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Summer depth distribution profiles of dissolved CO_2 and O_2 in shallow temperate lakes reveal trophic state and lake type specific differences

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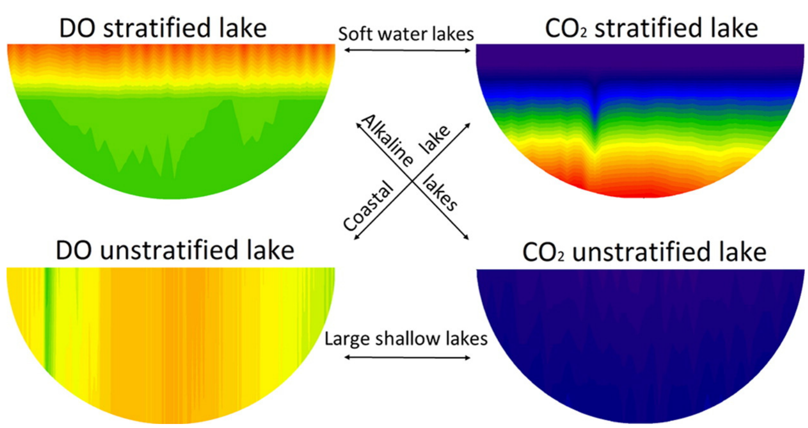
HIGHLIGHTS

- We measured CO_2 and DO profiles in 8 lake types at sub-hourly intervals over a week.
- Surface layers of alkaline and dystrophic lake were steadily supersaturated with CO_2.
- 3 lake types acted as CO_2 sinks, another 3 were in equilibrium with atmospheric CO_2.
- Vertical dissolved gas gradients occurred even in thermally non-stratified lakes.
- Differences in trophic state and depth accounted most for gas regime differences.

GRAPHICAL ABSTRACT



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ABSTRACT

Knowledge about dissolved oxygen (DO) and carbon dioxide (CO_2) distribution in lakes has increased considerably over the last decades. However, studies about high resolution dynamics of dissolved CO_2 in different types of lakes over daily or weekly time scales are still very scarce. We measured summertime vertical DO and CO_2 profiles at sub-hourly intervals during one week in eight Estonian lakes representing different lake types according to European Water Framework Directive. The lakes showed considerable differences in thermal stratification and vertical distribution of dissolved oxygen and CO_2 as well as different diurnal dynamics over the measurement period. We observed a continuous CO_2 supersaturation in the upper mixed layer of the alkalitrophic (calcareous groundwater-fed) lake and the dark soft-water lake showing them as CO_2 emitting "chimneys" although with different underlying mechanisms. In three lake types strong undersaturation with CO_2 occurred in the surface layer characterising them as CO_2 sinks for the measurement period while in another three types the surface layer CO_2 was mostly in equilibrium with the atmosphere. Factor analysis showed that DO% in the surface layer and the strength of its relationship with CO_2% were positively related to alkalinity and negatively to trophic state and DOC gradients, whereas deeper lakes were characterised by higher surface concentration but smaller spatial and temporal variability of CO_2. Multiple regression analysis revealed lake area, maximum depth and the light attenuation coefficient as variables affecting the largest number of gas regime indicators. We conclude that the trophic status of lakes in combination with type specific features such as morphometry, alkalinity and colour (DOC) determines the distribution and dynamics of dissolved CO_2 and DO, which therefore may indicate functional differences in carbon cycling among lakes.

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1. Introduction

Because aquatic primary producers consume CO_2 for photosynthesis at roughly the same rate as they release DO into water, and respiration can be seen as a reverse process of that, a strong coupling between DO and dissolved CO_2 in lake water could be assumed, at least in productive systems where the intensity of both processes is higher, making their effect on the concentration dynamics of dissolved gases more visible. Field measurements in lakes show that in some cases the dynamics of dissolved gases are indeed caused mainly by metabolism (Johnson et al., 2010.). In most cases, however, the distributions of DO and dissolved CO_2 are strongly decoupled for several reasons including CO_2 additions from allochthonous organic matter degradation (Jonsson et al., 2003) or volcanism (Jones, 2010), compartmentalisation of lake environments by thermal stratification (Baehr and DeGrandpre, 2004), pH dependence of dissolved CO_2 concentrations resulting from the functioning of the carbonate buffer (Marcé et al., 2015; Weyhenmeyer et al., 2015), nitrate or sulphate respiration in anoxic conditions (Liikanen et al., 2002), methanogenesis and methane release by ebullition (Casper et al., 2000), and anoxygenic photosynthesis (Bryant and Frigaard, 2006). Consistent low frequency oscillation in the CO_2 partial pressure, DO, and water temperature time-series may also be caused by hydrodynamic processes such as seiches (Baehr and DeGrandpre, 2002). Hence, the question remains, to what extent the distribution and dynamics of dissolved CO_2 and DO are controlled by trophic state determining the intensity of lake metabolism and what is the role of lake type specific features such as lake morphometry, alkalinity or water colour in modifying the gas regime.

Lakes are frequently super-saturated with CO_2 relative to the atmosphere (Cole et al., 1994; Prairie et al., 2002; Jonsson et al., 2003; Kortelainen et al., 2006). CO_2 supersaturation can be caused by several alternative processes: by negative net ecosystem production (NEP; Cole et al., 2000), photochemical degradation of dissolved organic carbon (DOC) (Vachon et al., 2016) or high dissolved inorganic carbon (DIC) inflow from surface- or groundwater (Marcé et al., 2015; Weyhenmeyer et al., 2015). Excluding the temperature effect on gas solubility, DO supersaturation in lakes can only be reached by positive net ecosystem production (NEP > 0 if primary production exceeds respiration) occurring during limited time in the growing season when chemical and physical conditions support intensive photosynthesis. Therefore, supersaturation of the surface layer of lakes with dissolved CO_2 is more common in various geographic regions than supersaturation with DO.

Nowadays advanced sensor technologies are widely applied in aquatic studies. Diurnal variation in water temperature and DO profiles in different lake types is already well-known (Smith and Bella, 1973; Melack, 1982; Gelda and Effler, 2002; Sadro et al., 2011; Obrador et al., 2014). However, direct observations of daily dynamics of dissolved CO_2 in lakes are still rare, probably because of the relatively low reliability and accuracy and high cost of CO_2 sensors. A robust, accurate and responsive sensor-based method for direct and continuous measurement of dissolved CO_2 has been elaborated and tested in tropical, temperate and boreal streams and ponds (Johnson et al., 2010). Regarding lakes, sensor measurements of CO_2 have been reported for the upper mixed layers of some lakes (Dinsmore et al., 2009; Johnson et al., 2007; Vachon and del Giorgio, 2014) or for the surface and bottom layers (Baehr and DeGrandpre, 2002, 2004), while we have not found data on continuous profile measurements of CO_2.

In most of in situ studies (Frankignoulle et al., 2001; Jones and Mulholland, 1998; Hope et al., 2001; Billett and Moore, 2008; Sakagami et al., 2012) dissolved CO_2 concentration is still determined by the commonly used headspace method of Kling et al. (1991). As noted by Johnson et al. (2010), attempts to use automated sampling to increase sampling frequency for this method face the problem of degassing of dissolved CO_2 in the sample bottle.

In this paper we present the vertical distribution of dissolved CO_2 and DO in 8 hemiboreal lake types obtained by direct continuous in situ measurements using optical sensors. Each lake in our selection represents one of the eight lake types in Estonia according to the European Water Framework Directive (WFD) typology (Table 1). Despite Estonia being a small country, the diverse geological setting supports a broad variety of natural lake types. Based on six indicators of the gas regime, we study how the broad range of observed saturation levels of both CO_2 and DO and their coupling is related to lake type and trophic state parameters. We demonstrate the existence of gradients in the distribution of dissolved gases even under isothermal conditions of lakes and discuss the potential of vertical CO_2 measurements as a method to enhance understanding of carbon dynamics in aquatic environments.

2. Material and methods

2.1. Study sites

This study was conducted in eight Estonian lakes (Fig. 1) each belonging to a different lake type according to the EU WFD typology which is based on lake area, alkalinity, conductivity, chloride content, thermal stratification, and colour (Table 1). The two largest lakes in Estonia, Peipsi (3555 km^2, fifth largest lake in Europe) and Võrtsjärv (270 km^2), form individual types referred to, correspondingly, as V-Large and Large. They were allocated to separate lake types in the WFD compliant lake typology (ME, 2009), because strong wind induced mixing makes them incomparable with smaller lakes in the region, whereas stronger sediment resuspension in the shallower Võrtsjärv causes higher turbidity and light limitation clearly distinguishing it from the deeper Peipsi.

The remaining ~1200 small lakes are grouped into six types (Ott, 2006; ME, 2009). To make the text easier to follow, the eight lakes in this study are further referred to by their abbreviated type names (Table 1). In addition, the lakes in this study differed also by catchment land use, trophic status, and water retention time (Table 2). All lakes were rather shallow with a mean depth <10m. Measurements in all lakes were carried out within a 2-month period from July to September 2014. (See Table 3.)

Our selection of lakes represented rather adequately the broad range of lake characteristics of the region both by type specific features and along the trophic scale. The size of lakes ranged from 2 ha to >200.000 ha, i.e. over 5 orders of magnitude, Chl *a* over 3 orders, K_d and TP over 2 orders, and DOC and HCO_3^- over one order of magnitude. According to the trophic scale, the lakes ranged from oligotrophic to hypertrophic category. Also the indicator values characterising CO_2 and DO distribution had similarly broad ranges. This extensive variability included in all variables was certainly instrumental for the analysis enabling a strong manifestation of their impacts although determined a transformation of most of the variables to reduce the skewness of their distribution.

2.1.1. Alkalitrophic lakes (Alk)

Äntu Sinijärv is a source lake fed by karstic ground waters and represents highly alkalitrophic (>290 HCO_3^- mg L^{-1}) lakes in Estonia. Lakes of this type are very local in the Pandivere Upland area (only a few elsewhere) and there are only 60 lakes of that type in Estonia (Ott and Kõiv, 1999). With a mean light attenuation (K_d) of 0.16 ± 0.02 m^{-1} for the photosynthetically active spectral region measured in 1995–96, Äntu Sinijärv was the most transparent lake in Estonia (Nõges, 2000).

2.1.2. Non-stratified lakes with medium alkalinity (MedAlk)

This is the most abundant lake type in Estonia, comprising approximately 1/3 of our lakes (Ott and Kõiv, 1999). These lakes are relatively shallow, with medium water retention times and may exhibit only episodic thermal stratification.