates across sites, but all locations provided complete annual coverage for 2024. Each FPV installation was equipped with a climate station (WS510-UMB, Lufft) mounted on the array, continuously recording at 15-minute intervals: global horizontal irradiance (accuracy <1% at 1000 W m^{-2}), wind speed (accuracy ± 0.3 m s^{-1} for 0–35 m s^{-1}, ± 5% for > 35 m s^{-1}), wind direction (accuracy < 3° RMSE for > 1 m s^{-1}), air temperature (accuracy ±0.2 °C for –20 to 50 °C, otherwise ± 0.5 °C), and relative humidity (accuracy ± 2% RH). Long-wave radiation fluxes were additionally measured at the system centre at module height using a pyrgeometer (SGR3, Kipp & Zonen; accuracy < 5%).

Thermal stratification and temperature gradients were assessed using thermistor chains (accuracy ±0.1 °C) deployed beneath the FPV system (MFPV) and in adjacent open water (MREF I). Each chain extended 10 m into the water column, with temperature measurements recorded at 0.5 m vertical intervals and an hourly temporal resolution. Instrument setups were

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standardised across sites, and all sensors were synchronised via a daisy-chain Modbus network to ensure continuous and temporally aligned data acquisition.

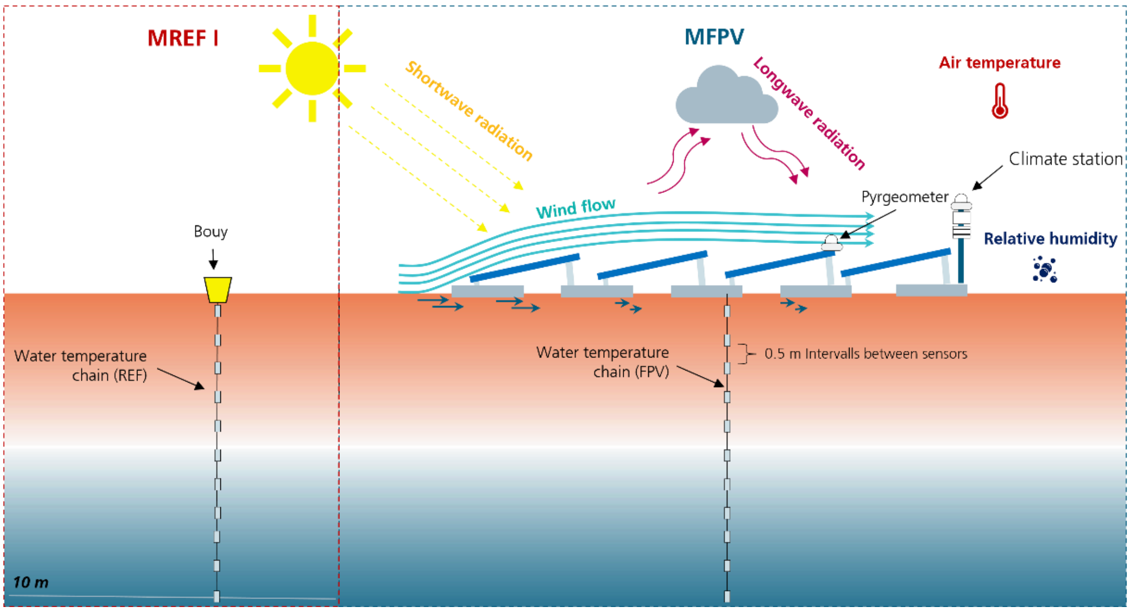

Figure 2: Schematic overview of the monitoring setup showing the open-water reference site (MREF I) and the FPV-covered site (MFPV). Both locations are equipped with vertical water temperature chains. Key meteorological forcing variables measured by the installed sensors – shortwave radiation, longwave radiation, wind speed, air temperature, and relative humidity – are illustrated in corresponding colours.

2.3 Data processing and example analyses

2.3.1 Intra-annual extremes

Data from all monitoring stations were quality-checked to remove outliers and ensure temporal alignment across sensors. To illustrate potential applications of the dataset, two distinct one-week periods representing exceptionally cold winter conditions during lake circulation and exceptionally warm summer conditions during stratified conditions were identified for each site. These periods provide examples for comparative analyses of thermal responses across sites.

Associations between key meteorological variables – shortwave radiation, longwave radiation, air temperature, wind speed, and relative humidity – and water temperature deviations beneath FPV relative to the open-water reference were explored to illustrate the analytical potential of the dataset. For each variable, mean values were calculated for the selected analysis periods. In addition, the vertical mean water temperature difference between FPV and reference conditions (ΔT_w) across the entire 10 m water column was computed as an integrated measure of the thermal response.

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2.3.2 Statistical analysis

Statistical relationships between ΔT_w and meteorological variables were explored using Pearson correlation coefficients (r-values) and associated p-values (t-test). Positive r-values indicate that an increase in a given meteorological variable (e.g., air temperature, shortwave radiation) is associated with higher water temperatures beneath FPV relative to the reference site, whereas negative r-values indicate that increasing values of the variable correspond to cooling effects beneath FPV.

2.3.3 Seasonal analysis

To demonstrate the potential for seasonal analyses using the dataset, the large-scale FPV system on Lake Sekdoorn was selected as an example case. This site was selected due to its extensive coverage (26% of lake surface) and the use of an east–west oriented rafted-float design, which is increasingly adopted in recent FPV projects across Europe. The example analysis focused on changes in the influence of shortwave radiation, air temperature, and wind speed on ΔT_w from the full circulation period in late winter, through the onset of stratification in spring, to the fully developed stratified phase in summer. In addition to ΔT_w, deviations in thermocline depth (ΔTD) between FPV and reference sites were analysed, with TD calculated based on the 24-h moving average. Negative ΔTD values indicate a deeper thermocline beneath the FPV system compared to the reference location, whereas positive values reflect a shallower thermocline under FPV.

2.4 Data quality assurance and technical validation

Data quality assurance included sensor calibration according to manufacturer specifications, routine maintenance and cleaning, temporal synchronisation of all monitoring systems, and the removal of implausible values identified during quality control. Sensor accuracies are reported in Sect. 2.2. Temporal consistency between meteorological and water temperature observations was verified prior to analysis. Cleaning and functional checks were carried out at least quarterly. While occasional data gaps occurred due to maintenance activities or temporary sensor malfunction, these were documented and retained in the published dataset. Overall, the harmonised monitoring approach provides a consistent basis for comparative analyses across sites, climatic settings, and FPV configurations.

3 Results and Discussion

This section provides an overview of selected patterns represented in the dataset and demonstrates potential applications for analysing FPV–lake interactions across contrasting climatic settings. The analyses shown here are intended to illustrate the information content of the dataset.

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3.1 Thermal contrasts during selected intra-annual extreme periods

3.1.1 Cold-period monitoring

Lake Toules – Cold-period thermal response

During the selected cold-period interval at Lake Toules (Fig. 3), the FPV site showed pronounced cooling at the beginning of the period, with a mean ΔT_w of –0.12 °C and maximum deviations reaching –1.0 °C. This phase coincided with relatively warm, dry meteorological conditions (low relative humidity and low absolute moisture content in cold air) and low wind speeds. In the second half of the period, inverse stratification developed. Warming phases were rare and weak, occurring mainly during periods of high humidity or when inverse stratification transitioned to cold mixing conditions.

Correlation analysis identified relative humidity as the strongest positive driver of ΔT_w, while air temperature, shortwave radiation, and wind speed were negatively correlated. Compared to the open-water site, periods of higher humidity coincided with less cooling under FPV, consistent with suppressed evaporation and latent heat loss when the vapour-pressure deficit is small. This positive role of atmospheric moisture is in line with Yang et al. (2022), who found that under persistently humid tropical conditions FPV can increase water temperatures by stabilising the water column and suppressing evaporation, and with Prandini et al. (2025), who reported similar warming tendencies in a subtropical reservoir in Brazil under high humidity and reduced wind mixing. Although the alpine system differs fundamentally from these low-latitude reservoirs, the observations are consistent with the general tendency for water-saturated air conditions to reduce evaporative cooling beneath FPV. Conversely, under dry, sunny conditions the elevated, partly wind-permeable design at Toules still allowed some evaporation and mixing, which, in combination with shading-induced cooling, enhanced relative cooling beneath the array.

Overall, the observations illustrate that under cold, low-energy alpine conditions, FPV cooling relative to open water is likely driven primarily by reduced radiative heating, with a secondary contribution from evaporation that can persist under dry conditions. High humidity suppresses this evaporative component more strongly under FPV than in open water, narrowing the temperature difference. This balance appears sensitive to atmospheric moisture and could shift toward slight warming under persistently water-saturated air conditions.

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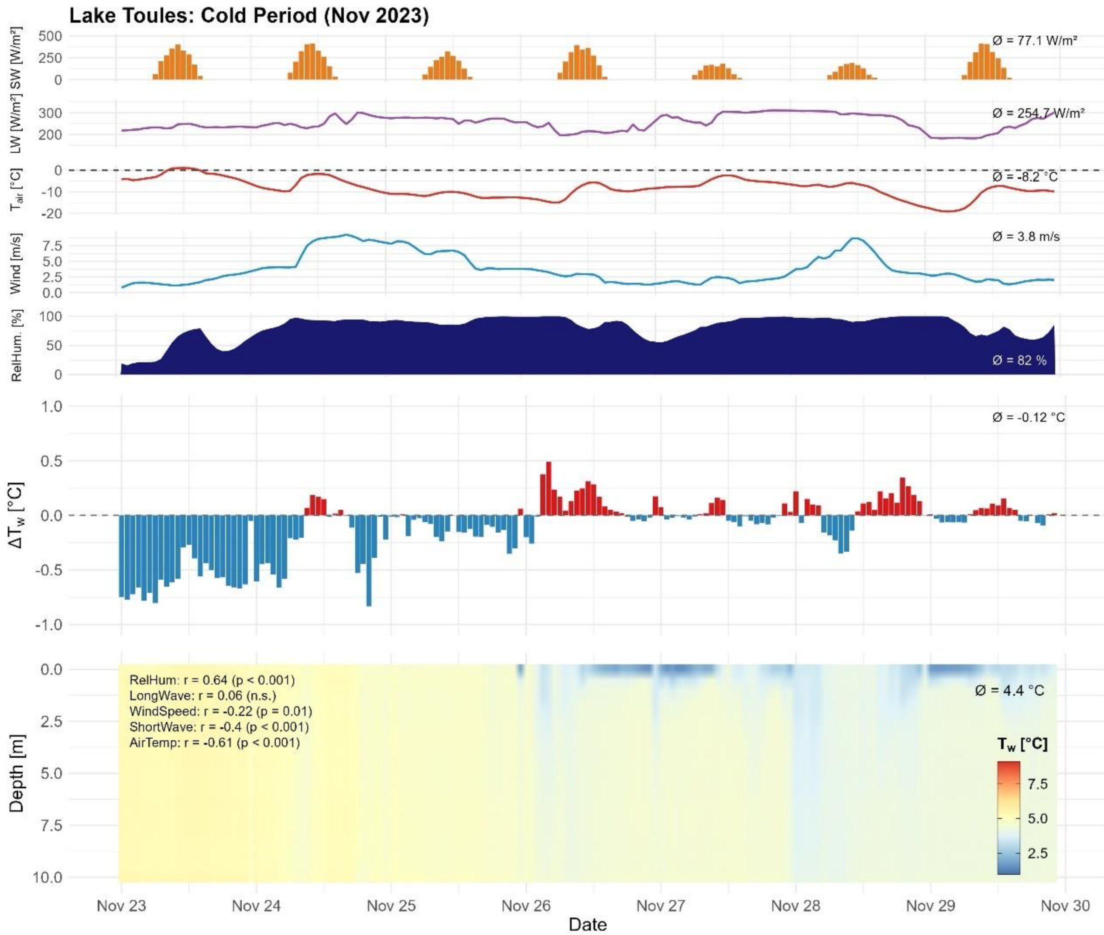

Figure 3: Example observations from the selected cold-period interval at Lake Toules (Nov 2023) including meteorological variables, ΔT_w between FPV and reference sites, exploratory correlation coefficients (r) and significance levels (p), and depth-resolved water temperature profiles beneath the FPV system.

Lake Sekdoorn – Cold-period thermal response

During the selected cold-period interval at Lake Sekdoorn (Fig. 4), the FPV site exhibited a persistent but moderate warming relative to the open-water reference, with a mean ΔT_w of +0.14 °C and no pronounced cooling phases. Water temperatures were higher than at Lake Toules (6.6 °C), while mean shortwave radiation was the lowest among the sites. Combined with relatively high mean longwave radiation, this suggests predominantly cloudy conditions during the observation period. Meteorological conditions were further characterised by highest relative humidity (92%, which at the mild observed air temperatures corresponds to a relatively high absolute moisture content) and mild air temperatures (9.7 °C), with moderate wind speeds. Correlation analysis revealed only a weak, negative relationship between shortwave radiation and ΔT_w, with all other variables showing no significant association.

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These results suggest that under mild, humid winter conditions in temperate lowland lakes, FPV shading may have a limited cooling effect and can even be associated with slight warming relative to open water. The dense east–west rafted-float design of the Sekdoorn installation strongly attenuates both shortwave input and wind exposure, which may reduce heat loss through evaporation, limit wind-driven mixing, and trap a greater portion of the longwave radiation emitted from the lake surface. This mechanism of longwave trapping and suppressed latent heat loss is consistent with findings by Yang et al. (2021), who showed that FPV systems can increase near-surface water temperatures by reducing shortwave radiation, enhancing longwave radiation, and lowering latent heat flux. Under the observed high-humidity conditions, suppressed evaporation likely contributed to the small but persistent positive ΔT_w signal, as the FPV-covered water retained more heat than the open-water reference. Overall, the observations indicate relatively stable thermal conditions during the selected period, with only weak short-term relationships between meteorological variables and ΔT_w.

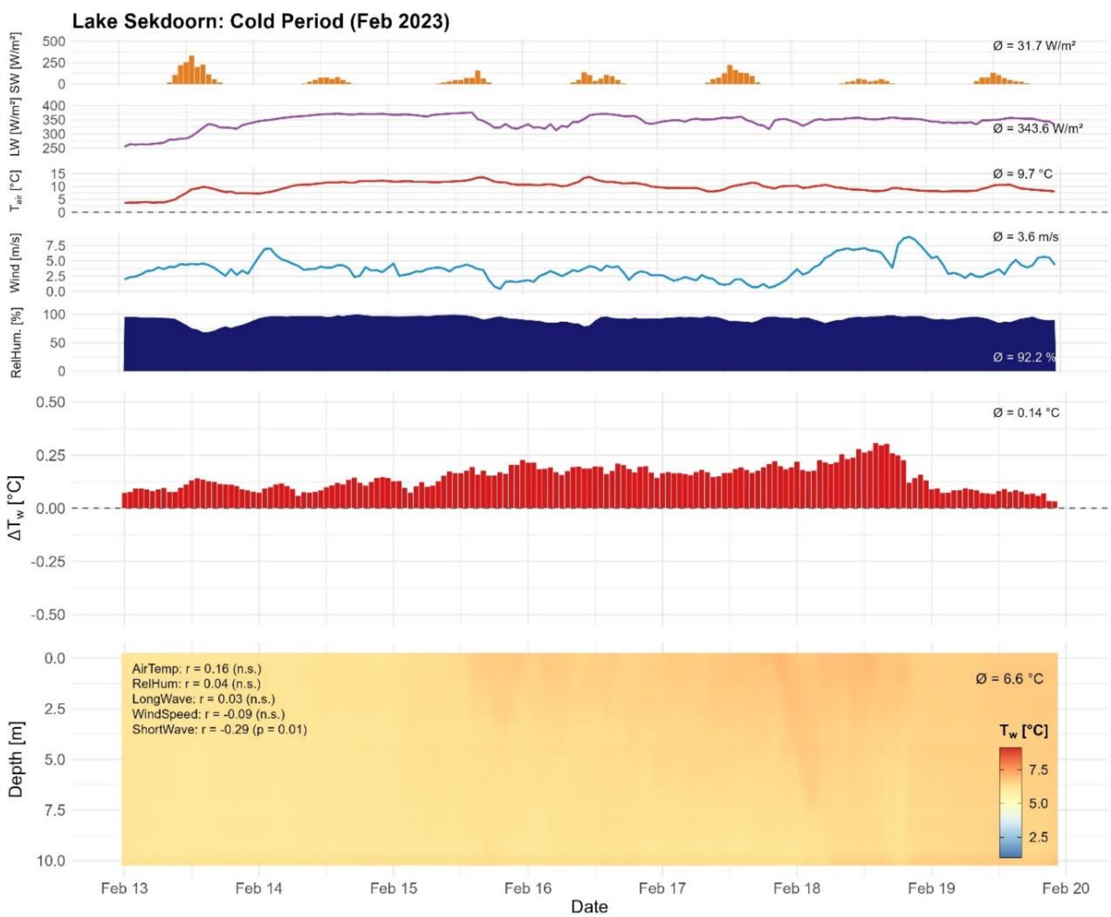

Figure 4: Example observations from the selected cold-period interval at Lake Sekdoorn (Feb 2024) including meteorological variables, ΔT_w between FPV and reference sites, exploratory correlation coefficients (r) and significance levels (p), and depth-resolved water temperature profiles beneath the FPV system.

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Lake Leimersheim – Cold-period thermal response

During the selected cold-period interval at Lake Leimersheim (Fig. 5), the FPV site showed predominantly small cooling effects relative to the open-water reference, with a mean ΔT_w of –0.04 °C. Cooling phases were frequent but of low magnitude, interspersed with brief, minor warming events. Mean water temperatures matched those at Lake Sekdoorn (6.6 °C), with warmer surface and cooler deep-water layers, alongside intermediate shortwave radiation and the lowest mean wind speeds of the three sites. Meteorological conditions featured moderate relative humidity (84%, which at the mild observed air temperatures indicates a moderate to high absolute moisture content) and mild air temperatures (9.5 °C). Correlation analysis revealed a strong negative relationship between shortwave radiation and ΔT_w, a moderate negative correlation with relative humidity, and positive associations with wind speed and longwave radiation.

These results suggest that in temperate continental lakes during mild winter conditions, FPV-induced thermal deviations are small but can vary with meteorological forcing. The modular pure-float design of the Leimersheim installation substantially reduces shortwave input and wind exposure, limiting direct warming and wind-driven mixing beneath the array. The strong negative correlation with shortwave radiation indicates that under higher irradiance, the FPV-covered water warms more slowly than open water. The positive link with wind speed at Lake Leimersheim suggests that wind events primarily enhance mixing and heat loss in the open-water reference area, while having limited influence beneath the FPV. The modular pure-float design sits close to the water surface and provides substantial shelter from wind, restricting turbulence and evaporation under the array. As a result, higher wind speeds tend to narrow the temperature difference between FPV and open water, producing a positive ΔT_w response. The negative correlation with relative humidity indicates that under drier conditions evaporative cooling was more pronounced in open water than beneath the sheltered FPV. Overall, the observations illustrate that thermal variability at Lake Leimersheim was primarily associated with variations in irradiance and atmospheric moisture during the selected period.

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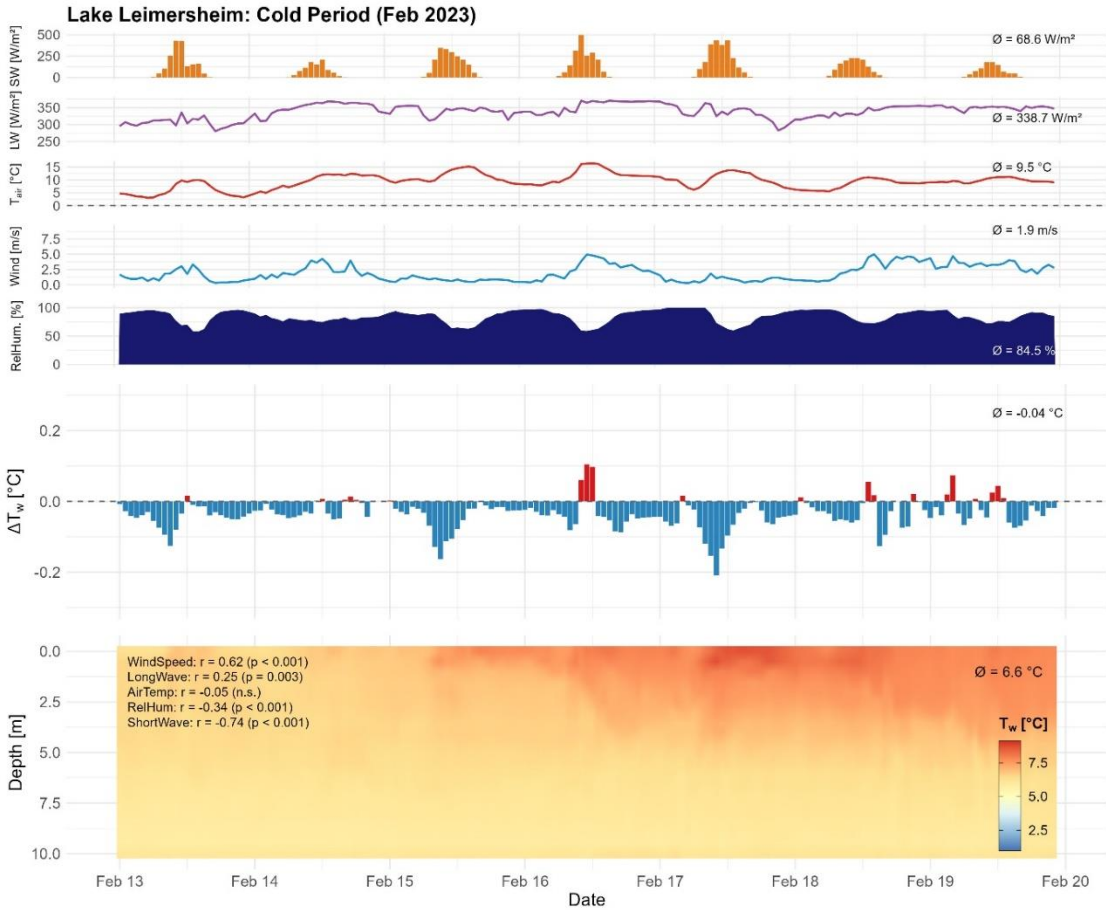

Figure 5: Example observations from the selected cold-period interval at Lake Leimersheim (Feb 2024) including meteorological variables, ΔT_w between FPV and reference sites, exploratory correlation coefficients (r) and significance levels (p), and depth-resolved water temperature profiles beneath the FPV system.

Comparative synthesis of cold-period drivers and processes

The cold-period observations illustrate distinct relationships between meteorological conditions and FPV-related water temperature differences across the three sites (Appendix Tab. A1). These differences likely reflect the combined influence of climatic setting and FPV system design.

- **Lake Toules** – Evaporative cooling can persist under dry, sunny conditions from partial wind exposure by open system design; effect suppressed under water-saturated air conditions (positive: relative humidity; negative: air temperature).
- **Lake Sekdoorn** – Dense system design strongly attenuating wind and shortwave input; high humidity suppressing evaporation; potential longwave trapping favouring warming below FPV (positive: no significant driver; negative: shortwave radiation).

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- **Lake Leimersheim** – Cooling dominated by shading; wind sheltering limits mixing and evaporation (positive: wind speed; negative: shortwave radiation).

3.1.2 Warm-period monitoring

Lake Toules – Warm-period thermal response

During the warm-period monitoring at Lake Toules (Fig. 6), the FPV site alternated between cooling and warming relative to the open-water reference, with cooling phases being more frequent and of greater magnitude (mean ΔT_w = –0.06 °C, several events below –0.2 °C). Thermal stratification was established, and the thermocline was consistently deeper beneath FPV than at the reference site. Meteorological conditions were characterised by high shortwave radiation, mild air temperatures, low wind speeds, and moderate relative humidity.

Correlation analysis identified relative humidity as the strongest positive association with ΔT_w, whereas wind speed and air temperature both showed strong negative relationships. Compared to open water, periods of higher humidity coincided with less relative cooling beneath FPV, consistent with suppressed evaporation and latent heat loss when the vapour-pressure deficit is low. In contrast, stronger winds and higher air temperatures were linked to more negative ΔT_w, suggesting that in this weakly stratified alpine reservoir, a larger air–water temperature contrast under FPV – combined with partial wind exposure – could increase the vapour-pressure deficit and allow some mixing with cooler subsurface water, thereby enhancing relative cooling compared to the open-water site. Shortwave and longwave radiation showed no significant correlations, likely reflecting the consistently reduced irradiance beneath the array and limited variability during the observation period rather than the absence of radiative effects.

Overall, the observations indicate that the relationships between ΔT_w and meteorological variables were broadly similar during warm and cold periods, with humidity acting as a positive and wind speed and air temperature as negative associations. The effects were more pronounced in summer, likely because greater short-term variability in meteorological conditions made them more apparent. The deeper thermocline beneath FPV further suggests altered vertical heat distribution under stratified conditions. Compared to the lower-altitude sites, these patterns likely reflect the combined influence of the alpine climate and the elevated, partly wind-permeable FPV design, which allows some evaporative heat loss to persist beneath the array. In larger or more enclosed FPV systems, even under similar climatic conditions, evaporation would likely be increasingly suppressed, potentially shifting the balance between cooling and warming.

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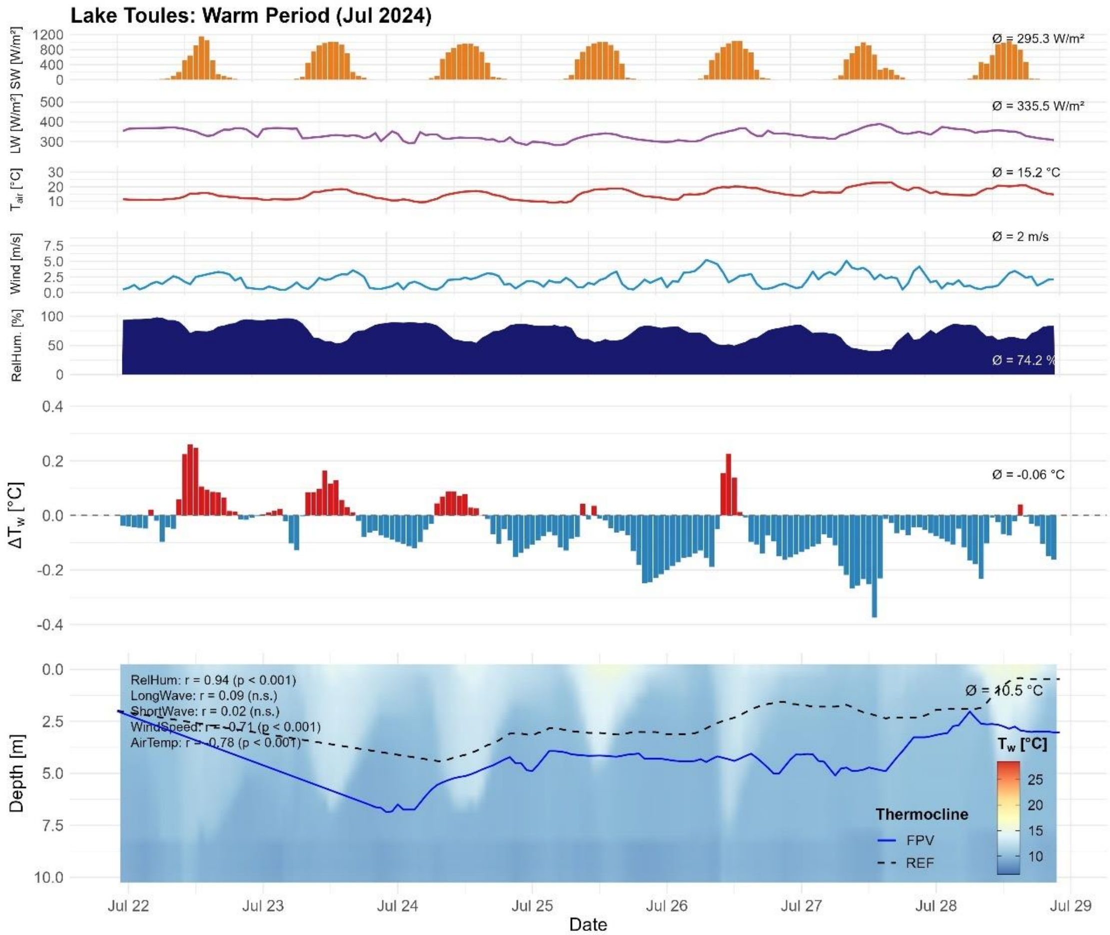

Figure 6: Example observations from the selected warm-period interval at Lake Toules (Jul 2024) including meteorological variables, ΔT_w between FPV and reference sites, exploratory correlation coefficients (r) and significance levels (p), and depth-resolved water temperature profiles beneath the FPV system.

Lake Sekdoorn – Warm-period thermal response

During the warm-period monitoring at Lake Sekdoorn, the FPV site showed negligible net cooling relative to the open-water reference, with short-term fluctuations between warming and cooling events (Fig. 7). Stratification was stable, with a deeper and more persistent thermocline than at Lake Toules. Meteorological conditions featured moderate shortwave radiation, warm air temperatures, and the highest wind speeds among the sites.

Correlation analysis identified wind speed as the strongest positive driver of ΔT_w, followed by relative humidity, while shortwave radiation and air temperature were negatively correlated. The positive wind–ΔT_w relationship suggests that wind cooled the open-water site more strongly, as mixing and evaporation beneath FPV were constrained by the sheltered, dense rafted-float design. High humidity further suppressed evaporation under FPV, limiting heat loss and allowing water beneath

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the array to remain relatively warmer. A similar mechanism was reported by Yang et al. (2022) for a tropical reservoir, where reduced latent heat flux under humid conditions led to systematic FPV warming. This comparison underscores humidity as a key driver that can shift FPV impacts from cooling towards warming across climatic zones. Higher shortwave radiation and warmer air temperatures corresponded to greater relative cooling under FPV, consistent with shading reducing direct heat gain and potentially increasing local temperature contrasts that support limited evaporation.

Overall, the observations indicate comparatively weak short-term relationships between meteorological variables and ΔT_w at Lake Sekdoorn, reflecting the combined influence of the sheltered FPV design and the humid lowland climate, both of which likely constrain evaporative losses.

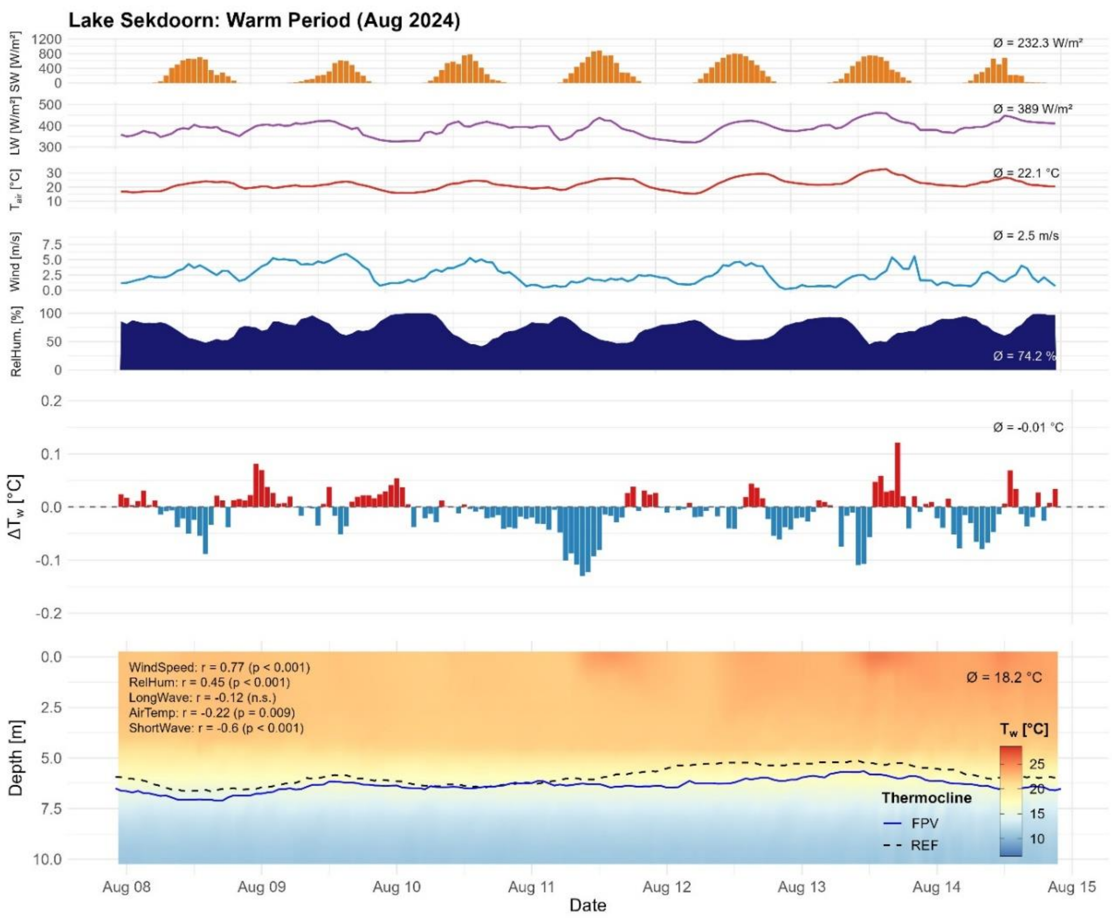

Figure 7: Example observations from the selected warm-period interval at Lake Sekdoorn (Aug 2024) including meteorological variables, ΔT_w between FPV and reference sites, exploratory correlation coefficients (r) and significance levels (p), and depth-resolved water temperature profiles beneath the FPV system.

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Lake Leimersheim – Warm-period thermal response

During the warm-period monitoring at Lake Leimersheim, the FPV site showed a pronounced and persistent cooling relative to the open-water reference, with a mean ΔT_w of –0.55 °C and no warming events (Fig. 8). Stratification was stable and the thermocline position similar between sites. Meteorological conditions featured moderate shortwave radiation, the warmest air temperatures among the three sites, and relatively low wind speeds.

Correlation analysis identified air temperature as the strongest negative association with ΔT_w, with shortwave and longwave radiation also showing negative relationships. Wind speed was the only positive driver, while relative humidity showed a weak, non-significant negative relationship. The positive wind–ΔT_w relationship, as also observed at Lake Sekdoorn, indicates that wind events cooled the open-water site more strongly than the FPV site, likely because mixing and evaporation beneath FPV were limited by the sheltered, low-profile array design. Higher air temperatures coincided with stronger cooling beneath FPV, consistent with shading reducing direct heat gain compared to the open-water site. The weak influence of humidity suggests that evaporation played only a minor role here. Even though relative humidity was the lowest and air temperatures the highest among the sites – conditions that would typically promote evaporation – the sheltered FPV design appears to have strongly limited air–water exchange beneath the array.

Compared to Lake Toules, the cooling signal at Leimersheim was stronger, more stable, and less sensitive to short-term meteorological variability, reflecting the sheltered, low-profile FPV design and the warm continental summer climate, which favours stable stratification and increases the sensitivity of surface waters to shading. Similar shading-driven cooling during warm summer periods has been reported elsewhere, including reductions of up to 3 °C (Nobre et al., 2025), delays in ecologically relevant temperature thresholds (Yang et al., 2022), and overall reductions in lake water temperature under FPV (Ilgen et al., 2023). As at Sekdoorn, wind acted as a positive driver, reducing the cooling difference by cooling the open-water site more strongly, while shading-induced cooling beneath FPV remained the dominant feature during the selected period.

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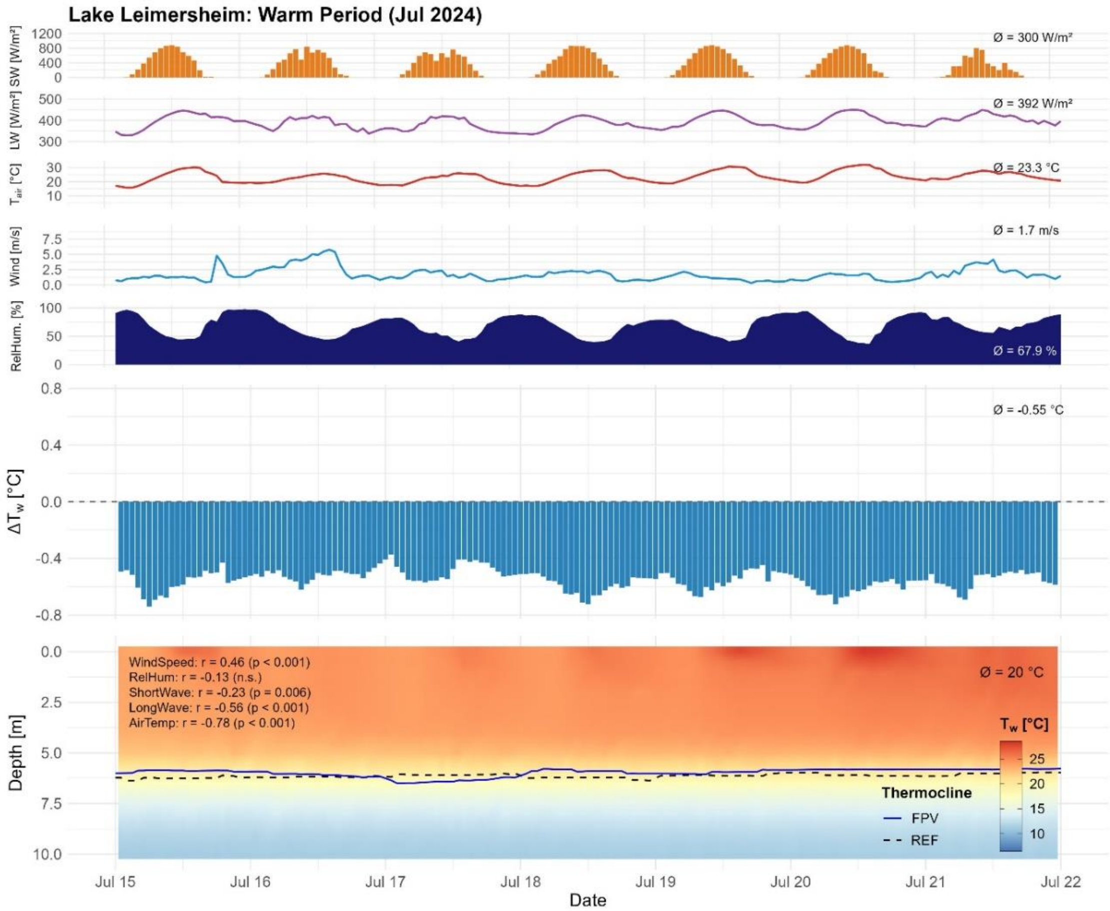

Figure 8: Example observations from the selected warm-period interval at Lake Leimersheim (Jul 2024) including meteorological variables, ΔT_w between FPV and reference sites, exploratory correlation coefficients (r) and significance levels (p), and depth-resolved water temperature profiles beneath the FPV system.

Comparative synthesis of warm-period drivers and processes

The warm-period observations again illustrate distinct relationships between meteorological conditions and FPV-related water temperature differences across the three sites (Appendix Tab. A2). The observed patterns likely reflect the combined influence of climatic setting, FPV system design, and seasonal amplification of shading and evaporation processes.

- **Lake Toules** – Humidity was associated with reduced cooling beneath FPV by suppressing evaporation and latent heat loss, whereas wind speed and air temperature coincided with enhanced cooling under the partly wind-permeable FPV design (positive association: relative humidity; negative association: air temperature).
- **Lake Sekdoorn** – The dense rafted-float design strongly attenuated wind and shortwave input, while high humidity likely further suppressed evaporation. The positive wind relationship reflects stronger wind-driven cooling in open water than beneath FPV (positive association: wind speed; negative association: shortwave radiation).

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- **Lake Leimersheim** – Shading was the dominant effect during the selected period, while the sheltered low-profile design limited wind-driven mixing and evaporation. The warm continental summer climate likely amplified shading-related cooling (positive association: wind speed; negative association: air temperature).

3.1.3 Cross-seasonal synthesis of meteorological drivers of ΔT_w

Across the three study sites, the thermal response beneath FPV during intra-annual extremes reflects the interaction between climatic setting and FPV system design. Figure 9 summarises both the mean ΔT_w differences between winter and summer and the correlations with key meteorological drivers. The left panel highlights that Lake Leimersheim exhibits the largest seasonal range in ΔT_w shifting from moderate cooling in winter to substantially stronger cooling in summer. In contrast, Lake Sekdoorn shows only small mean differences, while Lake Toules displays slightly stronger cooling in winter than in summer.

During the cold period, the dominant drivers differ between lakes (Fig. 9, winter panel). At Lake Leimersheim, shortwave radiation is the strongest negative driver, indicating that reduced solar input beneath FPV drives cooling, while wind speed shows a positive relationship reflecting stronger wind-induced cooling in open water. At Lake Sekdoorn, correlations with meteorological variables are weak, consistent with the small ΔT_w signal. The dense rafted-float design strongly attenuates wind and shortwave radiation, while high humidity suppresses evaporation, resulting in slight heat retention beneath FPV. At Lake Toules, the elevated and partially wind-exposed system allows evaporative cooling under dry conditions. Accordingly, relative humidity shows the strongest positive correlation with ΔT_w, whereas air temperature and shortwave radiation promote cooling beneath the array.

During the warm period, meteorological controls become more pronounced (Fig. 9, summer panel). At Lake Leimersheim, air temperature shows the strongest negative relationship with ΔT_w, indicating amplified shading-driven cooling during hot summer conditions. This corresponds to the strong seasonal increase in cooling visible in the ΔT_w panel. At Lake Sekdoorn, wind speed becomes the dominant positive driver, reflecting stronger wind-driven cooling in open water compared with the sheltered FPV area, while shortwave radiation remains the main negative driver. In contrast, Lake Toules shows a different seasonal behaviour: correlations remain similar to winter, with relative humidity acting as the strongest positive driver and wind and air temperature promoting cooling. However, the overall ΔT_w magnitude is slightly smaller than in winter.

Overall, Leimersheim and Sekdoorn show a clear seasonal shift in dominant meteorological drivers, while Toules maintains a similar driver pattern across seasons, with slightly stronger correlations in summer. At the same time, cooling beneath FPV becomes stronger in summer at Leimersheim and Sekdoorn, whereas at Toules the cooling effect is slightly stronger in winter. This difference likely reflects the development of stable summer stratification in Leimersheim and Sekdoorn, which increases the influence of surface energy fluxes on near-surface water temperature. The observations therefore indicate that, in addition to atmospheric forcing and FPV design, the lake mixing regime may contribute to modulating FPV-related temperature differences.

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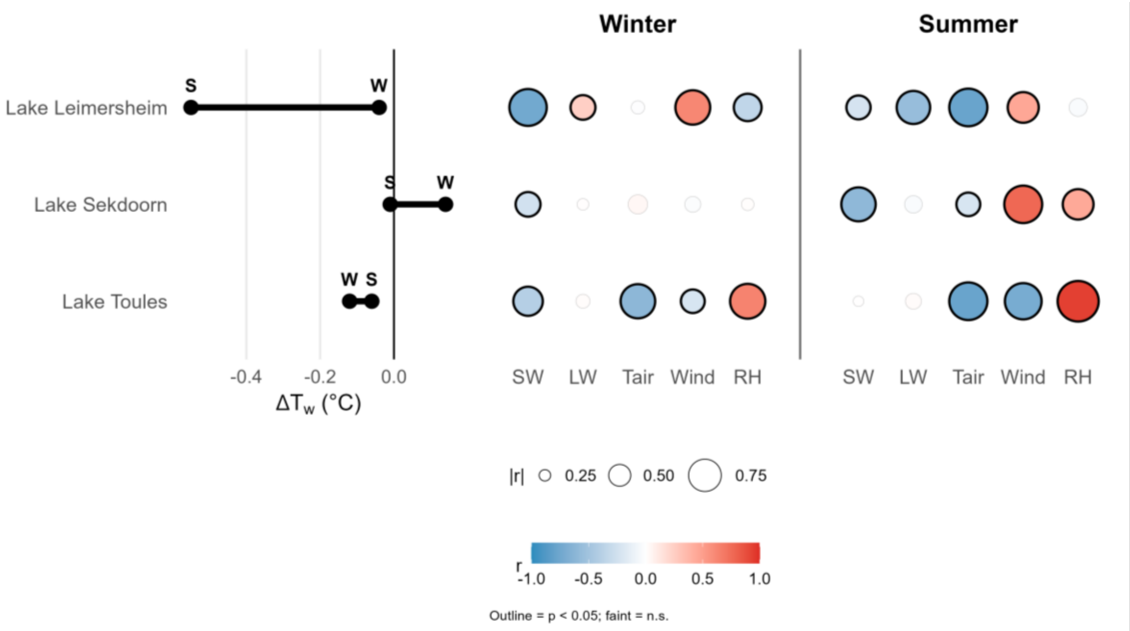

Figure 9: Seasonal comparison of FPV–open water temperature differences (ΔT_w) and their relationships with meteorological variables at Lakes Leimersheim, Sekdoorn, and Toules. The left panel shows mean ΔT_w for winter and summer. The right panels display Pearson correlations between ΔT_w and shortwave radiation (SW), longwave radiation (LW), air temperature (Tair), wind speed (Wind), and relative humidity (RH). Circle colour indicates correlation direction (blue = negative, red = positive) and size represents magnitude (|r|). Outlines indicate significant relationships ($p < 0.05$).

3.2 Seasonal progression of water temperature differences across lake mixing regimes

To illustrate the seasonal analytical potential of the dataset, the utility-scale FPV system at Lake Sekdoorn was analysed across three characteristic lake mixing regimes: winter mixing, stratification onset, and stable summer stratification. Figure 10 illustrates the temporal evolution of meteorological forcing, ΔT_w, thermocline depth deviations (ΔTD), and the vertical temperature structure beneath the FPV. Figure 11 summarises the correlations between ΔT_w and key meteorological drivers across these regimes.

3.2.1 Winter mixing

During winter mixing, the water column was largely isothermal and ΔT_w remained small, with a slight positive offset indicating weak heat retention beneath the FPV (Fig. 10a). Variations in ΔT_w generally followed changes in atmospheric temperature, while shortwave radiation exerted only a minor influence due to low solar input during winter. Wind effects were limited, as the fully mixed water column allowed rapid redistribution of heat throughout the lake. The vertical temperature profiles confirm this behaviour, showing only weak and short-lived near-surface warming signals and minimal differences between FPV-covered and open-water areas.

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3.2.2 Stratification onset

With the onset of stratification in spring, ΔT_w patterns became more variable and increasingly alternated between cooling and warming phases beneath the FPV (Fig. 10b). This transition coincided with the formation and gradual deepening of the thermocline. During this period, daytime cooling beneath FPV contrasted with faster epilimnetic warming in open water, as radiative heating remained largely suppressed under the FPV array. Wind variability became more relevant during this stage. Episodes of stronger winds enhanced mixing in open water, while this mechanism remained attenuated beneath the FPV. As a result, thermal stratification developed more gradually beneath the array. The thermocline beneath FPV therefore appeared slightly deeper and more stable than at the reference site. Towards the end of the period, several unsettled weather episodes with lower air temperatures and increased wind speeds further amplified these contrasts. While open water cooled more rapidly due to enhanced mixing, the FPV-covered area retained heat more effectively.

3.2.3 Summer stratification

During summer stratification, ΔT_w amplitudes increased, displaying a clear diurnal pattern of daytime cooling and nocturnal warming beneath the FPV (Fig. 10c), a behaviour also observed in previous studies (Ilgen et al., 2023; Liu et al., 2024). Wind-driven mixing became the dominant mechanism controlling temperature variability in open water. Strong wind events produced rapid cooling of the surface layer through vertical mixing, whereas beneath the FPV this mechanism remained strongly suppressed. As a result, temperature declines beneath the FPV were generally slower. The thermocline beneath FPV was typically deeper and exhibited less pronounced short-term fluctuations compared with the open-water site. Sustained shading reduced radiative heating of the surface layer, while the attenuation of wind stress limited vertical perturbations of the stratified water column.

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(a)

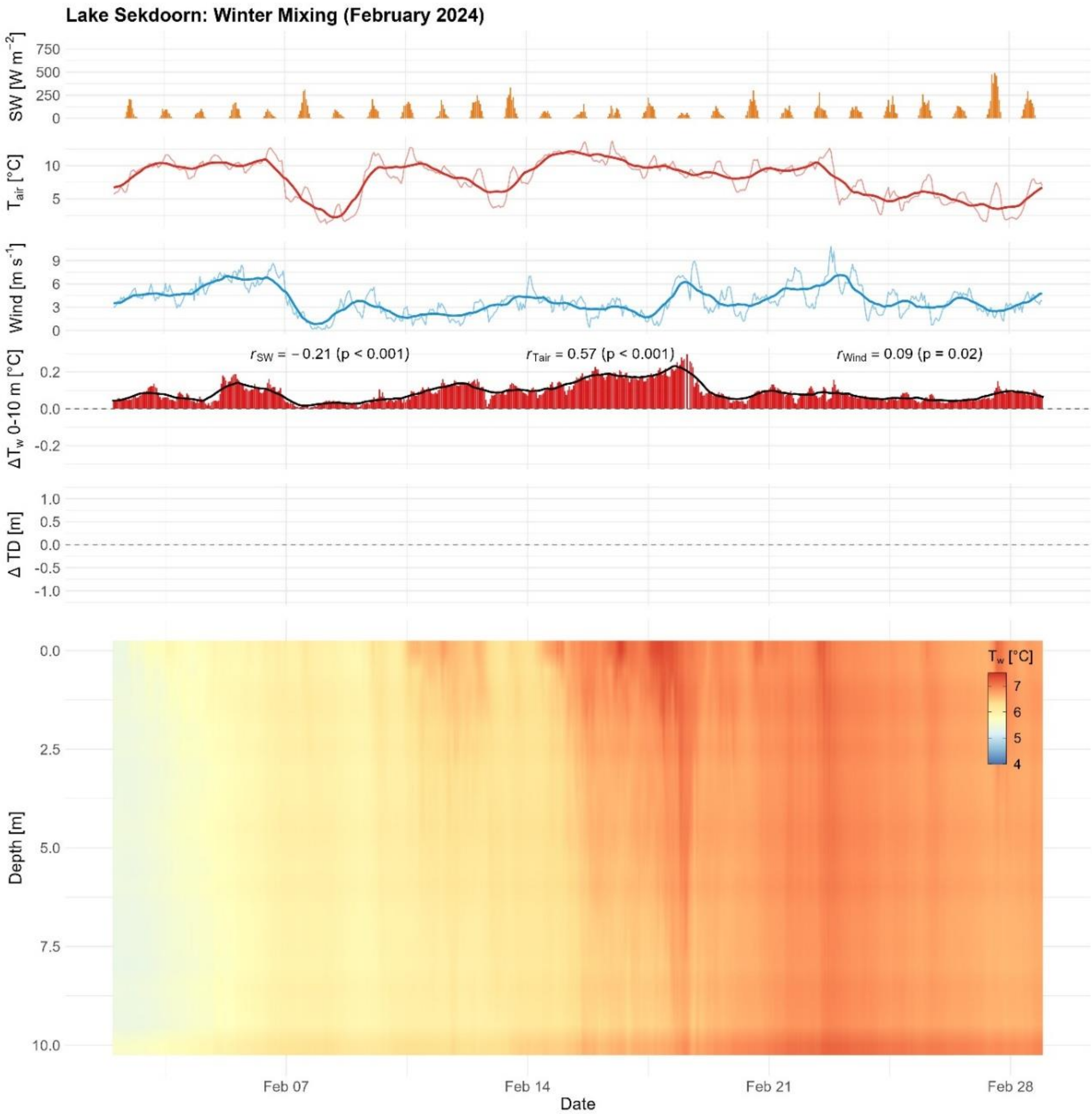

Figure 10: Seasonal progression of FPV-related thermal variability at Lake Sekdoorn for (a) winter mixing, (b) spring stratification onset, and (c) stable summer stratification. Each panel shows meteorological forcing, FPV–reference water temperature differences (ΔT_w), thermocline depth deviations (ΔTD), and the vertical water temperature profile beneath the FPV system. For air temperature (T_{air}), wind speed, and ΔT_w, thick lines indicate 24-h moving averages. Correlation coefficients and p-values are shown for the meteorological variables.

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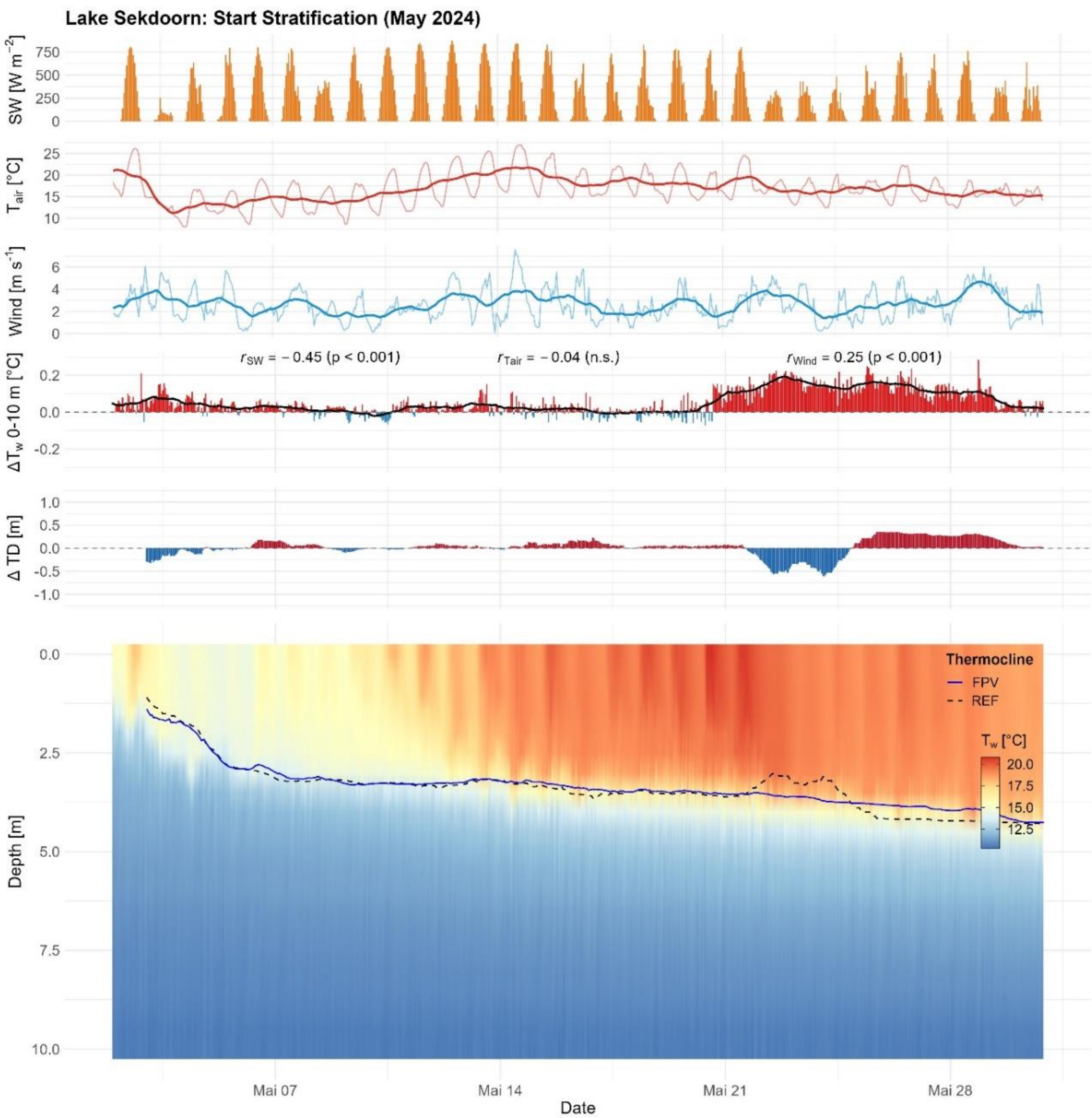
(b)



405 **Figure 10. – continued.**

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(c)

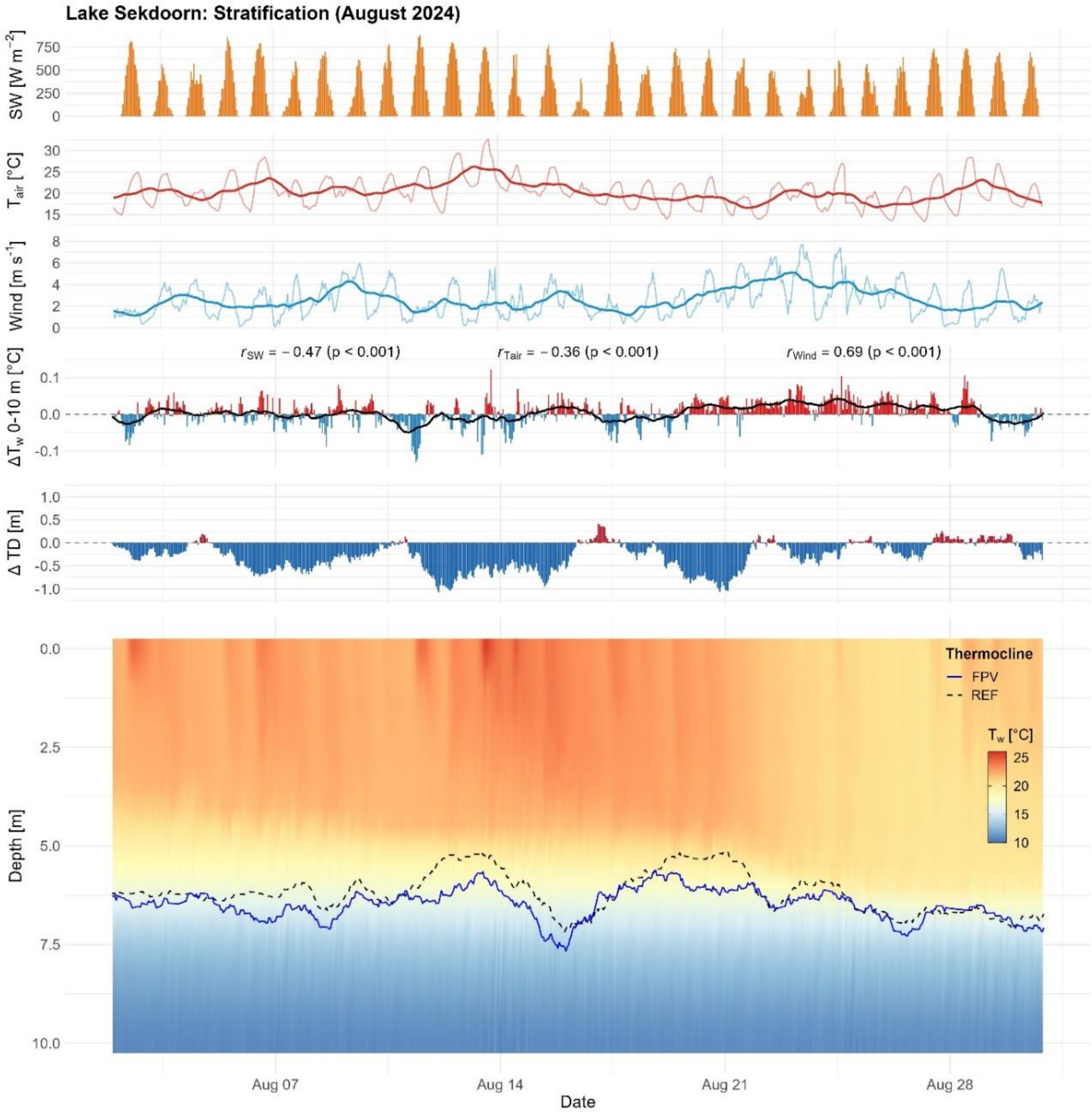

Figure 10. – continued.

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3.2.4 Comparative synthesis of seasonal drivers and processes

Key meteorological associations of ΔT_w varied systematically across the seasonal cycle, reflecting the transition between different lake mixing regimes (Fig. 11; Appendix Tab. A3). The correlation patterns illustrate a clear shift in dominant controls from atmospheric forcing during winter mixing to radiative and wind-driven processes during stratified conditions.

- **Winter mixing** – ΔT_w remained small but slightly positive, indicating weak heat retention beneath the FPV. Correlations show a moderate positive relationship with air temperature ($r = 0.57$) and a weak negative relationship with shortwave radiation ($r = –0.21$), suggesting that short-term radiative warming was suppressed beneath the array while reduced convective and evaporative heat losses promoted slightly warmer conditions. Wind influence remained negligible under fully mixed conditions.
- **Stratification onset** – As stratification began, the dominant control shifted towards radiative forcing. The stronger negative correlation with shortwave radiation ($r = –0.45$) reflects the increasing importance of shading, which suppressed epilimnetic warming beneath the FPV. At the same time, the growing influence of wind ($r = 0.25$) indicates enhanced mixing in open water relative to the sheltered FPV area.
- **Summer stratification** – During stable stratification, wind became the dominant driver ($r = 0.69$), highlighting the strong cooling effect of wind-driven mixing in open water. Beneath the FPV, this process was largely absent. Concurrently, sustained shading maintained negative correlations with shortwave radiation ($r = –0.47$) and air temperature ($r = –0.36$), indicating persistent suppression of radiative heating under the array. These opposing processes largely compensated each other, resulting in mean ΔT_w values close to zero.

Overall, the observations illustrate a seasonal progression in the dominant meteorological associations with ΔT_w, from air temperature during winter mixing to radiative forcing during stratification onset and wind-driven mixing during stable summer stratification. This progression likely reflects the increasing decoupling of the surface layer from deeper water masses as stratification develops, which amplifies the influence of surface energy fluxes. Consequently, FPV-related thermal variability appears to be influenced not only by atmospheric forcing and system design, but also by the prevailing lake mixing regime.

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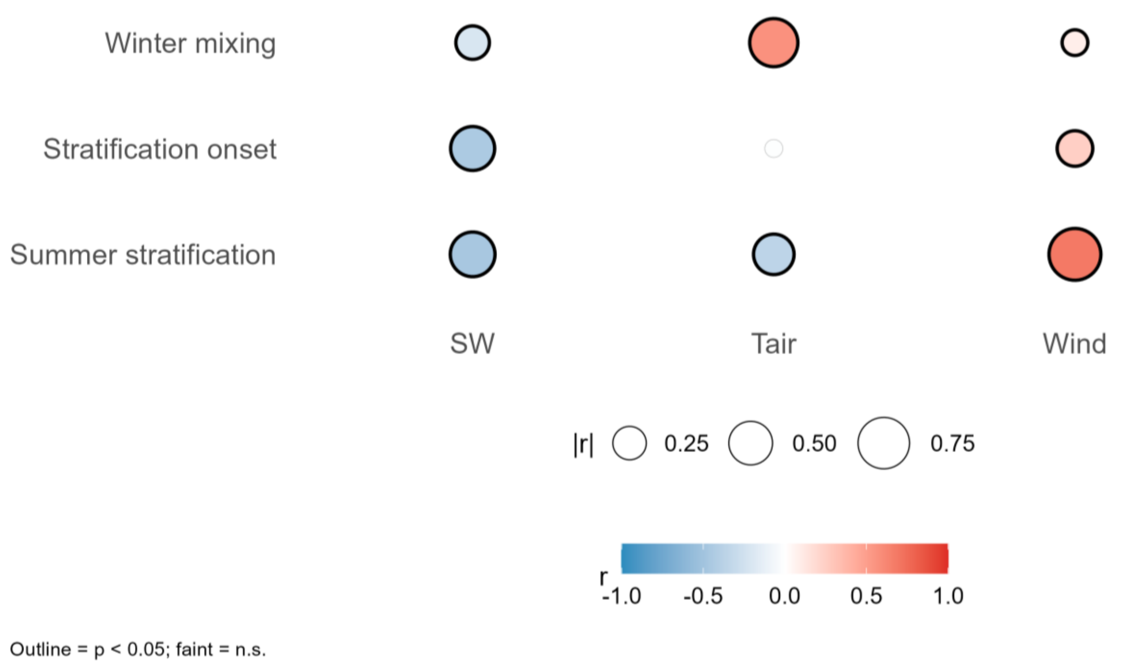

Figure 11: Seasonal relationships between FPV–reference water temperature differences (ΔT_w) and key meteorological variables across three lake mixing regimes at Lake Sekdoorn. Circle size indicates the correlation magnitude (|r|), colour indicates the correlation direction (blue = negative, red = positive), and outlines denote statistically significant relationships ($p < 0.05$).

4 Dataset limitations and reuse potential

4.1 Dataset limitations

The dataset has several limitations that should be considered when interpreting the observations. First, only three artificial lakes were included, and natural lake systems are not represented. Second, the monitoring period was limited to 2023 and 2024 and therefore does not capture long-term interannual variability. Third, observations were obtained at specific monitoring locations beneath FPV systems and adjacent reference sites and may not fully represent whole-lake responses. Finally, the investigated FPV systems represent specific design configurations and lake coverages, which may limit transferability to other FPV installations.

4.2 Dataset reuse potential

The dataset enables a wide range of applications beyond the illustrative analyses presented here. Potential applications include the calibration and validation of hydrodynamic lake models, the development of FPV parameterisations, comparative assessments across climatic regions and FPV configurations, climate adaptation studies, and future meta-analyses. The harmonised monitoring approach further provides a reference framework for future FPV monitoring campaigns and supports evidence-based environmental assessments of FPV deployment on inland waters (Ilgen et al., 2026a).

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In addition to continuous meteorological and water temperature observations, the dataset includes 79 water quality profiles collected during dedicated field campaigns using a multiparameter probe (EXO2, YSI). These measurements comprise a range of physical, chemical, and optical water quality variables, including dissolved oxygen, conductivity, pH, turbidity, chlorophyll-a, phycocyanin, and dissolved organic matter proxies. The combined availability of meteorological, thermal, and water quality data enables investigations of both physical lake processes and biogeochemical responses to FPV deployment, including analyses of stratification dynamics, oxygen conditions, phytoplankton development, and nutrient-related processes across contrasting lake environments.

5 Data availability

The dataset presented in this study is publicly available via https://doi.org/10.5281/zenodo.21156967 (Ilgen et al., 2026b). It comprises harmonised in situ data collected at three FPV study sites in Europe: Lake Leimersheim (Germany), Lake Sekdoorn (the Netherlands), and Lake Toules (Switzerland). Measurements were conducted at FPV installations and adjacent open-water reference sites during 2023 and 2024. The dataset includes depth-resolved water temperature profiles, multiparameter water quality observations, and high-frequency meteorological measurements. The repository further contains accompanying metadata and documentation to facilitate data interpretation and reuse.

6 Conclusions

This paper presents a harmonised multi-site monitoring dataset describing FPV-induced thermal variability across contrasting climatic settings, FPV system designs, and seasonal lake mixing regimes. By combining high-resolution field observations from three European lakes with illustrative analyses, the dataset captures a broad range of FPV–lake interactions and associated meteorological conditions.

The three study sites – Lake Toules (deep alpine reservoir), Lake Leimersheim (shallow continental gravel pit lake), and Lake Sekdoorn (deeper humid lowland sand pit lake) – differed markedly in climate, morphometry, and FPV system configuration. These contrasts translated into distinct ΔT_w patterns during cold- and warm-period extremes. The observations indicate that dense, low-profile arrays in warm continental climates were associated with strong shading-driven cooling, elevated open designs in alpine climates were associated with wind- and evaporation-driven cooling under dry conditions, and mild humid lowland settings exhibited minimal or positive anomalies due to heat retention, particularly under cloudy and stable winter conditions. Furthermore, site-specific differences in ΔT_w were linked to the balance between radiative forcing and wind-driven mixing, which varied with climatic setting and FPV design. Cold-period extremes were generally characterised by shading-induced cooling or heat retention depending on atmospheric moisture and wind exposure, while warm-period extremes showed seasonal amplification of shading and evaporation effects, with the strongest water cooling under hot, continental summer conditions. The example analysis of the utility-scale FPV system at Lake Sekdoorn further illustrated how meteorological

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relationships varied with lake mixing regime. Air temperature was most strongly associated with ΔT_w during fully mixed winter conditions, shortwave radiation during stratification onset, and wind speed during stable summer stratification. As stratification developed, shading increasingly contributed to cooling beneath FPV, while wind effects became more positive as wind-driven mixing preferentially cooled open water.

Beyond the illustrative analyses presented here, the dataset provides opportunities for a wide range of applications, including hydrodynamic model calibration and validation, the development of FPV parameterisations, comparative assessments across climatic regions and FPV configurations, and future climate adaptation studies. The harmonised monitoring approach further provides a reference framework for future FPV monitoring campaigns and supports evidence-based environmental assessments of FPV deployment on inland waters. In addition, the water quality profiles obtained using multiparameter sondes enable investigations of biogeochemical and ecological responses to FPV deployment, including analyses of dissolved oxygen dynamics, primary production proxies, phytoplankton development, water column stability, and relationships between physical forcing and water quality. Future extensions should expand the multi-site approach to additional lake types and FPV configurations, extend monitoring periods to capture interannual variability, and strengthen links between physical, biogeochemical, and ecological responses.

Author contributions

KI designed the study, coordinated the monitoring data compilation and harmonisation, performed the data analysis, and prepared the manuscript. JL contributed to the conceptual development of the study, advised on the monitoring design and data interpretation, and supported the preparation and publication of the dataset. DS contributed to the conceptual development of the study and provided scientific input and revisions to the manuscript.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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Appendices

Table A1. Pearson correlation coefficients (*r*) and significance levels (*p*) between ΔT_w and meteorological variables during the cold-period monitoring at the three study sites.

Site	ΔT_w (°C)	Shortwave radiation (r, p)	Longwave radiation (r, p)	T_{air} (r, p)	Wind speed (r, p)	Relative humidity (r, p)
Lake Toules	– 0.12	–0.40, <0.001	0.06, n.s.	–0.61, <0.001	–0.22, 0.01	0.64, <0.001
Lake Sekdoorn	+0.14	–0.25, 0.01	0.03, n.s.	0.16, n.s.	–0.09, n.s.	0.04, n.s.
Lake Leimersheim	–0.04	–0.74, <0.001	0.25, 0.003	–0.05, n.s.	0.62, <0.001	–0.34, <0.001

Table A2. Pearson correlation coefficients (*r*) and significance levels (*p*) between ΔT_w and meteorological variables during the warm-period monitoring at the three study sites.

Site	ΔT_w (°C)	Shortwave radiation (r, p)	Longwave radiation (r, p)	Air temperature (r, p)	Wind speed (r, p)	Relative humidity (r, p)
Lake Toules	–0.06	0.02, n.s.	0.09, n.s.	–0.78, <0.001	–0.71, <0.001	0.94, <0.001

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Lake Sekdoorn	–0.01	–0.6, <0.001	–0.12, n.s.	–0.22, 0.009	0.77, <0.001	0.45, <0.001
Lake Leimersheim	–0.55	–0.23, 0.006	–0.56 <0.001	–0.78, <0.001	0.46, <0.001	–0.13, n.s.

Table A3. Pearson correlation coefficients (r) and significance levels (p) between ΔT_w and meteorological variables at Lake Sekdoorn for different lake mixing regimes.

Period	Shortwave radiation (r, p)	Air temperature (r, p)	Wind speed (r, p)
Winter mixing	–0.21 (<0.001)	0.57 (<0.001)	0.09 (0.02)
Stratification onset	–0.45 (<0.001)	–0.04 (n.s.)	0.25 (<0.001)
Stratification	–0.47 (<0.001)	–0.36 (<0.001)	0.69 (<0.001)

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