Methanotrophy and chemoautotrophy within the redox gradient of a large and deep tropical lake (Lake Kivu, East Africa)

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Lake Kivu (East Africa) is a large (2370 km^2) and deep (maximum depth of 485 m) meromictic lake. Its vertical structure consists of an oxic and nutrient-poor mixed layer down to 70 m maximum, and a permanently anoxic monimolimnion rich in dissolved gases (methane and carbon dioxide) and inorganic nutrients. Seasonal variation of the vertical position of the oxic-anoxic interface is driven by contrasting precipitation and wind speed regimes between rainy (October-May) and dry (June-September) season, the latter being characterized by a deepening of the oxic zone, and an increased input of dissolved gases and inorganic nutrients. Our work aimed at quantifying methanotrophic and chemoautotrophic production within the redox gradient of Lake Kivu and identifying the micro-organisms involved in these processes using phospholipid-derived fatty acid markers and their carbon stable isotope composition. Our approach combined both natural stable isotope abundance analysis and ^{13}C-labelling (^{13}C-DIC ; ^{13}C-CH_4) experiments. Sampling was carried out at two stations in Lake Kivu during rainy (February 2012) and dry (September 2012) season conditions. Methanotrophic bacterial production rates were highly variable (from 0.1 to 7.0 μmol C L^{-1} d^{-1}), but maximum values were always observed at the oxic-anoxic interface when the CH_4:O_2 ratio varied between 0.1 and 10, suggesting that the majority of methane was oxidized aerobically. Furthermore, strong stable isotope labelling of monounsaturated C16 fatty acids indicate that active methane oxidizers were related to the group of type I aerobic methanotrophs (gammaproteobacteria). Despite the dominance of aerobic methane oxidation, significant methanotrophic bacterial production rates were found below the oxic-anoxic interface during the rainy season, indicating that at least a fraction of the upcoming methane may be oxidized anaerobically. This observation was further confirmed by the strong labelling at these depths of the 10Me16:0 fatty acid, biomarker for sulphate-reducing bacteria, the syntrophic partners of anaerobic methane-oxidizing archaea. The methanotrophic bacterial growth efficiency (MBGE) was variable (2-50%), and inversely related to methane concentration. Maximum chemoautotrophic bacterial production rates were recorded well below the oxycline, in sulfidic waters. However, during the rainy season, significant dark C fixation rates were measured near the oxic-anoxic interface, in a nitracline where sulphide was absent, suggesting that another energy source was involved. Incorporation of labelled carbon in the 16:1ω9c ; 16:1ω7c and 18:1ω7 fatty acids suggest that the active chemoautotrophic organisms belong to the phylum proteobacteria. Together, the vertically integrated methanotrophic and chemoautotrophic production rates were 31 mmol m^{-2} d^{-1} and 41 $mmol^{-2}$ d^{-1} during the rainy and dry season, respectively. These values are comparable to the net phytoplanktonic production rates in Lake Kivu ranging between 12 and 160 mmol m^{-2} d^{-1} (on average 52 mmol m^{-2} d^{-1}). Our results indicate that methanotrophs and chemoautotrophs contribute substantially to the carbon cycle in Lake Kivu.