Article

Response of boreal lakes to episodic weather-induced events

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Abstract

Weather-induced episodic mixing events in lake ecosystems are often unpredictable, and their impacts are therefore poorly known. The impacts can be short-lived, including changes in water temperature and stratification, but long-lasting effects on the lake's biology may also occur. In this study we used automated water quality monitoring (AWQM) data from 8 boreal lakes to examine how the episodic weather-induced mixing events influenced thermal structure, hypolimnetic dissolved oxygen (DO), fluorometric chlorophyll estimates (Chl-*a*), and lake metabolism and how these events varied in frequency and magnitude in lakes with different characteristics. Rise in wind speed alone had an effect on the lakes with the weakest thermal stability, but a decrease in air temperature together with strong wind induced mixing events in all lakes. The return period of these mixing events varied widely (from 20 to 92 d) and was dependent on the magnitude of change in weather. In lakes with strong stability, thermal structure and hypolimnetic DO concentration were only slightly affected. Weather-induced mixing in the upper water column diluted the surface water Chl-*a* repeatedly, whereas seasonal maximum occurred in late summer on each lake. Although Finnish lakes have been characterized with stable stratification during summer, we observed many substantial mixing events of relatively short return periods relevant to both chemical and biological properties of the lakes.

Key words: automated water quality monitoring, chlorophyll *a*, episodic events, hypolimnetic oxygen, lakes, production, stability

Introduction

The dynamics of freshwater lakes are nonlinear (Carpenter et al. 2011) and variable on both spatial and temporal scales (Levin 1992, Heini et al. 2014), which leaves the detection of many short-term physical and biological processes outside the limits of traditional water quality monitoring (Kratz et al. 2006). Abrupt changes in lake ecosystems are often driven by weather-induced episodic events (Jennings et al. 2012, Klug et al. 2012, Crockford et al. 2014), and therefore modern tools, including automated water quality monitoring (AWQM), are needed to understand these changes (Benson et al. 2009, Kallio et al. 2010, Hamilton et al. 2014).

Because lakes provide numerous important ecosystem services, such as drinking water supply, fisheries, and recreation (Aylward et al. 2005, Kratz et al. 2006), it is important to understand their response to

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Table 1. Location and limnological characteristics of the study lakes. Chlorophyll *a* (Chl-*a*), water colour and total phosphorus represent mean summer (Jun-Aug) values in the epilimnion or the uppermost 1 m layer. Data from HERTTA-database of Finnish Environment Institute (SYKE). A_o is surface area of the lake .

Lake	Lat	Long	A_o, km^2	Max depth, m	Mean depth (z), m	$\frac{z}{\sqrt{A_o}}$	Mean Chl-*a*, µg L^{-1}	Mean colour mg L^{-1} Pt	Mean total phosphorus, µg L^{-1}
Jyväsjärvi	62°15′N	25°47’E	3	25	7.0	4.0	10.8	70	25
Pallasjärvi	68°01′N	24°12’E	17	36	9.0	2.2	2.1	13	5
Vesijärvi	61°15′N	25°47’E	44	42	6.8	1.0	9.6	10	27
Vanajavesi	61°08′N	24°16’E	103	24	7.7	0.8	16.0	50	24
Pyhäjärvi	61°01′N	22°17’E	155	26	5.5	0.4	7.2	17	20
Konnevesi	62°38′N	26°24’E	189	57	10.6	0.8	4.2	25	6
Yli-Kitka	66°07′N	28°39’E	237	41	6.6	0.4	3.9	30	9
Päijänne	62°09′N	25°47’E	1050	95	14.2	0.4	5.9	29	13

weather-induced episodic events, which are likely to become more severe in the future (Dokulil 2013, IPCC 2014). Future climate scenarios predict that the North Atlantic weather system will become more unstable with heavier storms (Hov et al. 2013). In northern Europe, a longer open-water season and stratified period are also expected, increasing exposure of lakes to external forcing, which in turn may alter their internal dynamics (Huttula et al. 1992, Bergström et al. 2011, Forsius et al. 2013).

A strict seasonality, with full turnover in spring and autumn (Lewis 1983), characterizes dimictic boreal lakes and causes dramatic changes in their physical, chemical, and biological parameters (Bengtsson 1996, Pulkkanen 2013). During the stratified season, intermediate disturbances (from minutes to days with their own seasonality) can be important to lake ecosystem functioning (Padisák 1993, Flöder and Sommer 1999). During summer, recurring low pressure systems with cool air and high wind speed can cause mixing in lakes by lowering the water-column stability and deepening the epilimnion (Spigel and Imberger 1987). A partial or complete overturn in stormy weather (Soranno et al. 1997) will introduce hypolimnetic water into the epilimnion (Jennings et al. 2012). Mixing can inject oxygen and heat into the deeper water layers, and the resulting nutrient upwelling from the hypolimnion can cause sudden algal blooms (Kallio 1994, Soranno et al. 1997).

In Finland, weather in summer is characterized as a variation between the eastern high and low pressure systems travelling across the country in a southwest to northeast direction. These systems, occurring periodically and lasting typically from 3 to 5 days, vary in their temperature and wind conditions (Heino 1994). Thermal stratification in summer is a typical phenomenon in most Finnish lakes (Kuusisto 1981), and therefore any major changes in temperature and dissolved oxygen (DO) stratification may affect their productivity by changing the nutrient availability and, subsequently, the biotic activity in the lake, as has been shown elsewhere (e.g., Charlton 1980, Nõges et al. 2011, van de Bogert et al. 2012).

In this study we used comprehensive on-site meteorological and AWQM data from 8 boreal lakes in Finland and combined manually collected low-frequency data to study the response of the lakes to weather-induced mixing events. The study included a simultaneous monitoring period in all study lakes. Specifically, we concentrated on the stratified summer period and aimed to quantify the frequency of the mixing events and changes they caused in water column stability, hypolimnetic DO, fluorometric chlorophyll *a* (Chl-*a*) estimates, and (case wise) metabolism estimates. In addition, we aimed to determine the essential drivers of the events and quantify their magnitude.

Methods

Study lakes

For the multi-lake comparison, AWQM and discrete datasets were combined from 8 Finnish lakes representing areas from northern (68°N) to southern (61°N) Finland: Pallasjärvi, Yli-Kitka, Konnevesi, Jyväsjärvi, Päijänne, Vesijärvi, Vanajavesi, and Pyhäjärvi (Fig. 1). The lakes are mostly dimictic with the exception of polymictic Pyhäjärvi. The lakes represent a wide range of surface area (3–1050 km^2) and maximum depth (24–95 m). Their trophic status varies from oligotrophic to eutrophic and water colour from clear to humic (Table 1).

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Table 2. Sampling depths (m) and years (in Jun-Aug) for automated and discrete monitoring of water temperature, dissolved oxygen (DO) and Chlorophyll *a* (Chl-*a*) in the study lakes (basins).

Lake (basin)	Depth (m) for temperature	Depth (m) for DO	Depth (m) for Chl-*a* (in 2013)	Study years	Citation
Jyväsjärvi	1, 2, 5, 7, 10, 15	15		2013	Kuha et al. 2016
Pallasjärvi	1–33 (1 m step)	33*		2013	Lohila et al. 2015
Vesijärvi (Kajaanselkä)	1, 5, 15, 25	25	1.0	2011, 2013	Anttila et al. 2013
Vanajavesi (Vanajanselkä)	1.5, 2, 3–10,* 14,* 23*	25*	1.0	2013	Heini et al. 2014
Pyhäjärvi	1, 5,* 10,* 15,* 26*	25*	1.0	2009, 2013	Lepistö et al. 2010
Konnevesi (Näreselkä)	1–40 (1 m step)	1.5, 40	1.5	2013, 2014	Kuha 2016
Yli-Kitka (Vasik-kaselkä)	1.5, 30	30		2013	Karjalainen and Hellsten 2015
Päijänne (Ristinselkä)	1, 5, 10, 15, 25, 35, 50, 70, 90	90*		2013	Kuha 2016

*Discrete water temperature or dissolved oxygen concentration data obtained from Hertta-database maintained by Finnish Environment Institute (SYKE).

Data

AWQM data for summer (Jun, Jul, Aug) water temperatures were available from all lakes during 2013 (Table 2). Water temperature was measured by AWQM at 10 min to 3 h intervals from surface water (1.0 or 1.5 m) and from selected depths at the same interval, or with discrete sampling at a 1-4 week interval (Table 2). Water temperature data were measured with temperature data loggers or profiling systems (Table 3). Similarly, AWQM data of near-bottom DO concentrations were available from 4 of the study lakes and discrete data from others (Table 2). Optical DO sensors were used for data collection (Table 3). With identical specification, additional summer AWQM data of water temperature and DO from other years were available from lakes Konnevesi, Vesijärvi, and Pyhäjärvi (Table 2). In summer 2013, automated Chl-*a* (fluorescence) data, measured with single-wavelength fluorometers, were available from the surface water (1.0 or 1.5 m) from 4 of the study lakes at a 1–3 h interval (Table 2). The fluorometric data were calibrated to Chl-*a* concentration (µg L^{-1}, measured in laboratory with ethanol extraction) by using site-specific calibration equations (linear regression). In lakes where cyanobacteria are known to make a major contribution to chlorophyll, multiple linear regressions were used in calibration, accounting for both Chl-*a* and phycocyanin (PC) fluorescence, measured with PC fluorometers simultaneously with chlorophyll fluorescence and calibrated with cell counts of cyanobacteria (Table 3). These fluorometric Chl-*a* estimates consist of

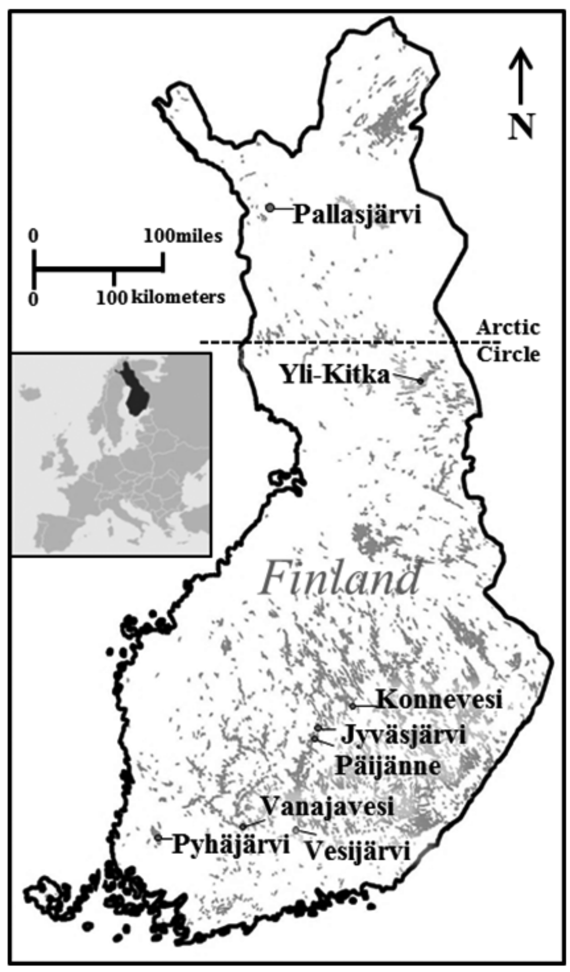

Fig. 1. Locations of the study lakes in Finland.

Table 3. Instrumentation used on the study lakes (basins) and chlorophyll *a* (Chl-*a*) sensor calibration with linear regression.

Lake (basin)	Meteorological station	Water temperature sensor	Dissolved oxygen sensor	Chl-*a* sensor (in 2013)	Chl-*a* sensor calibration
Jyväsjärvi	Vantage Pro 2, Davis Ins. Co., Hayword, CA, USA	Thermochron 1922L, Express Thermo, San Jose, CA, USA	3835, Aanderaa Data Ins., Bergen, Norway		
Pallasjärvi	uSonic-3, Metek GmbH, Elmshorn, Germany; Pt100 thermosensor	Tinytag Aquatic 2 TG-4100, Gemini Data Loggers, Chichester, UK			
Vesijärvi (Kajaanselkä)	Vaisala WXT520, Vaisala Co., Helsinki, Finland	NTC, WTW GmbH, Weilheim, Germany	FDO 700 IQ, WTW GmbH, Weilheim, Germany	MicroFlu, Trios, Rastede, Germany	0.97 × sensor + 5.98 × PC −3.46, $R^2 = 0.97$, $n = 7$
Vanajavesi (Vanajanselkä)	WMO station 02863, Finland	YSI600, YSI Inc., Yellow Springs, OH, USA	YSI600, YSI Inc., Yellow Springs, OH, USA	YSI600, YSI Inc., Yellow Springs, OH, USA	0.88 × sensor +8.85, $R^2 = 0.39$, $n = 12$
Pyhäjärvi	WXT510, Vaisala Co., Helsinki, Finland	Marvet, Helox13-25, Elke Sensor Oy Tallinn, Estonia	Marvet, Helox13-25, Elke Sensor Oy Tallinn, Estonia	MicroFlu, Trios, Rastede, Germany	sensor +4.00 × PC −0.69, $R^2 = 0.88$, $n = 10$
Konnevesi (Näreselkä)	a-Weather, a-Lab Ltd., Keuruu, Finland*	YSI6600V2-4, YSI Inc., Yellow Springs, OH, USA	YSI6600V2-4, YSI Inc., Yellow Springs, OH, USA	YSI6600V2-4, YSI Inc., Yellow Springs, OH, USA	7.85 × sensor −3.09, $R^2 = 0.75$, $n = 38$
Yli-Kitka (Vasikkaselkä)	DS18B20, Vaisala Co., Helsinki, Finland	T100, EHP Tekniikka Ltd, Oulu, Finland	Hach-Langen LDO Berlin, Germany		
Päijänne (Ristinselkä)	Jyväsjärvi data used (distance 20 km)	TSIC50x, IST AG, Ebnat-Kappel, Switzerland	4175C, Aanderaa Data Ins., Bergen, Norway		

*Lake Jyväsjärvi station (~55 km from Konnevesi) used for solar radiation data. PC = cyanobacterial biomass estimated with phycocyanin fluorometer.

nighttime fluorescence (average of values measured between 24:00 and 09:00 h) to avoid effects of non-photochemical quenching on measurements (Huot and Babin 2010, Huotari and Ketola 2014).

As an index for water column stability, we calculated the Schmidt Stability Index (*Sc*; kJ cm^{-2}) using automatically and manually measured water temperature profiles (Schmidt 1928, Idso 1973) as follows:

$$Sc = \frac{g}{A_o}\int_{z_o}^{z_m}(\rho_z - \rho_m)(z - z_g)A_z dz \quad (1)$$

where g is acceleration due to gravity (cm s^{-2}), A_o is surface area of the lake (m^2), z_m is maximum depth of the lake (m), A_z is area of the lake at depth z (m^2), ρ_m is average density during the isotherm (g m^{-2}), ρ_z is density (g m^{-3}) at depth z, and z_g is the depth of the center of gravity during the isotherm (m). The sum of all depths was calculated for the depth of the water column (dz).

On-lake or near-shore meteorological stations at the study lakes measured wind speed, air temperature, humidity, and solar radiation at 1–30 min intervals (Table 3). The wind speed data were corrected to the reference height of 10 m (U_{10}, m s^{-1}; Amorocho and DeVries 1980) to remove the effect of measurement height between the stations:

$$U_{10} = U_z\left[1 - \frac{C_D^{0.5}}{\kappa}\, ln\left(\frac{10}{z}\right)\right]^{-1}, \quad (2)$$

where κ is von Karman's constant (0.4) and U_z is wind speed (m s^{-1}) measured at height z (m) above water surface. Values used for bulk transfer coefficient over water, C_D, were 1.0×10^{-3} for U_{10} <5 m s^{-1} and 1.5×10^{-3} for >5 m s^{-1}. All meteorological data were averaged to 30 min according to the least frequent data to remove the effect of sampling interval between the stations. Additionally, daily (or nightly for Chl-*a*) averages of individual variables were calculated for both AWQM and meteorological data.

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Table 4. Meteorological and limnological variables during the strong mixing events in 2013 and the seasonal maximum stabilities in the study lakes. The disruption of stratification was indicated with hypolimnetic dissolved oxygen (DO) response (Yes = complete renewal of hypolimnetic DO; + = 1–2 mg L^{-1} introduction of DO; No = no change or decrease in DO). Sc is the Schmidt Stability Index.

Date	Lake	Wind speed, m s^{-1}		Air temperature, °C		Water temperature, °C				Maximum *Sc* kJ cm^{-2}	Mixing Yes/No	DO renewal
						Surface		Near bottom				
		Event max	Seasonal mean	Max	Min	Before	After	Before	After			
9 Jun 2013	Pallasjärvi	18.0	3.6	16.3	6.1	14.3	9.4	5.0	5.0	353	No	No
7 Jul 2013		20.7		15.4	10.5	15.5	13.3	6.4	6.5		No	No
10 Jun 2013	Yli-Kitka	4.4	1.8	14.8	6.1	15.0	12.2	2.5	2.6	85	Yes	Yes
7 Jul 2013		5.2		17.9	9.6	17.8	14.9	8.2	14.4		Yes	+
7 Aug 2013		4.5		19.8	12.6	19.8	16.8	10.1	10.4		No	No
30 Jun 2013	Konnevesi	11.3	3.1	19.8	16.6	22.2	18.5	5.8	5.8	519	No	No
6 Jul 2013		8.0		19.9	15.5	20.4	18.3	5.9	6.0		No	No
14 Jul 2013		14.7		17.9	11.7	19.4	12.2	6.0	6.1		No	No
7 Aug 2013		11.4		20.4	15.1	21.3	17.5	6.2	6.4		No	No
14 Jul 2013	Jyväsjärvi	7.8	2.9	18.5	12.6	21.8	17.2	6.1	6.1	258	No	No
8 Aug 2013		6.7		21.2	13.9	22.3	18.9	6.1	6.1		No	No
14 Jul 2013	Päijänne	7.8	2.9	18.5	12.6	22.9	16.5	4.7	4.9	1125	No	No
28 Jul 2013		5.9		20.7	19.0	21.3	16.9	5.0	5.1		No	No
29 Jun 2013	Vesijärvi	2.8	1.9	18.6	13.8	21.4	19.1	6.1	6.3	181	No	No
15 Jul 2013		5.2		20.0	12.7	20.6	16.5	6.4	6.8		No	No
11 Aug 2013		4.8		21.3	13.1	20.7	17.7	6.9	7.2		No	No
15 Jul 2013	Vanajavesi	11.8	2.8	23.4	16.9	20.1	16.9	8.9*	9.4*	182	No*	No*
29 Jul 2013		7.2		23.8	19.6	20.3	18.0	9.4*	9.9*		No*	No*
11 Aug 2013		11.3		24.0	17.5	20.0	17.8	9.9*	10.5*		No*	No*
8 Jun 2013	Pyhäjärvi	11.1	4.9	17.8	12.6	20.2	16.7	nd	8.4*	18	No*	No*
14 Jul 2013		14.7		19.3	14.4	20.6	16.7	10.1*	18.8*		Yes*	Yes*
8 Aug 2013		11.4		19.5	14.6	20.8	18.2	18.6*	nd		Yes*	Yes*

*Additional physical and/or chemical data obtained from HERTTA; database maintained by Finnish Environment Institute (SYKE) or other discrete sampling. nd = no data.

For subsequent analysis after observing the high-frequency data, we selected mixing events followed by a noticeable decrease (events that caused monotonic decrease for ≥2 days) in daily average surface water (1 or 1.5 m) temperature. Events that decreased the surface water temperature by >2 °C were studied more closely (hereafter referred to as high disturbance events). Maximum and minimum values from wind speed (U_{10}), air temperature, water temperature, and DO data were then determined from the high-frequency (30 min or 3 h) data during these events.

The return period (RP, number of days) for the events was calculated as (Mays 2010):

$$RP = (n + 1)/m, \quad (3)$$

where m is the rank of the event and n is the number of recorded days (e.g., 92 d for full record in Jun, Jul, and Aug 2013).

Relationships between the surface water (1.0 or 1.5 m) temperature decrease (°C) and the maximum wind speed, maximum mean daily wind speed (both expressed as change from the seasonal mean wind speed for each site), and decrease in the air temperature during the events were described by linear regressions. Relationships between RP and the maximum wind speed, maximum mean daily wind speed, and decrease in the air temperature during the events were described with log-linear regressions.

To evaluate the renewal or cessation of the DO reserves in the hypolimnion during the events, change in the DO concentration (mg L^{-1}) was examined from the near bottom (1 m above sediment) AWQM and discrete data during the mixing events. The effects on hypolimnetic DO were then divided into subgroups; complete, substantial (+), or no renewal of the DO in the hypolimnion; substantial renewal represented up to a 2 mg L^{-1} increase in the observed DO concentration.

Table 5. Meteorological and limnological variables during the high disturbance events in Konnevesi in 2014, in Vesijärvi in 2011 and in Pyhäjärvi in 2009 and seasonal maximum stabilities in the study lakes. The disruption of stratification was indicated with hypolimnetic dissolved oxygen (DO) response (Yes = complete renewal of hypolimnetic DO; + = 1–2 mg L^{-1} introduced DO, No = no change or decrease in DO).

Date	Lake	Wind speed, m s^{-1}		Air temperature, °C		Water temperature, °C				Maximum seasonal Sc kJ cm^{-2}	Mixing Yes/No	DO renewal
						Surface		Near bottom				
		Event max	Seasonal mean	Max	Min	Before	After	Before	After			
8 Jun 2014	Konnevesi	5.4	2.8	21.0	5.7	17.9	14.5	6.8	6.8	661	No	No
12 Jun 2014		8.5		14.8	9.7	16.8	11.9	6.8	6.8		No	No
8 Aug 2014		5.2		20.5	14.6	23.6	20.0	7.3	7.4		No	No
2 Jul 2011	Vesijärvi	4.1	2.0	26.1	15.1	23.1	20.8	9.6	9.8	176	No	No
10 Jul 2011		4.8		23.3	15.8	23.3	20.9	9.8	10.1		No	No
27 Jul 2011		4.9		23.6	14.1	23.1	21.1	10.1	10.3		No	No
1 Jun 2009	Pyhäjärvi	10.5	5.0	21.2	9.1	17.2	13.6	13.6	13.1	57	Yes	+
2 Jul 2009		13.8		25.4	14.2	21.1	17.6	13.4	17.0		Yes	Yes
9 Aug 2009		11.9		25.0	14.0	21.3	17.6	18.7	17.5		Yes	Yes

Hourly surface (1.5 m) DO data from Konnevesi were used to calculate daily rates of net ecosystem production (NEP), gross primary production (GPP), and respiration (R) in the lake. Solar radiation data from Jyväsjärvi meteorological station (55 km southwest from Konnevesi) were used to estimate photosynthetically active radiation (PAR). Hourly water temperature profiles were obtained by interpolating from the 3 h profiler data. NEP, GPP, and R were calculated by the open-water method (Odum 1956) using LakeMetabolizer, an R 3.2.2 package implementation of free-water metabolism models (Venables et al. 2015 ; L.A. Winslow et al. 2016).

Results

Mixing events and return period

Altogether, 50 weather-induced mixing events were recorded in the study lakes. In 2013, 2–4 of the events per lake were determined as high disturbance events (continuous decrease in daily surface water temperature >2 °C; Table 4). These high disturbance events typically occurred within a few days in all the study lakes and were related to low pressure weather systems passing over Finland. During other study years, 3 high disturbance events were determined in lakes Konnevesi, Vesijärvi, and Pyhäjärvi (Table 5). The events were related to the highest wind speeds and largest air temperature changes recorded at each site (Table 4 and 5).

In summer 2013, the first low pressure system causing high disturbance mixing events passed over Finland in June, the second in July, and the third in August. During the first event in mid-June, no full overturn was observed in any lake (Fig. 2, Table 4), and Yli-Kitka, a large northern lake, was not yet stratified (Fig. 2II). The second mixing event in July caused a complete overturn in lakes Yli-Kitka and Pyhäjärvi but not in other lakes (Fig. 2II and VIII, Table 4). These 2 lakes had the lowest water column stability (Table 4). The third mixing event in early August led to warming of deeper waters, but no complete mixing was observed in any of the study lakes (Fig. 2, Table 4). At the time of the mixing event, Pyhäjärvi had not yet fully recovered from the earlier mixing in July (Fig. 2VIII). In the northernmost lake, Pallasjärvi, autumnal mixing had already begun in early August (Fig. 2I).

Data from the other study years indicated 3 high disturbance events in Konnevesi, Vesijärvi, and Pyhäjärvi (Table 5). In Konnevesi, mixing was caused by increased daily wind speeds ranging from 5.2 to 8.5 m s^{-1} and a simultaneous drop in air temperatures (Table 5). In Vesijärvi, relatively low wind speeds (<5 m s^{-1}) resulted in the transport of heat into the hypolimnion during the events (Table 5). In 2009, 3 high disturbance events were observed in Pyhäjärvi, all related to high wind speed and a simultaneous drop in air temperature (Table 5). Additionally, complete mixing of the water column in Pyhäjärvi occurred on 13 June and 18 July, although these were not classified as major events in the data due to weak stratification of the lake. Maximum wind speeds during these events were 8.9 and 7.8 m s^{-1}, and air temperatures decreased to 10.4 and 13.7 °C from 19.8 and 21.9°C, respectively.

When all the events, defined as a 2-day continuous decrease in the surface water temperature, were compared to meteorological drivers, no significant relationship between surface water temperature decrease and maximum (30 min) wind speed was found (Fig. 3a) during the events. A positive relationship was observed, however, between surface water temperature decrease and maximum daily wind speed during the events (Fig. 3b; R^2 = 0.352, p = 0.012, n = 50). The event-related decrease in air

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temperature also correlated positively with the decrease in the surface water temperature (Fig. 3c; R^2 = 0.466, p = 0.001, n = 50). The RP of the disturbance in the water column did not correlate with the maximum wind speed (Fig. 3d) but had a significant relationship with the maximum daily wind speed (Fig. 3e; R^2 = 0.121, p = 0.014, n = 50) and with the air temperature decrease during the events (Fig. 3f; R^2 = 0.310, p < 0.001, n = 50). RP for the high disturbance events varied between 20 and 92 d.

During the studied summers, complete mixing occurred only in lakes Yli-Kitka and Pyhäjärvi, and their Sc remained <100 kJ cm^{-2} (Fig. 4a). Jyväsjärvi, the smallest and most humic of the study lakes, had the most stable water column, indicated by the highest post-event difference between surface and near-bottom water temperatures (Fig. 4b–c).

Hypolimnetic dissolved oxygen response

In each lake, DO concentration of the hypolimnion responded differently to the high disturbance events. Distinct increases in DO concentrations were observed when the lakes were extensively mixed. Only lakes Yli-Kitka and Pyhäjärvi had a complete renewal or substantial increase in their hypolimnetic DO reserves during the events (Table 4 and 5). Before the first mixing event in June 2013, Yli-Kitka had not formed stable stratification and therefore had no hypolimnetic DO deficit. During the second mixing event in July, the hypolimnetic DO concentration increased from 9.1 to 9.5 mg L^{-1} in the lake (Table 4). Conversely, in mesotrophic Pyhäjärvi, the hypolimnetic conditions were entirely related to DO reserves mixed downward from the

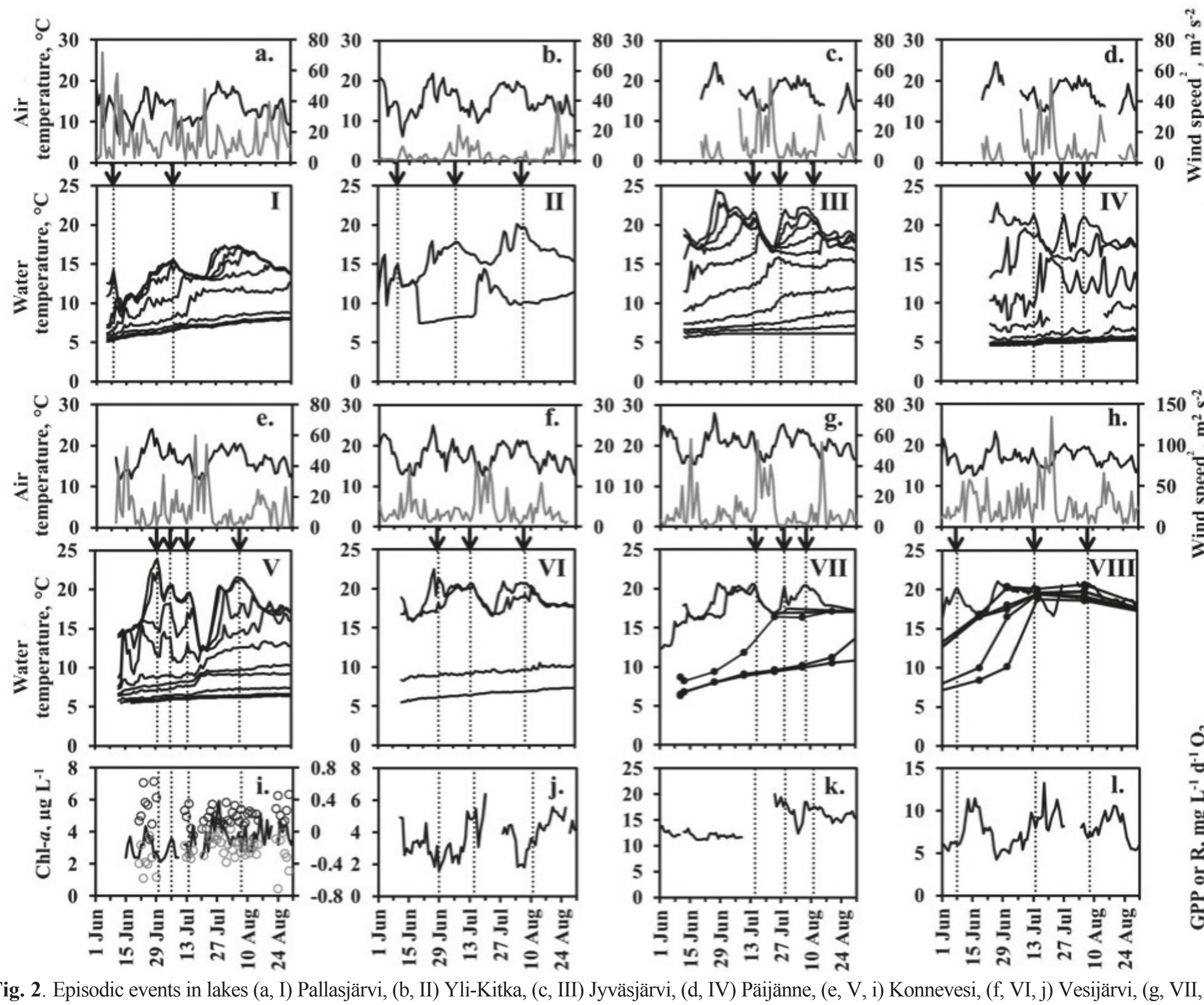

Fig. 2. Episodic events in lakes (a, I) Pallasjärvi, (b, II) Yli-Kitka, (c, III) Jyväsjärvi, (d, IV) Päijänne, (e, V, i) Konnevesi, (f, VI, j) Vesijärvi, (g, VII, k) Vanajavesi, and (h, VIII, l) Pyhäjärvi during summer (Jun–Aug) 2013: (a–h) daily averages of meteorological variables, (I–VIII) daily averages of water temperature at selected depths, (black points) daily gross primary productivity (GPP), and (grey points) respiration (R: plotted on negative scale to illustrate consumption of oxygen O_2; i: from Konnevesi only), and (i–l) nighttime averages of chlorophyll a estimates (Chl-a: from Konnevesi, Vesijärvi, Vanajavesi, and Pyhäjärvi only). Note the squared wind speed scale. See Table 2 for details: for lakes with profiler, the selected depths are in the following order from top line: 1, 2, 3, 5, 7, 10, 15, 20, 25, 30, 35, and 40 m according to lake depth. Black arrows and vertical dashed lines indicate timing of high disturbance in the surface (1.0 or 1.5 m) water temperature (decrease in temperature >2 °C). Black circles = data from discrete sampling.

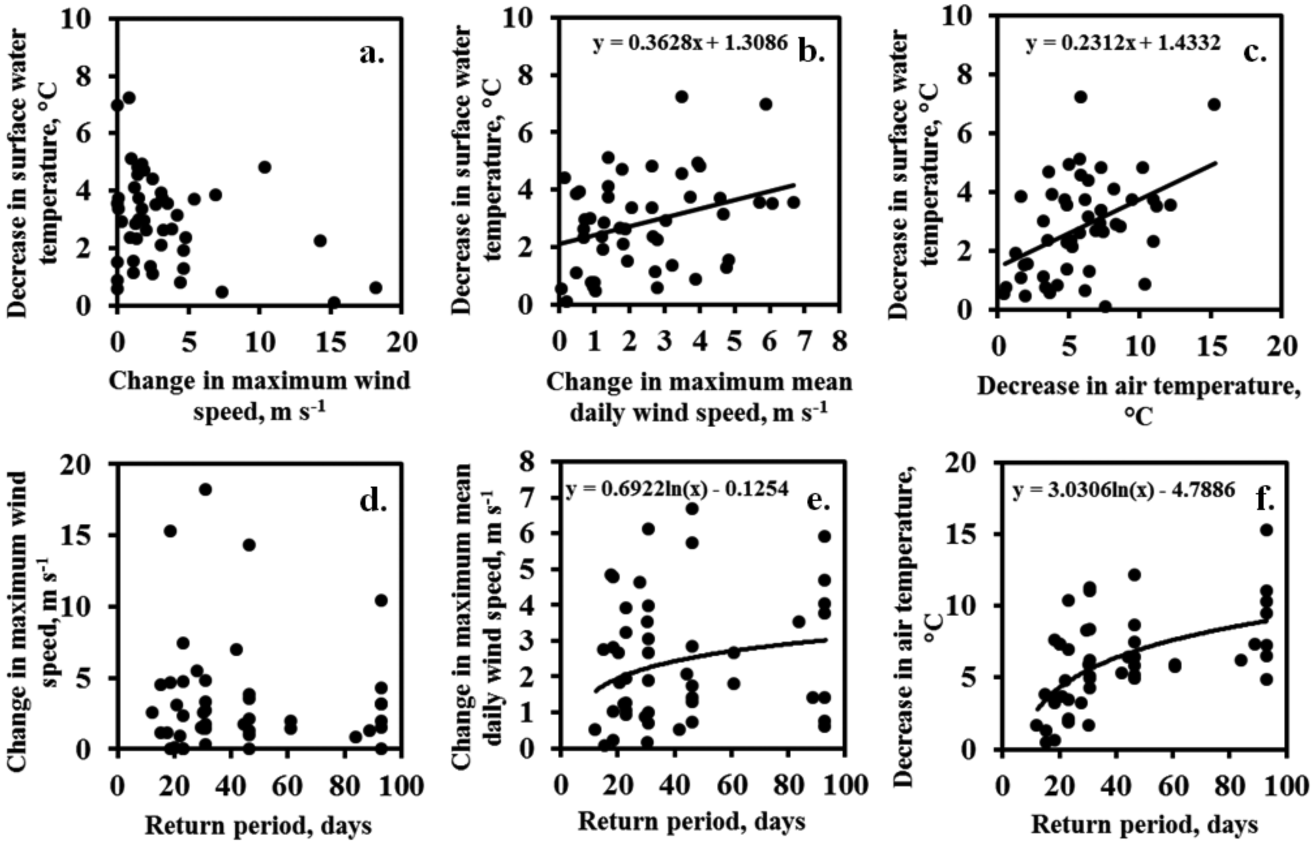

Fig. 3. Surface water (depth of 1.0 or 1.5 m) temperature decrease (°C), and return period (days) of events plotted against (a, d) the maximum (30 min) wind speed and (b, e) the maximum mean daily wind speed, expressed as change from the seasonal mean wind speed for each site, and (c, f) decrease in the air temperature during the events.

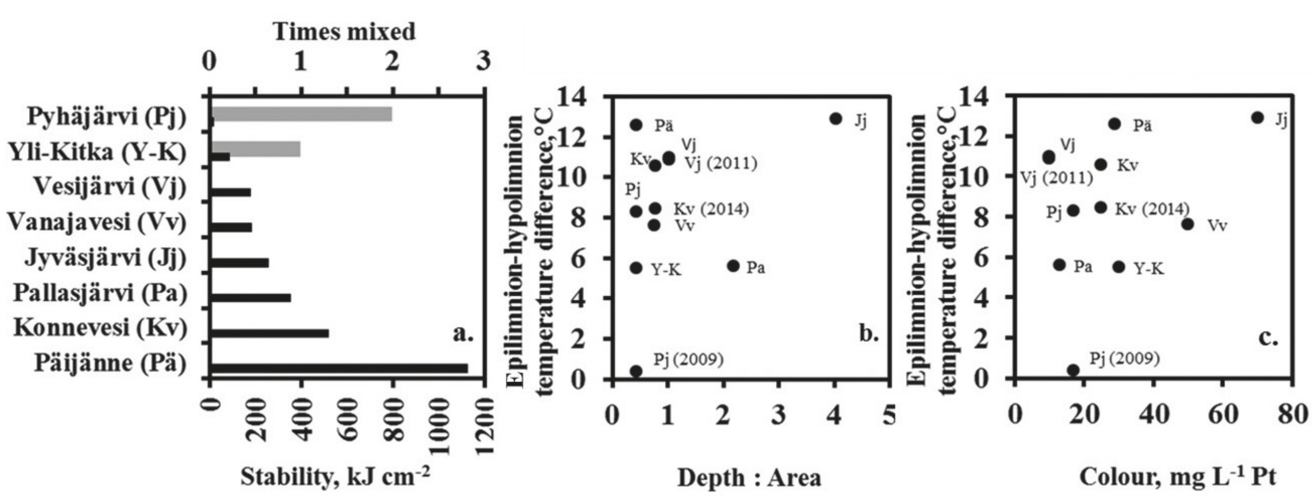

Fig. 4. Maximum seasonal stability (black bars) and number of occasions of complete mixing (grey bars) on the study lakes in 2013; (a) lake characteristics plotted against average difference in water temperature between epilimnion and hypolimnion after the events, (b) lake mean depth to surface area ratio, and (c) water colour in the study lakes.

 DOI: 10.5268/IW-6.4.886

upper water column. Longer stratification periods led to a decrease of the hypolimnetic DO reserves. In 2009 the 3 episodic mixing events resulted in substantial increase or complete renewal of hypolimnetic DO concentration in the lake (Table 5); on 1 June hypolimnetic DO concentration increased from 9 to 10.0 mg L^{-1}, on 2 July from 3.9 to 8.7 mg L^{-1}, and on 9 August from 0.6 to 8.2 mg L^{-1}. The 2 other mixing events (on 13 June and 18 July) caused no substantial change in the surface water temperature due to weak stratification but increased the hypolimnetic DO concentrations. On 13 June and 18 July the DO increased from 8.1 to 10.7 mg L^{-1} and from 3.5 to 7.0 mg L^{-1}, respectively. In the other study lakes, no substantial increases in the hypolimnetic DO concentrations were observed.

Chlorophyll and lake metabolism response

In summer 2013, the highest Chl-*a* values were measured in Vanajavesi and the lowest in Konnevesi, varying between 11.2 and 20.0 µg L^{-1} and 1.4 and 6.0 µg L^{-1}, respectively (Fig. 2). In Vesijärvi, Chl-*a* varied between 1.6 and 6.4 µg L^{-1}, with the lowest values recorded toward the end of stratified season (Fig. 2j). In Vanajavesi, Chl-*a* remained at a relatively constant level (11–15 µg L^{-1}) in the beginning of summer, but after the mixing event in mid-July, Chl-*a* increased from the pre-event average of 12.1 to 16.4 µg L^{-1} (Fig. 2k). Unfortunately, in July there was a gap in the Vanajavesi data, and we could not evaluate the effects in the lake in detail. In Pyhäjärvi, the first mixing event preceded the substantial increase in Chl-*a* (from 5.7 to 11.2 µg L^{-1}) starting on 11 June. On 25 June, however, the Chl-*a* values had already returned to the previous level (Fig. 2l). In all study lakes, all maximum Chl-*a* values were recorded within 10 days, starting on 18 July in Pyhäjärvi. In most lakes, the high disturbance events diluted the surface water Chl-*a* by mixing with metalimnetic and hypolimnetic water, resulting in lower Chl-*a* concentrations. Mean daily NEP (GPP − R) in Konnevesi varied between −0.3 and 0.2 mg L^{-1} d^{-1} O_2, with a seasonal average close to zero. Estimates of GPP and R remained low throughout the season, both having their highest values in the early summer at the beginning and toward the end of thermal stratification (Fig. 2i).

Discussion

Changes in wind speed and air temperature are known to modify thermal stability and heat distribution of lakes (Imboden and Wüest 1995, Wilhelm and Adrian 2008). In agreement with that, our study lakes also responded to the episodic weather-induced events, but their response varied depending on the strength of thermal stratification, which in turn depended on, among other factors, the morphometric characteristics of the lake. Low pressure systems with high wind speeds, but with no substantial change in air temperature, caused complete mixing only in Pyhäjärvi, a large, weakly stratified clear-water lake in southern Finland. Yli-Kitka, a large clear-water northern lake, has been considered dimictic, but a cold and windy period in July 2013 resulted in a complete mixing of the lake. By contrast, the smallest and most humic lake, Jyväsjärvi, had the most stable water column, typical of small brown-coloured lakes (Bowling and Salonen 1990). Shallow lakes are usually more vulnerable to mixing than deeper lakes (Boehrer and Schultze 2008, Arvola et al. 2010, Woolway et al. 2015), but strong external forcing for complete mixing may also be needed if the lake is small enough and sheltered against wind (Bowling and Salonen 1990, Nordbo et al. 2011).

The short return periods found in this study were similar to those found in other strongly stratified lakes in Europe. For example, Blelham (UK) and Slotssø (Denmark), studied by Jennings et al. (2012), also had short return periods (0.1–0.2 yr). In both lakes, the recovery period of stratification was <15 d. In our study lakes wind speeds were only moderate compared to those recorded by Jennings et al. (2012), but even after strong wind, the lakes may have short-lived response in their stability. For instance, the effects of hurricane Irene on the thermal stratification of lakes in the United States and Canada were observable for only 1 week (Klug et al. 2012).

Both Jennings et al. (2012) and Klug et al. (2012) showed that despite short-term effects on thermal conditions, the weather-forcing related effects on chemistry and biology of the lakes can be long lasting. Responses to nutrient and dissolved organic carbon concentration changes as well as changes in metabolic processes may affect the productivity of lakes (e.g., Drakare et al. 2002, Coloso et al. 2011, Solomon et al. 2013). In our lakes, the effects on the hypolimnetic DO conditions were relevant only in the lakes with weak stability and after substantial mixing. DO content of the water column is known to be strongly linked to mixing (Golosov et al. 2012), and when mixing occurs after a long stratified period with hypolimnetic anoxia, upwelling of accumulated hypolimnetic nutrients may fertilize phytoplankton production (e.g., Huisman et al. 1999, Wilhelm and Adrian 2008, Crockford et al. 2014). In our study, Vanajavesi showed the most prolonged increase in Chl-*a* after the episodic mixing, but a similar increase was also observed in Konnevesi. Despite the change in Chl-*a* in Konnevesi, however, no changes in GPP and/or R could be found, which contradicts observations by Obrador et al. (2014) that mixing may influence the metabolic activity of a lake. The estimate of lake metabolism in Konnevesi was based on the results of one DO sensor at the surface, therefore providing a rough estimate of the metabolism (van de Bogert et al. 2012, Obrador et al. 2014).

In lakes Vesijärvi and Pyhäjärvi, water column mixing clearly decreased Chl-*a*. Mixing is known to dilute Chl-*a* in deeper water layers (MacIntyre et al. 2009), but changes in the thermal stability may also affect the community composition of phytoplankton (Wilhelm and Adrian 2008, Nõges et al. 2010, Cottingham et al. 2015) because mixing conditions generally favor diatoms (Reynolds 2006), whereas stagnant stable conditions are beneficial to cyanobacteria (Paerl and Huisman 2008). In Pyhäjärvi, the early summer bloom originates from a rapid succession of diatoms in the water column (Kallio et al. 2010), typical for many temperate and boreal lakes (e.g., Wetzel 2001), but also partly from the resuspension of settled phytoplankton that mixing in the lake promotes (Finnish Environment Institute, unpubl. data).

This study demonstrated that, in summer, lakes in Finland may face similar episodic weather-induced mixing events regardless of their geographical location because the low pressure areas entering from Atlantic Ocean can cross the whole country (Heino 1994). High wind speeds together with a decrease in air temperature could lead to a rapid change in thermal stratification of any of the study lakes, which cannot be detected by less frequent traditional monitoring. The climate-related changes in air temperature are predicted to take place mostly in autumn and winter in northern Europe (Jylhä et al. 2010), without any direct effect on wind speeds or cold periods in summer (Hov et al. 2013). In the future, however, a changing climate may support stronger storms in summer and consequently more efficient mixing periods during the stratification. Increasing wind speeds have already been observed in northern Europe, but their relationship to climate change is not known (Blenckner et al. 2009, Donat et al. 2011, Brönnimann et al. 2012, Hov et al. 2013). In the future, the stratified period in Europe is predicted to lengthen (Blenckner et al. 2009) in both dimictic (Bergström et al. 2011) and polymictic lakes (Adrian et al. 2009), and hypolimnetic oxygen depletion may become more prevalent. However, if the stratified period in European lakes lengthens in the future as has been predicted (Adrian et al. 2009, Blenckner et al. 2009, Bergström et al. 2011), hypolimnetic oxygen depletion may become more prevalent in both dimictic and polymictic lakes.

Considering projected future changes in weather-induced events, more detailed studies with short- and long-term perspectives of the response of lake ecosystems are needed (Jentsch et al. 2007, Williamson et al. 2009). Networking AWQM has untapped potential (Goodman et al. 2015, Hamilton et al. 2014), but our study clearly shows that uniform measuring schema with hypothesis-oriented data collecting and mining is demanded for extensive and profound analysis of data from the AWQM networks.

Conclusions

Our results demonstrated that several weather-induced incomplete or complete mixing events per summer may take place in each of the study lakes independent of their geographic location. The lakes responded to the episodic weather-induced events individually, however, depending on their morphometric characteristics, trophic status, and other specific properties. AWQM data provide a unique opportunity to analyze in detail the responses of the study lakes. With caution, the results could be applied to other boreal lakes with less frequent sampling to predict their sensitivity to weather-induced mixing.

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