UNIVERSITÉ DU QUÉBEC À MONTRÉAL

EFFETS D'UN ABAISSEMENT ARTIFICIEL DE LA THERMOCLINE D'UN LAC SUR LES DYNAMIQUES PHYSIQUES ET LES TRANSFORMATIONS DE CARBONE: PROJET TIMEX

MÉMOIRE

PRÉSENTÉ

COMME EXIGENCE PARTIELLE

DE LA MAÎTRISE EN BIOLOGIE

PAR

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AVANT-PROPOS

Étant donné la grande quantité de lacs présents au Québec et au Canada, il est de notre devoir en tant que limnologiste de bien comprendre l'impact des changements climatiques sur cette ressource essentielle qu'est l'eau douce des lacs. Les résultats de la recherche contenue dans ce mémoire font partie d'un projet de plus grande envergure appelé le projet TIMEX, qui a pour objectif d'améliorer les connaissances concernant les impacts d'un abaissement de la thermocline causé par un changement du régime des vents sur la dynamique des lacs. Ce projet est une collaboration entre 4 chercheurs : Yves Prairie (UQAM), Beatrix Beisner (UQAM), John Gunn (Laurentian University, Sudbury) et Marc Amyot (Université de Montréal). Mon projet de maîtrise tente plus précisément de mieux comprendre les dynamiques physiques du lac, ainsi que les transformations au niveau du cycle du carbone.

Ce mémoire par articles est constitué de deux chapitres distincts écrit en anglais dans le but d'une publication dans un journal scientifique. L'échantillonnage, les analyses ainsi que la rédaction ont été effectué par moi-même. Mon directeur Yves Prairie m'a épaulée tout au long du processus et a participé activement à la rédaction et la correction de tout le mémoire. Ma co-directrice, Beatrix Beisner, a participé à la correction des deux articles. Le chapitre I de ce mémoire (cadre physique du projet) sera soumis au Canadian Journal of Fisheries and Aquatic Sciences, alors que le chapitre II (dynamique du carbone) sera soumis au journal Inland waters: Journal of the International Society of Limnology.

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BACI	Before-After-Control-Impact
B1	Bassin contrôle
B2	Bassin abaissé
B3	Bassin mélangé et abaissé
C	Carbone
C-DOM	Matière organique dissoute colorée
CID	Carbone inorganique dissous (en mg L^{-1})
CH_4	Méthane
Chla	Chlorophylle a (en mg L^{-1})
CO_2	Dioxyde de carbone
COD	Carbone organique dissous (DOC en anglais, en mg L^{-1})
COP	Carbone organique particulaire (en mg L^{-1})
DO	Oxygène dissous (en mg L^{-1})
ELA	Experimental Lakes Area
e_z	Turbulent kinetic energy dissipation rate (en m^2 s^{-4})
FRQNT	Fonds québécois de la recherche sur la nature et les technologies
GES	Gaz à effet de serre (GHG en anglais)
GIEC	Groupe d'experts Intergouvernemental sur l'Évolution du Climat (IPCC en anglais)
GRIL	Groupe de Recherche Interuniversitaire en Limnologie et en environnement aquatique
H	Hydrogène
IL	Lumière incidente
K_d	Coefficient d'atténuation de la lumière (en m^{-1})
K_z	Coefficient de diffusivité verticale (en cm^2 s^{-1})
k_{600}	Standardized gas transfer velocity (en m d^{-1})
LA	Lake analyzer
L_N	Lake number
$MgCl_2$	Dichlorure de magnésium
CRSNG	Conseil de Recherches en Sciences Naturelles et en Génie du Canada (NSERC en anglais)
N^2	Fréquence de Brunt-Väisälä (buoyancy frequency en anglais, en s^{-2})
O_2	Oxygène
PAR	Photosynthetic active radiation
pCO_2	Pression partielle de CO_2 (en ppm ou en *u*atm)
RTR	Relative thermal resistance
S_T	Nombre de Schmidt (en J m^{-2})
TIMEX	Thermocline Induced Mixing EXperiment

PT	Phosphore total (TP en anglais, en mg L^{-1})
W	Nombre de Wedderburn
mgC m^{-2} d^{-1}	Milligramme de carbone par mètre carré par jour
PgC a^{-1}	Pétagramme de carbone par année
ppm	Partie par million
*u*atm	Microatmosphère

RÉSUMÉ

Le vent joue un rôle important dans la stratification thermique des lacs et une augmentation de la vitesse maximale des vents liée aux changements climatiques pourrait conduire à un abaissement de la thermocline des lacs. Un tel abaissement pourrait avoir des effets importants sur la structure physique du lac, entraînant des conséquences sur la dynamique de transformation du carbone, ainsi que sur l'émission des GES du lac vers l'atmosphère. Le projet TIMEX a pour objectif de manipuler expérimentalement la stratification thermique, par un brassage avec une éolienne aquatique, d'un des 3 bassins du lac Croche (Laurentides) pour simuler une augmentation de la vitesse maximale des vents. Un bassin contrôle et un bassin partiellement modifié ont aussi été utilisés. Le but spécifique de cette étude est d'observer les effets du changement de stratification sur le contenu en chaleur de la colonne d'eau ainsi que sur la stabilité et la capacité de transport entre ces couches. Ensuite, nous voulons mieux comprendre les transformations au niveau du cycle du carbone, soit sur la production et les flux de CO_2. Comparé au bassin contrôle, le bassin expérimental du projet a subi une homogénéisation de la colonne d'eau dû à une importante perte de stabilité de la stratification. Cette augmentation de transport dans la colonne d'eau a entrainé un transfert important du contenu de chaleur de la surface vers l'hypolimnion. Ces changements de température ont induit des flux de CO_2 ainsi qu'une respiration pélagique environ deux fois plus élevés. Étant donné que les différents scénarios climatiques prévoient que les impacts sur les écosystèmes iront en grandissant, les lacs pourraient devenir une source encore plus grande de carbone pour l'atmosphère par des émissions accrues de CO_2.

Mots clés: vents, changements climatiques, thermocline, stratification, stabilité, dioxide de carbone, méthane, lac, respiration, flux, projet expérimental.

INTRODUCTION ET ÉTAT DES CONNAISSANCES

À la suite des nouvelles connaissances acquises sur l'impact d'une accumulation de gaz à effet de serre (GES) dans l'atmosphère, ainsi que les données les plus récentes sur l'augmentation certaine des concentrations atmosphériques de ceux-ci (IPCC 2007), il est important de comprendre la dynamique naturelle de ces gaz, pour ensuite arriver à mieux comprendre les changements climatiques et l'impact de l'émission de ces gaz anthropiques. Le dioxyde de carbone (CO_2) est le plus important gaz à effet de serre anthropique dans l'atmosphère car il a une grande persistance dans le temps (Solomon et al. 2009). À cause de cette persistance et des hauts niveaux d'émissions anthropiques actuelles de CO_2, l'accumulation de plus en plus importante de CO_2 dans l'atmosphère change chaque jour la magnitude et la direction des changements de climat (IPCC 2007).

La plupart des bilans globaux de carbone, comme celui du GIEC (Groupe d'experts Intergouvernemental sur l'Évolution du Climat; IPCC (2007)), ont longtemps considéré les lacs et rivières comme de simples tuyaux transportant le carbone du réservoir terrestre vers le réservoir océanique. Au courant des dernières décennies, une meilleure compréhension des écosystèmes aquatiques a permis de démontrer qu'ils ne sont pas uniquement des transporteurs, mais que de nombreux échanges et transformations de carbone ont lieu à l'intérieur de ceux-ci (Kling, Kipphut and Miller 1991; Cole et al. 1994; Casper et al. 2000). Cole et al. (2007) ont proposé, dans une importante revue de littérature, un nouveau budget de carbone pour les écosystèmes aquatiques. Ils y concluent que des 1.9 PgC a^{-1} qui sont transportés des écosystèmes terrestres vers les écosystèmes aquatiques, seulement 0.9 PgC a^{-1} se rendent réellement à l'océan. Cette perte s'expliquerait par des flux de carbone de la surface du lac vers l'atmosphère de 0.9 PgC a^{-1} et par un stockage dans les sédiments de 0.2 PgC a^{-1} (Cole et al. 2007). N'étant plus seulement un transporteur de carbone, l'écosystème aquatique devient un important émetteur de carbone, principalement sous forme de flux de CO_2 se dirigeant de la surface du lac vers l'atmosphère. Ces flux sont causés par les différences de concentration en gaz entre l'atmosphère et l'eau de surface du lac. Selon la première loi de Fick, les flux se dirigent des régions ayant la plus grande concentration vers les zones de plus faible concentration dépendant du gradient entre les concentrations. La pression partielle de CO_2 globale de l'atmosphère se situe au environ de 394 ppm (NOAA/ESRL 2013), et celle des lacs est généralement sursaturée par rapport à cette pression partielle, ce qui explique la diffusion des gaz de la surface de l'eau en direction de l'atmosphère pour la majorité des lacs.

Un lac est considéré comme sursaturé lorsque les concentrations deviennent plus élevées dans les eaux de surface par rapport à celle de l'atmosphère. La concentration de CO_2 de surface dépend du ratio entre le taux de respiration (production de CO_2) et le taux de photosynthèse (consommation de CO_2) dans les lacs (Liikanen et al. 2002). De plus, la capacité de transport de ce GES dans la colonne d'eau et les apports externes du bassin versant jouent un rôle important dans les concentrations de CO_2 de l'eau de surface et ces apports externes sont souvent la cause première de la sursaturation d'un lac (Kalff 2002).

Dans les lacs oligotrophes, où la respiration est majoritairement plus importante que la photosynthèse, les lacs tendent à être sursaturés en CO_2, car la production dépasse la consommation de CO_2. À l'opposé, les lacs eutrophes ont tendance à être beaucoup moins sursaturés ou carrément sous-saturés en CO_2 par rapport à l'atmosphère, étant donné une productivité très importante qui vient compenser la respiration (Pace and Cole 2002).

Les écosystèmes aquatiques tempérés sont majoritairement sursaturés en CO_2 et représentent des sources de carbone pour l'atmosphère (Cole et al. 1994; Jonsson, Karlsson, et Jansson 2003; Sobek et al. 2003; Sobek 2005; Tranvik et al. 2009) dû à une production de CO_2 plus grande par la respiration que ce que le lac consomme via les organismes photosynthétiques. Étant donné que les lacs occupent un pourcentage important (~ 20 %) du territoire canadien, ils joueraient un rôle majeur dans le passage du carbone d'origine terrestre vers les océans et l'atmosphère (Cole et al. 1994). Il est donc devenu essentiel de bien comprendre leur fonctionnement ainsi que leur apport au budget régional (Liikanen et al. 2002; Kortelainen et al. 2006) et au budget global de carbone (Schindler 1998; Kortelainen et al. 2006; Cole et al. 2007).

0.1 Cycle de transformation du carbone dans les lacs

Le cycle du carbone dans un lac représente les échanges sous différentes formes entre les milieux terrestre, aquatique et atmosphérique ainsi que les processus internes de transformation du carbone dans le lac (Figure 0.1) (Prairie and Cole 2009).

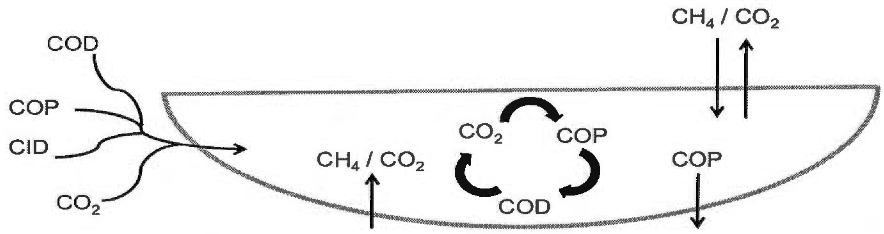

Figure 0.1 Cycle du carbone dans un lac, modifié de Prairie et Cole (2009).

0.2 Apports de carbone

Le carbone peut se retrouver dans les lacs sous différentes formes; en carbone organique dissous (COD), carbone organique particulaire (COP), carbone inorganique particulaire (CID), méthane (CH_4) et CO_2. Le COD est produit par les organismes autotrophes qui absorbent le carbone sous forme de CO_2 pendant la photosynthèse (ou chimiosynthèse) pour le transformer en composés organiques et aussi par la décomposition du COP par les bactéries. Une grande partie du carbone présent dans les lacs provient d'apports externes venant du bassin versant sous forme de COD allochtone. Ce COD vient de la production primaire de la zone terrestre, des rivières, des ruisseaux et des eaux souterraines du bassin versant qui se déversent par la suite dans le lac (Kalff 2002). Dans une majorité de lacs, le carbone d'origine allochtone est la majeure source de carbone pour le métabolisme et la chaîne trophique des lacs (Perga, Bec and Anneville 2009; Cole et al. 2011). Le carbone peut aussi provenir du lac lui-même, par la production de COD par la production primaire du lac. Les composés organiques produits peuvent ensuite sédimenter vers le fond du lac sous forme de COP et être décomposé dans les sédiments (Kalff 2002). Cette minéralisation de la matière organique peut aussi avoir lieu directement dans la colonne d'eau, principalement sous forme de respiration aérobique. De plus, les eaux souterraines et de surface peuvent aussi apporter une quantité plus ou moins grande de carbone sous différentes formes, entre autre en CO_2 (Kling, Kipphut and Miller 1992; Striegl and Michmerhuizen 1998). La photo-oxidation constitue aussi une certaine source de CO_2 et de COD dans le lac (Jonsson et al. 2001).

0.3 Production de CO_2

Le carbone présent dans un lac proviennent en grande partie de la respiration autochtone qui peut avoir lieu en milieu oxique ou anoxique. La respiration provient de la dégradation de la matière organique dans le but d'obtenir de l'énergie (Pace and Prairie 2004). Le principal sous produit de la respiration est le CO_2. Même si tous les organismes du lac respirent pour produire l'énergie nécessaire à leur survie, les données de respiration représentent généralement l'activité des micro-organismes (Pace and Cole 2000). De plus, la respiration hétérotrophe représente la majeure partie de la respiration lacustre malgré que les organismes capables d'effectuer la photosynthèse respirent aussi durant certaines périodes (respiration autotrophe) (Jensen et al. 1990). Les taux de respiration sont fortement influencés par la disponibilité en COD et en nutriments (Pace and Cole 2000) et suivent les mêmes tendances que les concentrations en chlorophylle (Pace and Prairie 2004). Ensuite, la température de l'eau joue un rôle très important dans la respiration (Den Heyer and Kalff 1998; Pace and Prairie 2004), démontrant la relation importante entre le métabolisme des organismes et leur température corporelle (Pace and Cole 2000). En effet, des variations de température entre 4 et 25 °C peuvent causer des variations des taux de respiration d'un ordre de magnitude; par conséquent une même différence de température n'aura pas le même effet sur la respiration dépendant de la température de l'eau. Par exemple, un changement de température de 4 à 5 °C dans l'hypolimnion équivaut à une augmentation de 20 - 25 °C dans l'épilimnion (Pace and Prairie 2004).

Les sédiments sont un milieu particulièrement riche en carbone et en nutriments, pouvant atteindre des concentrations jusqu'à 1000 fois plus élevée que dans la colonne d'eau, et représentent donc un milieu où la respiration est un processus biologique très important (Liikanen et al. 2002; Pace and Prairie 2004). Par contre, le taux de respiration dans ce milieu est très variable en fonction des changements de température et de profondeur. Une augmentation de la température hypolimnétique stimule rapidement la minéralisation de la matière organique, ce qui provoque une augmentation de la libération de CO_2, ainsi que du phosphore des sédiments (Liikanen et al. 2002). En effet, la respiration des sédiments est un facteur important causant la sursaturation des lacs (Kortelainen et al. 2006) et une minéralisation par les bactéries plus importante dans les sédiments des lacs sursaturés en carbone augmente effectivement la production et la libération de gaz vers l'atmosphère. À l'opposé, elle diminuerait par la même occasion la quantité de carbone organique stockée dans les sédiments. Dans le cas d'une augmentation de respiration benthique, le carbone serait transféré de manière plus importante vers l'atmosphère que vers les sédiments (Gudasz et al. 2010).

La respiration pélagique se situe au niveau de la colonne d'eau. Elle s'y produit généralement à un taux moins important que dans les sédiments parce que la colonne d'eau a une capacité moins grande à accumuler les nutriments et le carbone nécessaire à la respiration (Wainright and Hopkinson 1997). Par contre, la respiration pélagique domine généralement dans la respiration totale d'un lac étant donné que le grand volume d'eau de ce milieu compense pour le taux de respiration légèrement plus bas. En plus, l'intensité des turbulences à l'interface eau-sédiment permet la libération d'une quantité plus ou moins grande de nutriments et de carbone en provenance des sédiments vers la colonne d'eau de l'épilimnion et peut ainsi soutenir une respiration plus ou moins élevée (Jensen et al. 1990).

La variabilité de facteurs tel que la quantité de carbone et de nutriments disponibles et la température de l'eau entre lacs de même région ou de différentes régions va donc être déterminante pour la respiration. Toutefois, au sein d'un seul lac, il est aussi possible d'observer une grande variabilité en fonction de la profondeur. En effet, la stratification thermique crée un gradient important de matière dissoute, de gaz dissous et de température qui peuvent causer des changements importants du taux de respiration en fonction de la profondeur.

0.4 Stratification thermique

La stratification thermique d'un lac correspond à la séparation de la masse d'eau en différentes zones de température et de densité. Au printemps, suite à la fonte du couvert de glace, l'eau de toute la colonne d'eau, réchauffée tranquillement par la radiation solaire, se mélange par brassage thermique. La stratification thermique apparaît lorsqu'un gradient de température et de densité entre l'eau de surface et celle de profondeur apparait, créant une résistance au mélange qui est plus grande que la force des vents. L'épilimnion correspond à la couche supérieure d'eau chaude, turbulente et moins dense en contact avec l'atmosphère, où un mélange est encore possible grâce à la force des vents. L'hypolimnion est quant à lui la couche d'eau de profondeur, où la respiration domine sur la production primaire, dû à l'absence ou la présence limitée de lumière. L'eau de cette zone se situe normalement entre 4 à 6 °C, et est dense et très peu turbulente. Lorsque la stratification thermique est bien établie et qu'il n'y a aucune autre perturbation physique majeure, les deux couches ne se mélangeront pas l'une avec l'autre car leur différence de densité et de température est trop élevée (Imberger and Patterson 1989). Le métalimnion correspond à la zone limitrophe entre ces deux couches d'eau et elle consiste en un important gradient de température et de densité. La thermocline se situe au milieu du métalimnion (Kalff 2002).

La stratification thermique est entre autre importante pour la photosynthèse (Tilzer et Goldman 1978), pour le cycle des nutriments (Carmouze, Arze et Quintanilla 1984; Fee et al. 1992) et pour la distribution verticale des organismes vivants (de Stasio et al. 1996). En effet, l'apparition d'un gradient de densité lors de la stratification thermique limite de manière importante le déplacement de la chaleur, de la matière, des gaz et de certains organismes. De plus, ce gradient de densité peut varier grandement et venir jouer un rôle direct dans l'intensité de ces transports. En effet, il est relié à la différence de température entre l'eau de surface et celle de profondeur. Pour un lac de même profondeur maximale, si une différence de température est grande, la colonne d'eau aura une stratification très stable alors que pour une faible différence de température, la stabilité sera grandement réduite. Il est possible d'évaluer cette stabilité avec différents indices tel que le nombre de Schmidt (S_T), le « Lake Number » (L_N), le nombre de Wedderburn (W), la « Buoyancy frequency » (N_2) et la « Relative Thermal Resistance » (*RTR*) (Read et al. 2011).

La stratification thermique peut être affectée par des facteurs tels que la température de l'air, la radiation solaire, la couverture nuageuse, le vent, les précipitations (Forsius et al. 2010), le mouvement des eaux ainsi que la morphométrie des lacs. Les mouvements d'eau d'un lac seraient quant à eux fortement influencés par la force des vents (George 1981). Selon la relation établie par Gorham et Boyce (1989), il est possible de calculer la profondeur de la thermocline selon l'intensité des vents :

$$h \cong 2.0\left(\frac{\tau}{g\Delta\rho}\right)^{1/2} L^{1/2}$$

où h est la profondeur de la thermocline, τ est le stress associé au vent ($t = \rho u_*$, où ρ est la densité de l'eau de surface et u_* est la friction de vélocité), g est l'accélération gravitationnelle, $\Delta\rho$ est le contraste de densité de l'eau entre l'épilimnion et l'hypolimnion et L est la longueur du lac estimée par la racine carrée de son aire.

0.5 Impact des changements climatiques sur les lacs

Il est maintenant bien établi que l'accumulation des GES dans l'atmosphère cause des variations climatiques importantes, telles que l'augmentation de la température atmosphérique, des précipitations, de l'intensité des vents forts et de la fréquence des phénomènes météorologiques extrêmes (IPCC 2007).

Selon plusieurs études (Hondzo and Stefan 1993; Schindler et al. 1996; Livingstone 2003), ces changements climatiques pourraient avoir un effet important sur la stratification des lacs. Par contre, il n'y a pas vraiment de consensus sur la direction que prendraient de tels changements. En effet, une augmentation des vents causerait un brassage plus important de la masse d'eau du lac, créant une température hypolimnétique plus élevée, ainsi qu'une différence du gradient de température moins importante entre l'hypolimnion et la surface. Ce brassage du lac causé par les vents engendrerait également une augmentation de la profondeur de la thermocline (Schindler et al. 1990; Kalff 2002; Peeters et al. 2002) et une perte de stabilité dans la colonne d'eau. D'un autre côté, un réchauffement atmosphérique prédit lors de changements trop rapide du climat causerait un établissement plus rapide de la stratification thermique au début de la saison estivale ainsi qu'une augmentation des températures de l'eau de surface des lacs (Hondzo and Stefan 1993; de Stasio et al. 1996, Winder and Schindler 2004) . Dans un tel cas, une diminution de la profondeur de la thermocline serait possible (Hondzo and Stefan 1993; de Stasio et al. 1996) et la stratification thermique serait aussitôt plus stable (Winder and Schindler 2004). Cependant, dans le cadre de ce projet de recherche, uniquement l'augmentation de la force des vents forts sera utilisée comme facteur de perturbation climatique.

Une hausse de l'intensité des vents forts augmente l'intensité et la puissance des mouvements d'eau dans la couche d'eau de surface des lacs (Gorham and Boyce 1989). L'énergie engendrée par les vents plus forts est en mesure d'abaisser la thermocline en combattant la résistance au mélange de la stratification thermique (Kalff 2002). Un tel abaissement de la thermocline vient altérer de manière importante la stabilité de la colonne d'eau, ce qui entraine des changements dans le volume des différentes couches d'eau ainsi que dans la température de l'eau de chacune de celles-ci. De plus, une augmentation du mélange de la colonne d'eau occasionne un mélange plus intense des sédiments de surface, ce qui permet un relargage accru de phosphore (Boström et al. 1988; de Montigny and Prairie 2004) et de COD (Jensen et al. 1990) des sédiments vers la colonne d'eau. Une augmentation de la température des sédiments causerait aussi des flux de carbone plus élevés des sédiments en direction de l'eau (Otto and Balzer 1998). De tels changements viendraient ainsi modifier la dynamique du cycle du carbone en transformant le rendement métabolique du lac.

En plus des impacts sur la production de CO_2, l'intensité des vents joue un rôle important directement dans les transferts (flux) de gaz entre la surface des lacs et l'atmosphère. En effet, une augmentation de la vitesse des vents causerait une libération plus grande de gaz vers l'atmosphère (Wanninkhof 1992). Ces flux sont influencés selon un coefficient de transfert, k, qui varie en fonction des turbulences créées par le vent à la surface de l'eau. L'augmentation de la présence de petits tourbillons déplace en permanence l'eau à la surface des lacs, ce qui conserve un gradient fort entre la concentration en CO_2 dans l'eau et celle dans l'atmosphère, et donc une diffusion importante (Vachon, Prairie, and Cole 2010). Par contre, cette augmentation de flux en fonction de la turbulence est vraie jusqu'à l'atteinte du maximum de production de CO_2 du lac.

0.6 Projet expérimental TIMEX (Thermocline Induced Mixing EXperiment)

Jusqu'à maintenant, les projets d'écosystèmes expérimentaux ont permis de mieux prédire les changements environnementaux et d'améliorer nos connaissances dans de nombreux domaines en écologie. Ils ont en effet permis d'isoler et de mettre en évidence de nombreux concepts clés, tel que l'impact du phosphore sur l'eutrophisation des lacs (Schindler 1974), les réponses des niveaux de contamination des poissons suite à des changements dans la déposition du mercure (Harris et al. 2007) et les impacts de l'acidification d'un lac sur l'ensemble de l'écosystème (Schindler et al. 1985).

Dans la présente étude, l'utilisation d'un lac expérimental permettra de mieux comprendre les impacts des changements climatiques, plus particulièrement l'impact de l'augmentation des vents sur la stratification thermique des lacs. Les quelques projets expérimentaux de modification de la stratification thermique qui ont déjà été effectués

(Schladow and Fisher 1995; Lydersen et al. 2007; Forsius et al. 2010) permettent de savoir que la stratification thermique a un rôle important à jouer dans le bilan de chaleur, la chimie de l'eau ainsi que sur les composantes biologiques d'un lac. Par contre, dans ces projets se produisait une déstratification complète de la colonne d'eau ou la création d'une stratification partielle par aération qui ne représentait pas des conditions idéales pour toutes études métaboliques sur le changement de stratification, l'altération étant trop importante. En effet, l'impact d'un abaissement de thermocline d'un lac causé par un changement dans le régime des vents et son effet sur la respiration et la production de CO_2 n'avaient jamais été observés avant aujourd'hui.

Le projet TIMEX (Thermocline Induced Mixing EXperiment) consiste à simuler l'effet des changements climatiques sur le régime thermique d'un lac et les impacts écologiques qui en découle. Il a pour objectif de manipuler dans un bassin expérimental la stratification thermique du lac par l'abaissement de la thermocline afin d'anticiper certains effets des changements climatiques sur les lacs et plus particulièrement l'impact de l'augmentation de l'intensité des vents forts (Cantin et al. 2011, Sastri et al. In press, Gauthier et al. In press, Gillespie et al. In prep, Perron et al. Submitted, Ouellet Jobin et al. Submitted et différents autres articles en préparation). Cet abaissement de la thermocline simule l'augmentation des vents, et donc un mélange plus important de l'eau de surface du lac, à l'aide d'une éolienne aquatique (SolarBee®) utilisant l'énergie solaire (Figure 1.2, chap. 1). Dans le présent projet expérimental, nous voulions représenter les vents deux fois plus élevés observés dans la zone des lacs expérimentaux (ELA) par Schindler et al. (1990). Le protocole de la manipulation expérimentale avec l'éolienne aquatique a donc été élaboré en appliquant cette augmentation de l'intensité des vents à l'équation de Gorham et Boyce (1989) pour obtenir un abaissement de la thermocline de 3.5 à 8 m (Cantin et al. 2011).

Dans le cadre de ce projet expérimental, mon projet de maîtrise vise en premier lieu à évaluer les altérations physiques de la stratification thermique, de la stabilité, des mouvements d'eau et du contenu en chaleur de la colonne d'eau découlant de l'abaissement artificiel créé par l'installation de l'éolienne aquatique. En deuxième lieu, il tente d'évaluer les impacts de tels changements physiques sur la production de CO_2 de chacune des couches de la colonne d'eau et sur le relâchement de ce gaz de la surface du lac vers l'atmosphère. Un nouveau bilan des transformations et des échanges de carbone dans l'environnement altéré permettra ensuite d'observer les changements majeurs et leurs implications dans l'équilibre global du cycle de transformation du carbone dans le lac.

Le lac Croche, naturellement séparé en trois bassins pratiquement identiques sur le plan morphologique, a été utilisé pour ce projet expérimental. Dans un premier bassin expérimental, les manipulations ont créé un bassin mélangé et abaissé (B3) ayant une thermocline plus profonde, ainsi qu'un plus grand mélange dans la masse d'eau de surface (épilimnion). Dans un deuxième bassin modifié partiellement (bassin abaissé, B2), la modification a causé un impact uniquement sur la profondeur de la thermocline, qui s'est aussi abaissée, mais moins que dans le bassin expérimental. Par la suite, un bassin contrôle (B1) représente un lac typique tempéré et non influencé par les changements climatiques en n'étant aucunement influencé par les modifications (Figure 0.2).

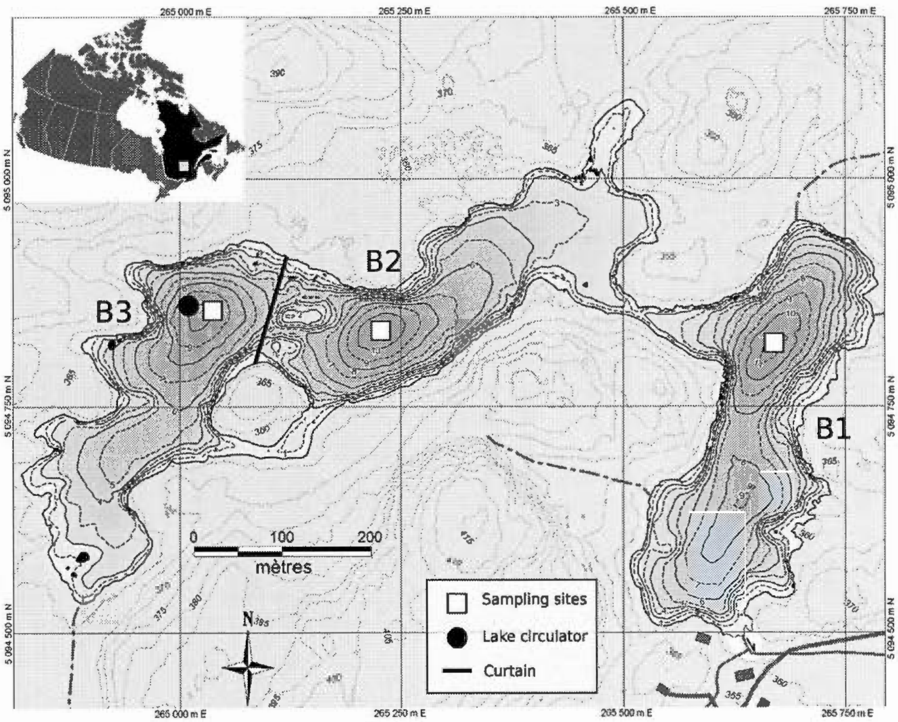

Figure 0.2 Carte bathymétrique du Lac Croche (Station de Biologie des Laurentides; Carignan, 2010). Les carrés blancs représentent les sites d'échantillonnage, le cercle noir représente l'éolienne aquatique et la ligne noire représente le rideau entre les bassins B2 et B3. B1 représente le bassin contrôle, B2 est le bassin abaissé et B3 est le bassin mélangé et abaissé.

Nous croyons qu'une telle altération artificielle de la stratification thermique causera une diminution importante de la stabilité de la colonne d'eau en diminuant le gradient de température entre l'épilimnion et l'hypolimnion, ce qui entrainera un transport accru de chaleur, de matière et de gaz dissous. À la suite de ces changements physiques et chimiques, nous prévoyons une augmentation importante de la production de CO_2 dans la colonne d'eau ainsi que dans les sédiments. Cette nouvelle production dans la colonne d'eau aura un impact directement sur les émissions de GES de la surface du lac vers l'atmosphère en augmentant de manière importante les flux de CO_2.

Ce projet de lac expérimental permettra de mieux comprendre l'impact de certains des changements climatiques sur un lac témoin, pour ensuite aider à la compréhension de ce qui pourrait se produire dans les autres lacs. En effet, c'est en connaissant bien à petite échelle les phénomènes d'origine naturels qu'il sera par la suite plus facile de départager les véritables effets anthropogéniques et d'éventuellement raffiner les données actuelles des bilans globaux de carbone. Étant donné la grande présence de lacs sur le territoire canadien, ces nouvelles connaissances nous permettront aussi de mieux comprendre le rôle que nous aurons à jouer pour protéger cette ressource naturelle d'une importance mondiale.

CHAPITRE I

ASSESSING THE EFFECTS OF ARTIFICIALLY DEEPENED THERMOCLINES AT A LAKE ECOSYSTEM SCALE USING A LAKE CIRCULATOR: I. THE PHYSICAL FRAMEWORK OF THE TIMEX PROJECT.

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1.1 Abstract

Thermal stratification is central to the physical, chemical and biological structure of a lake and is mainly driven by heat transfer from wind. As climatic scenarios predict an increase in intensity of wind speed, impacts of such wind regime shift on lakes need to be assessed. Using a lake circulator (Solar Bee®) simulating an increase in wind at lake surface at an ecosystem scale, we experimentally created a deepened and highly mixed epilimnion causing the thermocline to deepen from 4 to 8 m. However no change in surface turbulence was observed (k_{600}). Altered stratification caused a loss of water column stability and an increase in vertical transport, leading to a redistribution of heat from the epilimnion to the hypolimnion. Despite no change in total heat content, a change in the depth of surface layer led to an important increase in the surface area of sediment in contact with warm epilimnetic water. In a second experimental basin, a thermocline deepening from 4 to 6 m was induced by passive thermal conduction from the main experimental basin simulating an increase in penetration and heating by solar irradiance. In spite of this deepening, no significant change in stability and surface water mixing was observed implying no change in heat transfer was observed between strata. Our experimental manipulation demonstrates that an intensification of wind regime with climate change could lead to increased homogenization of the water column, enhancing the vertical transport of matter, heat, dissolved gases and planktonic organisms.

Keywords: climate change, experimental manipulation, heat content, sediment surface area, stability, stratification, thermocline, vertical transport, wind

1.2 Introduction

Thermal stratification controls much of the physical, chemical and biological functioning of lakes. It constrains the flux of matter (particulate and dissolved), nutrients, dissolved gases (O_2, CO_2, CH_4), energy (Fee 1979; Quay et al. 1980; Macintyre and Melack 1995; Boehrer and Schultze 2008) and, to a large extent, the distribution of lake biota (Schindler et al. 1996; de Stasio et al. 1996; Longhi and Beisner 2009; Cantin et al. 2011). Alterations to stratification could exert profound changes in terms of the suitability of the environment to certain species and thus influence biodiversity and community composition. In extreme cases, even small alterations of lake thermal structure can lead to large disruptions causing massive evasion of asphyxiating gases (Kling, Tuttle and Evans 1989; Touret, Grégoire and Teitchou 2010). In north temperate lakes, the impacts of such thermal regime variation, while not as intense, could nevertheless lead to important modifications of the ecosystem.

In dimictic lakes, the depth at which the thermocline forms is controlled by numerous factors, including light penetration (Fee et al. 1996; Snucins and Gunn 2000), heat exchange with the atmosphere (Schindler 1997) and most importantly, wind stress (George 1981; Gorham and Boyce 1989). Strong wind events constitute the main source of energy able to create surface current and turbulence regimes (George 1981; Imboden and Wüest 1995) strong enough to overcome the stability of the upper portion of the water column and thereby increase the thickness of the thermally homogeneous layer. Thus, wind is considered to be the major driver of thermocline depth owing to its ability to mix surface waters. This mixed surface layer corresponds to the volume of water that the maximum wind speed is able to destratify, while the thermocline represents the layer of water just underneath that is not wind mixed (George 1981; Gorham and Boyce 1989). Annual variation in the thermocline depth for a given lake is the result of a particular timing of wind events in relation to the phenology of lake stability. Between different lakes, fetch and lake size also largely determine thermocline depth in a given region with otherwise similar wind-induced characteristics (Patalas 1984; Gorham and Boyce 1989). Moreover, thermocline depth is also highly influenced by water clarity owing to heat transfer from solar irradiance (Snucins and Gunn 2000).

Increases in the atmospheric concentration of greenhouse gases (GHG; CO_2, CH_4, etc) predicted by the IPCC (2007) are expected to lead to change in air temperatures and precipitation, more extreme climatic events, longer ice free periods, and more frequent strong winds (IPCC 2007). Furthermore, alterations of the shoreline of lake are also expected to lead to transformation of wind regime at lake's surface (Schindler et al. 1996; Tanentzap, Yan and Keller 2008). Although the magnitude and even direction of these changes vary across different regions, numerous studies have shown that changes in climatic conditions have already led to important alterations in the thermal regime of north temperate lakes (Hondzo and Stefan 1993; Schindler et al. 1996; Livingstone 2003; Tanentzap, Yan and Keller 2008). Different climatic scenarios predict alternative impacts on lake stratification, but in all case, predict a change in thermocline depth, although the magnitude and direction remain uncertain. Of the possible scenarios, this study focuses primarily on the impacts of a predicted increase in wind speed on the thermal regime of a lake. In addition, we also assessed in a second experimental scenario the impacts of an increase in water clarity on thermal regime.

To this end, we initiated in 2008 a whole-system experimental platform with the purpose of simulating the effects of an intensified wind regime by artificially deepening the thermocline of an isolated basin of L. Croche (Quebec), a small oligotrophic lake on the Canadian Shield. The ultimate goal of the TIMEX (Thermocline-Induced Mixing EXperiment) project was to explore the biogeochemical and biotic responses to changes in thermal structure in a fully controlled setting. Our experiment differs uniquely from previous experimental manipulations of lake thermal regimes, which either induced the complete destratification of the water column (e.g., Steinberg 1983; Schladow and Fisher 1995) or a partial stratification with aeration techniques (e.g., Lydersen et al. 2007; Forsius et al. 2010), both techniques which largely preclude the study of lake metabolic properties through biogenic gas concentration and fluxes. In this paper, we describe the physical framework of the TIMEX experimental platform over which the biogeochemical and biotic responses are addressed in separate papers (Cantin et al. 2011, Sastri et al. In press, Gauthier et al. In press, Gillespie et al. In prep, Perron et al. Submitted, Ouellet Jobin et al. Submitted and several other manuscripts in preparation). More specifically, we examine here the extent to which several important physical properties were altered following the experimental manipulation of the vertical thermal structure, including heat content, light penetration, water column stability, vertical diffusivity and turbulence regime at the air-water interface.

1.3 Materials and methods

1.3.1 Study site

The TIMEX project occured in Croche Lake in the Laurentians region of Quebec (Figure 1.1) (45 °59'34"N 74 °00'34"W). This region is characterized by granitic or anorthosic bedrock of pre-cambrian origin, covered by 1-5 m of glacial till (Prichonnet 1977). L. Croche is a headwater lake with a 1.1 km^2 catchment consisting of mixed deciduous and coniferous forest and having almost no anthropogenic forcing, except for the few buildings of the field station adjacent to the first basin (B1). This 18 ha oligotrophic lake has no permanent surface inflows and only limited groundwater inputs (Richard Carignan, U. of Montreal, 2011; personal communication), with mean and maximum depths of 4.7 m and 11.4 m respectively. Its normal thermocline develops around 4 m during the summer period.

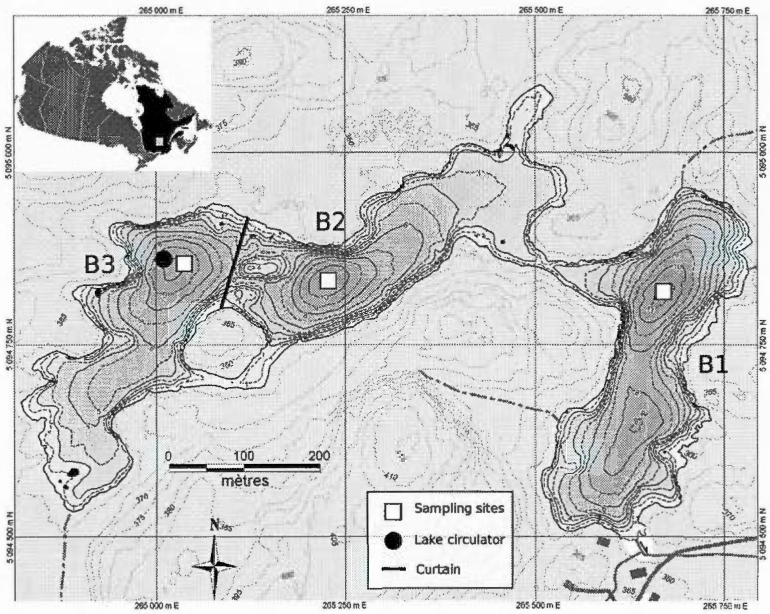

Figure 1.1 Bathymetric map of L. Croche (Station de Biologie des Laurentides; Carignan, 2010), the white squares represent the sampling sites, the black circle is the lake circulator and the black line shows the location of the curtain between B2 and B3. B1 is the control, B2 the deepened and B3 the mixed and deepened basins.

1.3.2 Experimental design

The primary objective of the TIMEX project was to manipulate the thermal regime of a lake so as to simulate some of the anticipated effects of a changing climate at the ecosystem scale, namely a lowering of the thermocline induced by the anticipated stronger winds (Gorham and Boyce 1989; Schindler et al. 1996) and secondly, by an increase in water clarity (Snucins and Gunn 2000). The bathymetry of L. Croche provides a nearly ideal setting in which to test this effect, owing to its three almost identical basins (Figure 1.1). A narrow and shallow 2 m channel separates the first (B1) and second (B2) basins. Mid-way between this second basin (B2) and the third (B3) is an island with a narrow and shallow (1 m deep) channel on one side and a shallow but larger section (120 m) on the other side. A black polyethylene curtain was placed along this longer shallow stretch to isolate the two basins. The curtain had the ability to transfer heat between B2 and B3 through passive thermal conduction. We could thus actively manipulate the thermocline in one basin (B3, mixed and deepened basin), measure the indirect effect of thermal structure changes in the second basin

(B2, deepened basin), and use a last basin as an unperturbed environment (B1, control basin). A lake circulator (Solar Bee, Model SB10000v18, H2O Logics Inc.) was used to deepen the thermocline in the experimental basin B3 (mixed and deepened). This lake circulator takes the water from a pre-determined depth (8 m in our study) and brings it to the surface, creating mixing in the epilimnion and a deepening of the thermocline to the depth just under that at which the water was originally taken from (Figure 1.2). If installed immediately after ice-out, the Solar Bee permits the establishment of a thermocline at the desired depth (8 m in our case). The second experimental basin (B2, deepened basin) experienced a deepened thermocline, although it did not occur as deeply (6 m) as a result of heat transfer across the curtain. Thus, B2 had a deepened thermocline, but no experimentally induced increase in epilimnetic mixing. The more isolated B1 was not affected by the thermocline manipulation, and served as control basin representing a typical temperate dimictic lake with a thermocline at 4 m.

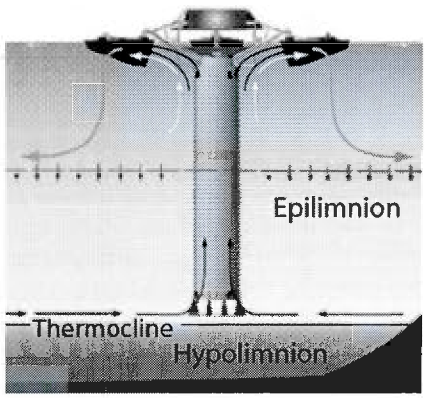

Figure 1.2 Deepening of thermocline using a lake circulator. Modified figure of the Solar Bee (H2O Logics Inc.).

Although the TIMEX manipulation began in 2008 following a preliminary sampling year, we focus on two years (2010 and 2011) in this particular study during which we obtained detailed measurements on physical and biogeochemical response variables. During the experimental year (2010), the lake circulator was in place for all the ice-free period. To obtain data in a control year in all basins, the lake circulator was removed from the experimental basin in 2011.

The depth at which the lake circulator was set (8 m) was chosed based upon a combination of modelling (Gorham and Boyce 1989) and empirical data from the Experimental Lakes Area (ELA) indicating that wind speed doubled over 20 years (1969-1988) presumably as a result of climate change and clearcutting (Schindler et al. 1990). Gorham and Boyce (1989) demonstrated a relationship between wind stress (via friction velocity, u_*) and thermocline depth. The thermocline of a lake is set at a depth where the average wind stress is no longer able to destratify the water column according to the relationship :

$$h \cong 2.0\left(\frac{\tau}{g\Delta\rho}\right)^{1/2} L^{1/2} \qquad (1)$$

where h is the thermocline depth (m), g is the acceleration due to gravity, $\Delta\rho$ is the difference in density between hypolimnion and epilimnion, L is the root square of the surface area of the lake, and $t = m^*\rho$ (where m^* is the friction velocity and ρ is the surface density). Parameterizing this model to simulate L. Croche, we observed that a thermocline deepening from the normal 4 m to a 7 m depth would occur with a doubling of maximum wind speed from 10 to 20 m/s.

1.3.3 Sampling and calculations

Meteorological data (wind speed, photosynthetic active radiation (PAR), air temperature, air pressure) were recorded every 15 minutes at a nearby meteorological station (~200 m). Continuous water temperature data were taken every 20 minutes using a thermistor chain composed of HOBO Temp Pro Loggers (± 0.2 °C accuracy) placed at every 0.5 m across the entire water column depth.

The three basins of the lake were sampled weekly from May through September, in both the experimental (2010) and control (2011) years. Water temperature profiles were measured at each 0.5 m with a YSI (Model 6600, Multi-parameter Water Quality Monitor, YSI incorporated). Surface (10 cm) micro-turbulence measurements (or turbulent kinetic energy dissipation rate; ε_z) were made with an acoustic Doppler velocimeter (ADV; SonTek, 10 MHz) for a 10 minutes period on each sampling date. Using the method described in Vachon, Prairie et Cole (2010), the horizontal turbulent kinetic energy dissipation rate (ε_z) was estimated in MATLAB to obtain a proxy of surface turbulence. Moreover, this ε_z was then transformed as an overestimation ratio and used to correct the k_{600} and the flux of gas to the atmosphere measurements. Values of ε_z under 0.000005 were rejected because the relation to overestimation ratio is not valid below this point. A light profile (PAR) was also taken on each sampling date with a radiometer (Li-Cor, LI-193SA, Lincoln, NE, USA) to obtain the air-water light ratio. The slope of the profile of depth in function of air-water light ratio represents the light attenuation coefficient (*Kd*). By integration, the average fraction of the incident light (*IL*) within the epilimnion was calculated as:

$$IL = (1 - e^{(-Kd * Z_{Epi})}) / Kd, \qquad (2)$$

and the reduction of light in the experimental basin epilimnion relative to the control basin was estimated as:

$$IL_{ratio} = \frac{Z_{Epi\_Control}(1 - e^{(-Kd * Z_{Epi\_Deepened})})}{Z_{Epi\_Deepened}(1 - e^{(-Kd * Z_{Epi\_Control})})} \qquad (3)$$

Thermocline depth represents the depth with maximum vertical difference in water density (Read et al. 2011). The strata (epilimnion, metalimnion and hypolimnion) were divided according to the upper and the lower limit of the maximum density gradient (metalimnion), representing respectively the shallowest and the deepest depth at which density changes of more then 0.1 (Read et al. 2011). The volumetric heat content of each strata was calculated using the water temperature profile (HOBO, average per day) and the volume of water in each 0.5 m layer (Wetzel and Likens 2000) and these values were then summarized for the whole water column and for the different strata.

Gas transfer velocity (k) was calculated with water partial pressure of CO_2 (pCO_2), ambient pCO_2, CO_2 flux and Kh (derived from water temperature):

$$k_{CO_2} = \frac{F_{CO_2}}{Kh(pCO_{2_{water}} - pCO_{2_{air}})} \tag{4}$$

and then standardized to a Schmidt number of 600 :

$$k_{600} = k_{CO_2}(\frac{600}{Sc_{CO_2}})^{-n} \tag{5}$$

As we are simulating an increase in wind speed with a deepening of the thermocline, we can transform the equation of Gorham and Boyce (1989) to estimate the friction velocity u_* with the deepening of the thermocline that was created with the manipulation:

$$u_* = \frac{h}{2}\sqrt{\frac{g\Delta\rho}{L\rho}} \tag{6}$$

to then converted this friction velocity u_* into maximum wind speed. We then applied the ratio between the calculated maximum wind speed between each of the modified basins and the control to the observed maximum wind speed data (0.5 % highest wind speed ; Meteorological station of the biological field station) for this lake to obtain the simulated maximum wind speed for each modified basin. Observed winds taken at the meteorological station (15 minutes) were corrected to represent wind at each minute (Dregger 2005).

The stability of the water column represents its degree of stratification. To evaluate this stability, we first used the Schmidt Stability Number (S_T) (Idso 1973). We used the Lake Analyzer (LA) created by Read et al. (2011) to calculate S_T. With the LA, we also calculated the buoyancy frequency (N^2), the Wedderburn Number (W) and the Lake Number (L_N).

The relative thermal resistance (*RTR*) was also used to evaluate the total water column stability but also the stability for several water column strata. It was calculated using the water temperature profile (HOBO) and the relation of Birge (1910):

$$RTR = \frac{(\rho_2 - \rho_1).10^6}{8} \tag{7}$$

where ρ represents the density of the water calculated from the equation of Read et al. (2011). *RTR* was calculated for the difference between each 0.5 m layer and then averaged for each stratum (epilimnion, metalimnion and hypolimnion) and for the whole water column. Effective vertical diffusivity (K_z) represents the intensity of vertical mixing in a stratified lake and also indicates the degree of mixing of matter, gases and energy. It is calculated using the flux of heat entering the aphotic zone ($\Delta heat\ content_z/Area_z$) and the difference of temperature ($\Delta temperature_z$) of each layer of water (Jassby and Powell 1975):

$$K_z = \frac{\Delta heatcontent_z * 10000}{Area_z * \Delta temperature_z} \tag{8}$$

1.3.4 Statistical analyses

The BACI protocol (Before-After-Control-Impact) was used to analyze the results of the experimental manipulation. The BACI procedure allows the comparison of results before and after a manipulation, for an experimental and a control site. In particular, it takes into account environmental variation caused by inter-annual patterns and natural between-basin differences, thus providing a robust estimation of the variation attributable to the manipulation (Stewart-Oaten, Murdoch and Parker 1986). In this current experiment, the difference between the mixed and deepened (B3) and the control basin (B1) represents the variation caused by a deepened thermocline and a mixed epilimnion; the difference between the deepened and the control basin (B2-B1) shows the variation caused by only a deepened thermocline. Finally, the difference between the mixed and deepened and the deepened basin (B3-B2) represents mostly variation caused by the mixing of the epilimnion. For example, the variation caused by the manipulation in B3 compared to control could be explained as:

$$(B3_{Experimentalyear} - B1_{Experimentalyear}) - (B3_{Controlyear} - B1_{Controlyear}) \tag{9}$$

Once these differences were calculated, paired t-tests (paired by observation date in the two years) were performed (Underwood 1997). One-way ANOVAs were also done to assess differences between basin averages over the sampling dates for each year separately. Outliers where identified with Studentized residuals (> 3). Because temperature data were collected continuously (each 20 minutes) for both summer sampling period, the sample size (n) was so great that all temperature results were statistically significant.

1.4 Results

1.4.1 Stratification

Meteological conditions (from May 1st to September 28th) for both experimental (2010) and control (2011) years where respectively similar (BACI test; $p>0,05$) for temperature (16.22 and 16.25 °C), wind speed (1.97 and 2.12 m s^{-1}) and precipitation (613 and 595 mm), so major variations in basins during experimental year (2010) could be mainly attributed to our experimental manipulation.

The introduction of the Solar Bee in B3 was successful in inducing important changes in the thermal regimes of the two manipulated basins. The thermocline was deepened by 2.7 m during the mixing period in B3 compared to the control (Figure 1.3) and was established below the input of water of the lake circulator tube. Although the apparatus was confined to B3, heat transfer from conduction through the curtain was sufficient to alter the thermal structure in B2 as well, albeit to a lesser extent. On average, the thermocline in B2 settled 1m deeper than in the control basin (Figure 1.3).

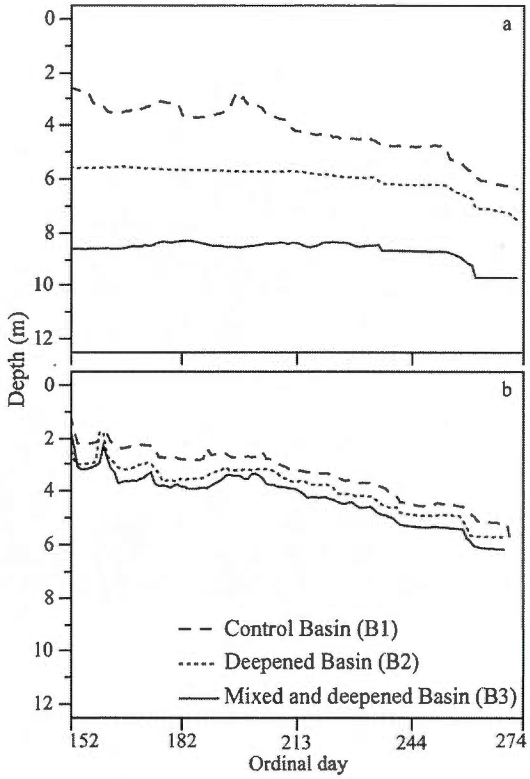

Figure 1.3 Thermocline depths (m) from June 1st to September 28th for the control (B1, dashed line), the deepened (B2, dotted line) and the mixed and deepened (B3, solid line) basins for the experimental (a) and the control (b) years. Significant deepening was observed for the deepened (+1.0 m, $p<0.0001$, $n=282$), and the mixed and deepened (+2.7 m, $p<0.0001$, $n=282$) basins in the experimental year using data transformed according to the BACI protocol.

The volume occupied by each stratum (epilimnion, metalimnion and hypolimnion) was also modified in both B2 and B3 compared to the control owing to the altered thermal structure (Figure 1.4). Most of the variation occurred in the epilimnion, which became much thicker in both experimental basins (0.3 m in B2 and 1.9 m in B3), while the hypolimnion depth decreased considerably (0.2 m and 1.1 m, respectively). The metalimnion depth also decreased by 0.5 m in B2 and by 0.9 m in B3.

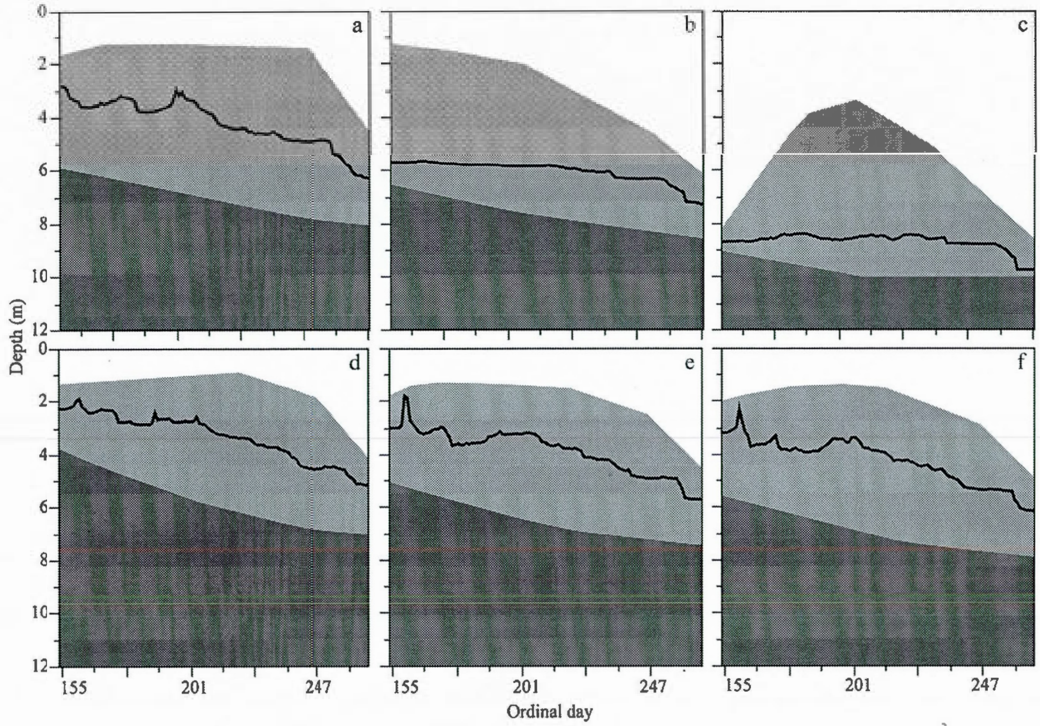

Figure 1.4 Depth (m) from June 4th to September 28th of the epilimnion (white), the metalimnion (light grey) and the hypolimnion (dark grey) in: (a) the experimental year for the control basin with a mean thermocline at 4.2 m, (b) the experimental year for the deepened basin with a mean thermocline at 6.0 m and (c) the experimental year for the mixed and deepened basin with a mean thermocline at 8.1 m; (d) the control year for the control basin with a mean thermocline at 3.2 m, (e) the control year for the deepened basin with a mean thermocline at 4.0 m and (f) the control year for the mixed and deepened basin with a mean thermocline at 4.3 m. Solid lines represents the position of the thermocline.

1.4.2 Volumetric heat content

The experimental manipulation of the vertical stratification regime resulted largely in a reorganization of the heat content within the water column, without significant changes in the overall heat content of the basins (Figure 1.5). Although not ecologically significant, the total heat content decreased in both manipulated basins but by only 0.6 °C in the deepened basin (B2) and 0.3 °C in the mixed and deepened basin (B3). The principal changes in heat content were observed in the hypolimnion where the average temperature (volumetric heat content) decreased by 0.9 °C in B2 but increased by 1.5 °C in B3. The average temperature remained stable in the epilimnia and the metalimnia of both experimental basins (~20 °C and 17 °C, respectively). Yet not significant, a decrease of 0.7 °C was observed in B3.

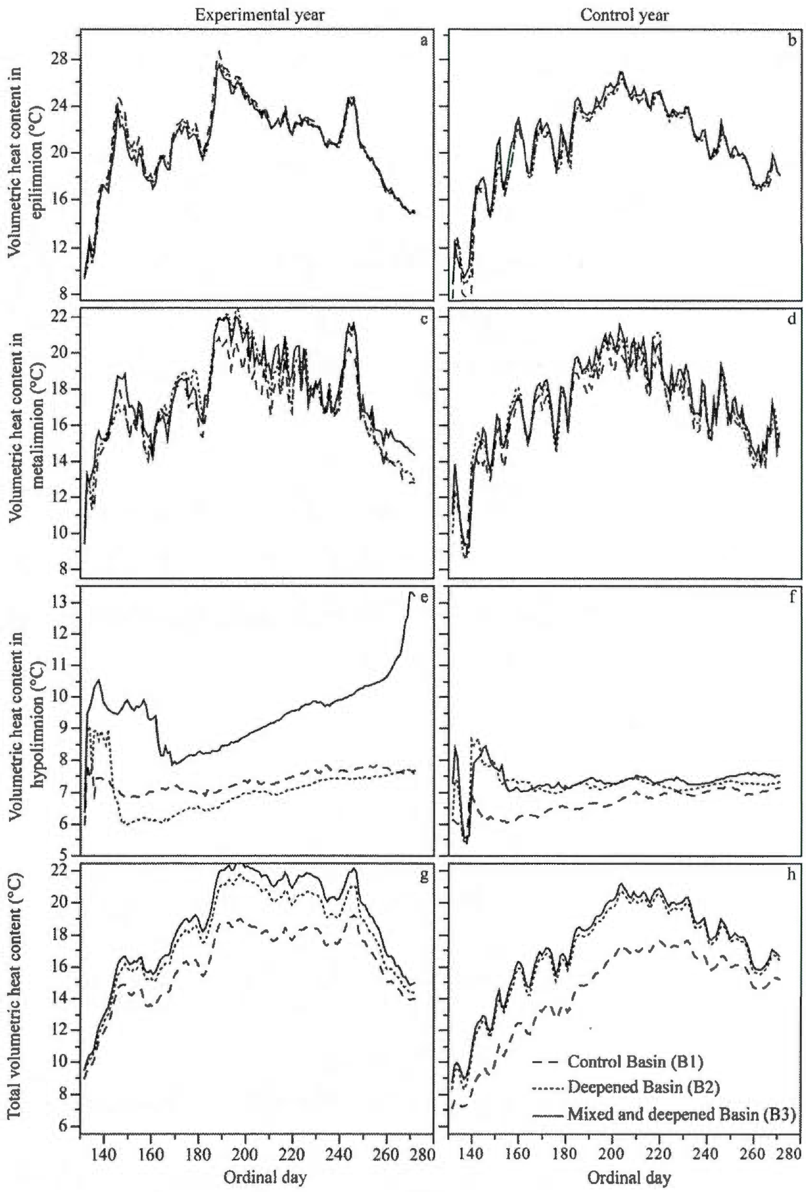

Figure 1.5 Volumetric heat content (°C) from May 11th to September 28th for the control (dashed line), the deepened (dotted line) and the mixed and deepened (solid line) basins in the epilimnion during the experimental (a) and the control (b) years, in the metalimnion during the experimental (c) and the control (d) years, in the hypolimnion during the experimental (e) and the control (f) years and total volumetric heat content during the experimental (g) and the control (h) years.

Although alteration to the overall heat content was modest, it had nevertheless larger consequences on the temperature regime experienced by the sediments, as an important increase in the layer of sediment in contact with warm water was observed. The average temperature of the sediment only increased by 0.3 °C in the mixed and deepened basin and decreased by 0.6 °C in the deepened basin. Nevertheless, when observing the sediment area over the thermocline (i.e., sediment area in contact with warm and mixed water), this area increased by 19.0 % (6981 m^2) in B2 and by 45.9 % (14094 m^2) in B3.

1.4.3 Turbulence and stability

At the water-atmosphere interface of both modified basins, there were no significant changes in surface micro-turbulence (ε_z) and standardized transfer velocity (k_{600}). Moreover, according to the relationship of Vachon and Prairie (2013), ε_z and k_{600} still followed the trends of a 0.01 km^2 lake, having values of $5x10^{-6}$ m^2 s^{-4} and 1.7 m d^{-1} respectively.

L. Croche is naturally stable with a Schmidt Stability number (S_T) of 87.28 J m^{-2}, a Weddlerburn Number (W) of 240, a lake number (L_N) of 220 and a buoyancy frequency (N^2) of 10^{-2} s^{-2} (Figure 1.6). No significant variation between basins was observed in the average N^2 and L_N. Although there was seasonal variation and increases in average W to 448 in B2 and 926 in B3, this variation does not represent an ecologically significant change as all $W >$ 1 represents the same surface mixed layer state. We also observed a seasonal variability in N_2, but it is still a non-ecologically significant variation.

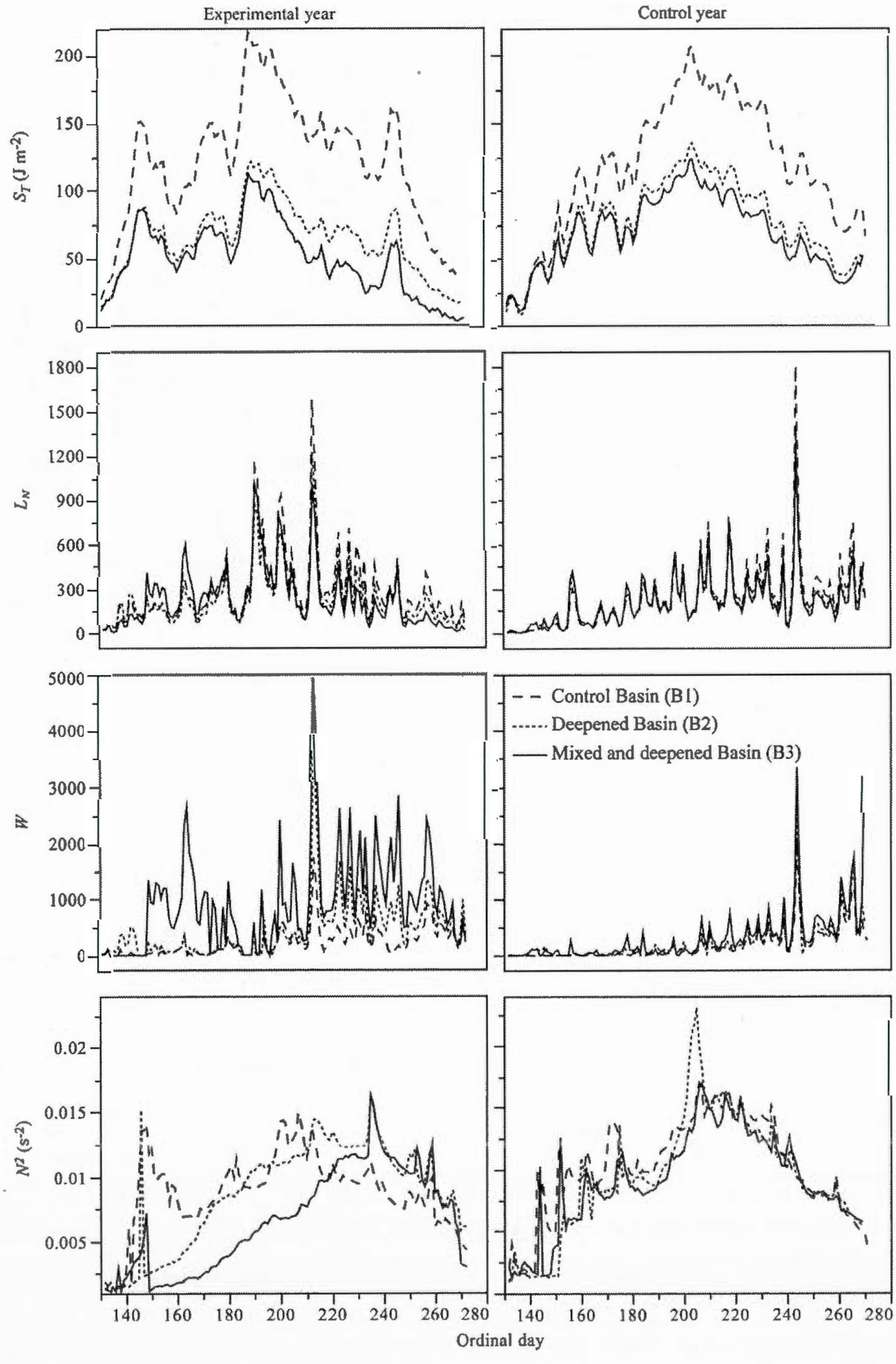

Figure 1.6 Schmidt Stability Number (S_T, in J m^{-2}), Lake Number (L_N), Wedderburn Number (W) and buoyancy frequency (N^2, in s^{-2}) from May 11th to September 28th in the control (dashed line), the deepened (dotted line) and the mixed and deepened (solid line) basins in the experimental and control years.

The main variation in water column stability was observed with the Schmidt Stability (S_T) as a decrease of 21.31 J m^{-2} in the mixed and deepened basin (B3). Moreover, we also observed a decrease in the total relative thermal resistance (*RTR*) by 3.21. The main decrease in the *RTR* in the water column was observed in the metalimnion (-6.01), and an increase in the *RTR* was observed in the epilimnion (5.57) of the mixed and deepened basin. The natural effective vertical diffusivity (K_z) of 0.05 $cm^2\ s^{-1}$ also increased significantly (+0.16 $cm^2\ s^{-1}$), representing a four-fold elevation relative to the control (Figure 1.7). This increase in K_z is related to a decrease in the stability of the stratification represented by a significant decrease in the S_T and in the *RTR*. For the deepened basin, the effective vertical diffusivity (K_z) was two-fold greater than the control. However, this change was mainly observed in the hypolimnion, and thus not associated with an increase mixing of the entire water column. Moreover, this increase in diffusivity is not really explained by the total *RTR* or stability. In fact, the hypolimnion and the metalimnion experienced almost no change of *RTR* (-0.61 and 0.93 respectively) despite an increase in *RTR* in the epilimnion (3.68).

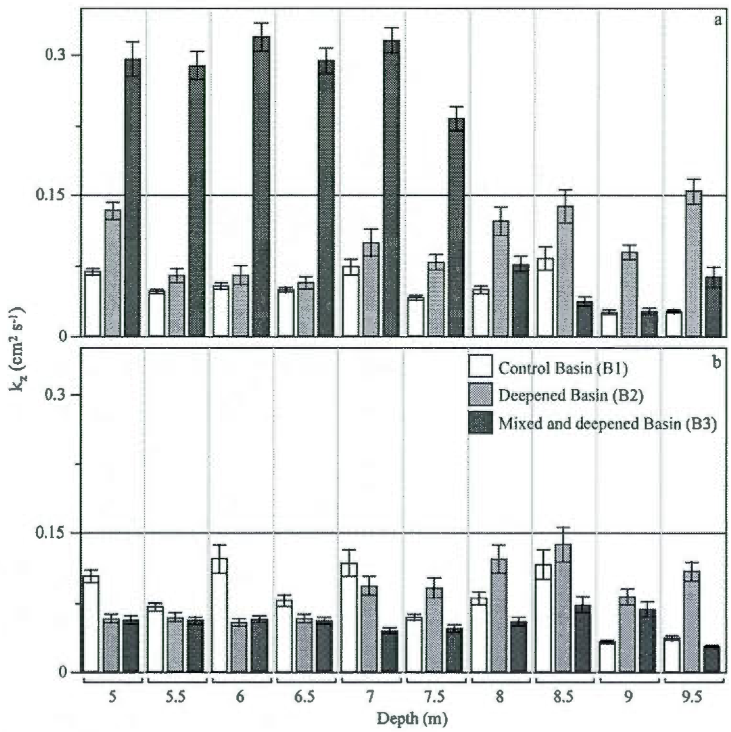

Figure 1.7 Mean vertical diffusivity, K_z, (cm^2 s^{-1}) per depth (each 0.5 m) from May 11th to September 28th for the control (white), the deepened (light grey) and the mixed and deepened (dark grey) basins for the experimental (a) and the control (b) years. Data are from only 5 to 9.5 m to exclude depths influenced by solar irradiance.

1.4.4 Light attenuation

Although the light attenuation coefficient (*Kd*) did not changed significantly between the basins (on average 0.34 m^{-1}, $p>0.05$), the thicker epilimnion implies that the average light regime experienced in the epilimnion was reduced by 13 % in the deepened basin and by 33 % in the mixed and deepened basin.

1.5 Discussion

Our whole-system experimental manipulation was first used to simulate deepening of the thermocline induced by the stronger winds forecast by several climate change scenarios (IPCC 2007). Using the relationship of Gorham and Boyce (1989, eq. 1), the observed lowering of the thermocline in B3 corresponded to an 80 % increase in the maximum wind speed (from 7.2 m/s, to a simulated maximum wind speed of 13.0 m/s). This simulated wind increase is very plausible (Schindler et al. 1990) and we therefore consider our experimental manipulation as an appropriate simulation of likely future limnological changes. Equivalent changes in maximum wind speed resulting from deforestation can also induce similar changes in thermal vertical structure (France 1997; Tanentzap, Yan and Keller 2008).

Given that our experimental setting does not exactly reproduce a change in wind regime but only its known within-lake impacts (i.e. thermocline deepening), we necessarily are ignoring a certain component of reality. For instance, our manipulation does not recreate the turbulence that strong winds would likely cause at a lake's surface (Crusius and Wanninkhof 2003; Vachon, Prairie and Cole 2010). No significant change in the two proxies of the surface turbulence (k_{600} and ε_z) were observed in our study as they continued to follow the trend expected for natural wind over a lake the size of L. Croche (Vachon, Prairie and Cole 2010) and are not influenced by our manipulation. Moreover, under natural conditions, increased winds would probably induce more cooling owing to lower temperatures experienced at night. Deepening the thermocline using the lake circulator created numerous modifications in physical lake properties similar to what a change in wind regime would do. However, the mixeing also resulted in the creation of two thermoclines. The first mechanical-induced thermocline was set right under the intake tube of the lake circulator and was thus directly created by mixing (simulating high wind speed). According to the manufacturer, the Solar Bee takes water from a layer of only 30 cm, creating a thermocline underneath it. It was the main thermocline that we observed at an average 8.1 m depth. There was an important increase in the depth of the metalimnion from mid-June to mid-July (Figure 1.4). During this period, a second thermocline (most probably induced by solar irradiance) was found at an average depth of 4.5 m. The presence of this second thermocline provides an explanation for the increase in thickness of the metalimnion during the first part of summer. Then, in mid-July, both thermoclines begin to merge into the one thermocline beneath the lake circulator.

Within the framework of this project, we also observed a deepening of the thermocline not induced by mixing of the surface layer, but instead through thermal transfer. This thermocline deepening simulates a change in stratification due to increases in water clarity. However, we are not exactly representing such shifts because our manipulation was not accompanied by any real change in water color (C-DOM on average 0.09, $p>0.05$).

1.5.1 Stability, Lake Number and vertical diffusivity

The thermocline manipulation resulted in a strong decrease of the water column stability, as shown by a decrease in the total relative thermal resistance (*RTR*) in the mixed and deepened basin compared to the control, especially in the metalimnion. This loss of thermal resistance generated an important increase in the effective vertical diffusivity (K_z). L. Croche has a naturally very low diffusivity, as the values of K_z are on average under 0.15 cm^2 s^{-1} for each depth. According to Imberger and Patterson (1989), average vertical exchange could range from 0.02 cm^2 s^{-1} (associated with lake with strong stratification) to 1 cm^2 s^{-1} (associated with lake with weak stratification). The experimental manipulation in the mixed and deepened basin (B3) significantly increased the diffusivity by four times (Figure 1.7). This increased the ability of the water column the mix, and thus, increased the exchange of nutrients, dissolved gases and energy (Mercier-Blais, Beisner and Prairie, chap. 2). Going from 0.05 to 0.2 cm^2 s^{-1} of effective vertical diffusivity, L. Croche is effectively losing an important part of its typical small lake's stable stratification in the mixed and deepened B3. Moreover, when looking at the effective vertical diffusivity for each depth, it is possible to see that this important increase occurred in the metalimnion (5 to 7.5 m) with a mean effective vertical diffusivity of 0.29 cm^2 s^{-1}, and that the hypolimnion (8 to 9.5 m) maintained the same diffusivity as the control (0.05 cm^2 s^{-1}). This observed increase of mixing in the intermediate layer thus led to an important homogenization of the water column. Moreover, having a normally stable hypolimnion (no change in *RTR* and diffusivity) confirms that our experimental manipulation (with the lake circulator) is recreating a realistic stratification. Essentially, we are creating a water column with a highly mixed epilimnion, a metalimnion with a lower temperature and density gradients, and a normal hypolimnion underneath the lake circulator intake tube. Furthermore, looking to temperature data from a lake similar in size and depth to L. Croche but experiencing mean wind speed two-fold stronger (6.3 m/s at 30 m), it is possible to see the same trends of stratification (thermocline at 7 m) as in our experimentally mixed and deepened basin. In the deepened basin (B2), diffusivity was on average two times higher (0.10 cm^2 s^{-1}) but the changes are not likely to be important enough to create significant physical and ecological impacts on the transport of matter, energy and dissolved gases. Moreover, with no change in diffusivity and only a small increase in *RTR*, the ability of the metalimnion (and the thermocline) to limit exchange between the epilimnion and hypolimnion remained the same in B2 as in absence of the treatment. The most important change in diffusivity only occurred in the hypolimnion, permitting more exchange in this stratum only, and not with the rest of the water column.

1.5.2 Heat content

Despite major changes in the stratification, no change in overall heat content was observed. This is not surprising given that the same amount of heat continued to enter the lake through solar irradiance; i.e., the same amount of heat in the water column was maintained. The mixed and deepened basin did experience an important accumulation of heat in the hypolimnion as a result of a change in the distribution of heat and not a new accumulation. The important increase in heat content of this stratum can be attributed to the facilitated vertical heat transport caused by the higher diffusivities (Imberger and Patterson 1989). Between 5 m and 7.5 m, there was an important exchange of heat that allowed the hypolimnion of this basin to warm. A smaller range of temperature variation in the vertical profile and a thicker zone of transition (metalimnion) meant that the temperature gradient was less pronounced than in a typical thermal profile. Although not statistically significant, we also observed a slight decrease in epilimnetic temperature. Overall, mixing redistributed the heat in the water column of the mixed and deepened basin. Due to the great volume of water, this minor decline in epilimnetic temperature is sufficient to explain the new accumulation of heat in the hypolimnion in this basin. In the absence of an increase in vertical diffusivity in the metalimnion of the deepened basin (B2), no increase in heat content was visible in the hypolimnion of the basin likely because, in the absence of mixing, the heat was not passed through the metalimnion.

In addition, as the epilimnion was deepened, without changes in the light penetration in both basins, a part of this stratum ended up in the aphotic zone. The presence of this shaded zone in the deepest part of the surface mixed layer could have important implications for phytoplankton production (Diehl et al. 2002; Diehl 2002).

1.5.3 Sediment transformation

Changes in the water column temperature profiles also had a great influence on the proportion of the sediment exposed to warm waters. With the deepening of the thermocline to

8m in the mixed and deepened basin, 45 % more sediment were in contact with warm epilimnetic temperature. Furthermore, our results demonstrate that even hypolimnetic sediments are likely to encounter higher temperature due to the increased vertical diffusivity and the associated heat transport. Based on Pace and Prairie (2004), those sediments newly in contact with warmer temperatures will probably experience increases in metabolism, leading to changes in carbon and nutrient releases to the water column. Moreover, major changes in temperature could also have impacts on the benthic community present in those sediments (Schindler et al. 1996), including the hatching of resting eggs of plankton (Caceres 1998), that could affect the amount of food available for higher trophic levels (e.g. fish). The presence of intense surface layer mixing caused by the lake circulator could also induce greater internal waves in the metalimnion of the mixed and deepened basin. Such waves would emerge from the lake circulator in all directions, breaking when shoaling at the limit of the metalimnion and the sediment, creating a turbulent benthic boundary layer. This could create important regions of exchange between thermal strata (Imberger 1998; Nishri et al. 2000). In the real case of an increased wind speed regime, this phenomenon would only happen in the direction of the prevailing wind, but would surely have a similar impact to the one observed in this experimental manipulation.

Considerable changes in surface water gas concentration coming from the change in mixing and diffusion of the water column will certainly lead to higher fluxes of gas to the atmosphere owing to a stronger gradient of concentration between lake water surface and atmosphere. However, considering no significant change in the two proxies of the surface turbulence (k_{600} and ε_z), our results indicated no evidence for a direct physical impact of the treatment on gas fluxes to the atmosphere. The absence of increase in surface turbulence of our experimental setting would reduce such impacts of mixing from winds on fluxes to the atmosphere. Clearly, increased winds could have even greater effects on C flux at lake surfaces than we could observe with this experimental design.

1.6 Conclusion

We observed that a deepening of the thermocline and an increased mixing of the surface mixed layer has great impact on the strong stratification of the small L. Croche

Considering only a deepening of thermocline without any mixing change, the physical effect on the lake was of a lower intensity and led to smaller transformations.

Previous work has shown that modifying the wind regime leads to an important increase in the mixing in the surface layer, directly causing thermocline deepening. Our study has shown that this modification will lead to change in the effective vertical diffusivity of the metalimnion, allowing increased exchange of heat (and also of dissolved gases and matter) from the surface to the bottom of the lake. The resulting warming of the hypolimnetic water reduces the temperature gradient and density of the metalimnion, directly altering stratification stability. However, increases in wind speed predicted in the IPCC (2007) climate change scenarios are still not likely to lead to a complete destratification of the water columns of lakes similar to L. Croche The hypolimnion will remain excluded from direct contact with the atmosphere, although exchanges should increase as a result. Furthermore, deepening of thermocline will have important impacts on sediment temperatures, because more sediment surface area will be in contact with warm water (due to both increased depth of the epilimnion and to increased temperatures in the hypolimnion). The main experimental basin of the TIMEX project was altered to represent many, but not all aspects of an increase in maximum wind speed and this current evaluation demonstrates that it provides the most suitable experimental platform to date available to experimentally test the effect of such modifications on the biology and biogeochemistry dimictic lakes. .

1.7 Acknowledgements

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CHAPITRE II

SHIFT IN THE SINK-SOURCE CARBON BALANCE OF LAKES FOLLOWING THERMOCLINE DEEPENING.

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2.1 Abstract

Intensification of wind regimes associated with climate change could lead to significant increases in lake surface layer mixing followed by a deepening of thermoclines worldwide. Such changes could have major impacts on carbon processing and gas dynamics in lakes, however these have yet to be assessed. We examined the impact of a deepened thermocline and increases in surface water mixing on pelagic respiration and CO_2 flux to the atmosphere in a controlled whole-lake experiment. As a result of our manipulation, each of these parameters increased two-fold compared to the control. Increased CO_2 production was observed in both the epilimnetic and hypolimnetic layers. In the epilimnion, the increased CO_2 production (187 mgC m^{-2} d^{-1}) was related to changes in depth and water volume as well as to an increase in DOC release from newly warmed sediments and its subsequent mineralization in the water column and led to an increase in CO_2 emission to the atmosphere of 129 mgC m^{-2} d^{-1}. Given predictions of more extreme meteorological events and wind speeds with climate change, our study suggests that lakes will become an even more important source of greenhouse gases to the atmosphere than they currently are. In fact, the overall increase in organic carbon mineralization (55 gC m^{-2} yr^{-1}) with thermocline lowering far exceeded the lake's current rate of carbon burial through sedimentation (2 gC m^{-2} yr^{-1}), thereby suggesting a strong shift in the source-sink carbon balance of lakes under climate change.

Keywords: carbon, carbon dioxide, climate change, emission, respiration, stratification, thermocline, wind

2.2 Introduction

Heterotrophic metabolism by bacteria is central to the dynamics of lakes by transforming organic carbon either into biomass than can eventually be transferred to higher trophic levels (Cole et al. 2002), or mineralized to CO_2 thereby contributing to the generalized carbon dioxide supersaturation observed in most aquatic systems (Duarte and Prairie 2005). Summer thermal stratification has a major impact on this dynamics in dimictic north temperate lakes, in part because it creates a layered environment with very different physical and chemical characteristics. Alterations to any of those characteristics may result in a rapid shift towards a new equilibrium between respiration and primary production as well as a modification in its distribution among compartments (e.g. water column vs benthic processes). Thus, depending on the magnitude and direction of these changes, the system as a whole shift more towards emissions or instead permanent burial in sediments. Previous studies have shown that a rise in carbon mineralization rates in the pelagic zone or the sediments could significantly alter CO_2 supersaturation levels and therefore flux to the atmosphere (Kortelainen et al. 2006) by transferring carbon from the terrestrial and geological reservoir to the lake water and eventually, to the atmosphere (Gudasz et al. 2010).

Climate change now being observed at a global scale appears mainly to be the result of the accumulation of greenhouse gas, GHG, (CO_2, CH_4, etc) in the atmosphere and is resulting in accelerated impacts on most ecosystems (IPCC 2007). In lakes, one of the anticipated effects of climate change is in the alteration of thermal stratification (Hondzo and Stefan 1993; Schindler et al. 1996; Livingstone 2003). The predicted increases in maximum wind speed and extreme wind events (IPCC 2007) accompanying both climate change and anthropogenic alteration to watershed, should lead to a deepening of the thermocline (Schindler et al. 1996). Change in the thermal structure will necessarily alter the heat content and its distribution, as well as the volume and sediment area of each stratum, leading to changes in respiration, and potentially to increase CO_2 flux to the atmosphere. Although the potential for a positive feedback as lakes could become a greater source of greenhouse gases are real, there is very little data addressing directly how shifts in the thermocline depth may influence overall lake metabolism and carbon dynamics.

To examine this hypothesis, we carried out the ecosystem-scale TIMEX (Thermocline Induced Mixing Experiment, see Cantin et al. 2011) experiment by lowering the depth of the thermocline in an isolated basin of a L. Croche to examine its impact on the carbon dynamics of the system. The results reported here pertain to an experimental (2010) and a control (2011) year. More specifically, we examined changes in CO_2 concentration in the water column, respiration rates and gas fluxes at the air-water interface that were induced by the experimental manipulation.

2.3 Material and methods

2.3.1 Study site

L. Croche is a small headwater lake (0.18 km^2) located on the territory of the Laurentian biological field station of University of Montreal (45 °59'34"N; 74 °00'34"W). This lake is underlain by the Canadian Shield consisting of a granitic or anorthosic bedrock covered by 1-5 m of glacial tills (Prichonnet 1977). Lake catchment (1.1 km^2) consists of mixed deciduous and coniferous forest with low anthropogenic forcing. The lake is representative of other Canadian Shield lakes in term of water depth (mean depth of 4.7 m) and thermocline depth (3.5 m during the summer period). Further, the lake has no permanent inflow and only limited groundwater input from the catchment (Richard Carignan, U. of Montreal, 2011; personal communication). This lake was chosen because it had three basins separated by shallower sections, which facilitated the isolation of each basin for the experiment (Figure 2.1).

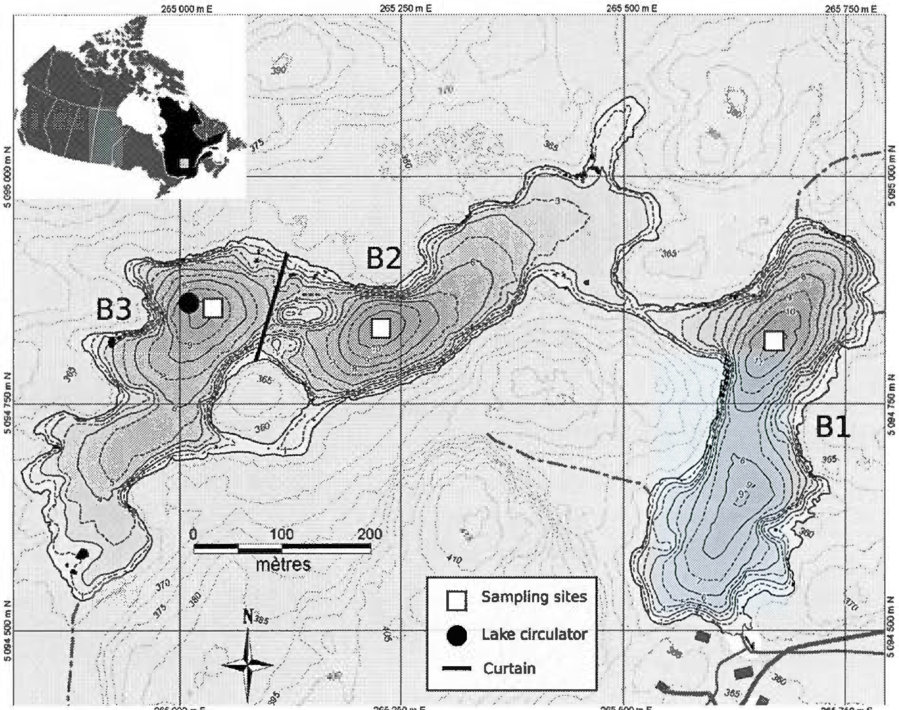

Figure 2.1 Bathymetric map of L. Croche (Station de Biologie des Laurentides; Carignan, 2010), the white squares represent the sampling sites, the black circle is the lake circulator and the black line shows the location of the curtain between B2 and B3. B1 was the control basin, B2 the deepened basin and B3 the mixed and deepened basin

2.3.2 Experimental design

As the purpose of the TIMEX project was to manipulate the vertical thermal structure of a lake to simulate some anticipated effects of a changing climate at the ecosystem scale, the stratification of an experimental basin (B3, mixed and deepened basin) was altered. We deployed a solar powered lake circulator (Solar Bee, Model SB10000v18, H2O Logics Inc.) in basin B3 as soon as possible after ice-out with its large intake tube (1 m diameter) lowered to a depth of 8m, corresponding to a simulated increase in maximum wind speed (0.5 % highest wind speed) from 7 m s^{-1} to 13 m s^{-1} (Cantin et al. 2011; Mercier-Blais, Beisner and Prairie chap. 1) according to the relationship of Gorham and Boyce (1989). A similar increase was observed at ELA (Schindler et al. 1990). Details on the impact of the experimental manipulation on the physical attributes of the lake are described in Mercier-Blais, Beisner and Prairie (chap. 1) but are briefly summarized in the results section.

2.3.3 Sampling methods

Sampling occurred weekly, at approximately the same time of day, from May to September, during both the experimental (2010) and control (2011) years at the deepest point in each basin. Continuous temperature data were also taken each 20 minutes over the entire summer period with an *in situ* thermistor chain composed of HOBO Temp Pro Loggers (± 0.2 °C accuracy) situated at each 0.5 m depth over the entire water column. Thermocline depth was calculated from the thermistor data as the depth at which the maximum density difference occurred (Read et al. 2011). To differentiate the position of the three thermal strata of the water column, the metalimnion was defined as occurring where density changed more than 0.1 per 0.5 m, while the epilimnion and the hypolimnion were the layer overlying and underlying it respectively (Read et al. 2011). The volumetric heat content was calculated using the HOBO temperature profile and the volume for each layer of 0.5 m (Wetzel and Likens 2000) and then summarized for each day for the whole water column and for each strata of water.

A meteorological station situated on the roof of the main building of the field station and next to the lake (~200 m) measured wind speed, photosynthetic active radiation (PAR), air temperature, air pressure, and precipitation at each 15 minutes over the whole sampling period. Water temperature, dissolved oxygen (DO), pH and conductivity profiles were done using a YSI-6600 (Multi-parameter Water Quality Monitor, YSI incorporated) at each 0.5 m depth.

2.3.3.1 Chemical analyses

Total phosphorus (TP) was sampled at each 2 m depth and analyzed in the laboratory using a UV/Visible spectrophotometer Ultraspec 2100 pro (Biochrom) at a wavelength of 890 nm with the molybdenum blue method after persulfate digestion (Griesbach and Peters 1991). Dissolved organic carbon (DOC) was sampled at the same depths and analyzed with an O.I. Analytical 1010 TIC-TOC analyzer (Weeltech enterprises Inc.). Total chlorophyll a (Chl-*a*) concentration was estimated fluorometrically in profile at each 0.5 m with a submersible spectrofluorometer (FluoroProbe, bbe-Moldaenke, Kiel, Germany). Volumetric concentration for each stratum and for the whole water column was then calculated for TP, DOC and Chl-*a*.

Colored dissolved organic matter (C-DOM) was sampled from the surface of the lake to the thermocline using an integrated tube sampler and the water was directly filtered through a 1.2 μm filter (Whatman disposable syringe filters, GF\C, 13 mm). The samples were kept in an opaque bottle at 4 °C until a subsequent absorbance analysis using a UV/Visible spectrophotometer Ultraspec 2100 pro (Biochrom) at a wavelength of 440 nm. Light data (PAR: photosynthetic active radiation) were obtained with the air-water light ratio from a light profile measured using a radiometer (Li-Cor, LI-193SA, Lincoln, NE, USA). The light attenuation coefficient (*Kd*) was calculated as the slope of the log relationship between the air-water light ratio and depth. Primary production (PP) was estimated from epilimnetic Chl-*a* using the relationship of del Giorgio and Peters (1993).

2.3.3.2 Gas dynamics

Weekly pCO_2 vertical profiles were carried at 0.5 m interval by pumping water with a peristaltic pump through a membrane contactor (Mini-module debubbler, Liqui-Cel, see Prairie and Cole 2009) coupled to an infra-red gas analyzer EGM-4 (Environmental gas monitor for CO_2, PPSystem) in a closed recirculating loop. Flux of CO_2 at the air-water interface was measured by floating chamber method as described in Vachon, Prairie and Cole (2010). Briefly, the 0.12 m^2 (31.2 L) chamber was connected to the EGM-4 also in a closed recirculating loop and we monitored the changes in pCO_2 at every minute for a period of 10 minutes. Flux measurements were made in duplicates and calculated from the linear regression slope, including a correction for the atmospheric temperature and pressure. Because Vachon, Prairie et Cole (2010) had demonstrated that floating chamber measurements tended to overestimate true flux because of the artificially induced turbulence created by the chamber itself, we concurrently measured near surface (10 cm) turbulence as kinetic energy dissipation rate (ε_z) with an acoustic Doppler velocimeter (ADV; SonTek, 10 MHz sampling at 25Hz) as in Vachon, Prairie et Cole (2010) and applied the correction proposed therein. Values of ε_z below 5 x 10^{-6} m^2 s^{-3} were rejected because they fell outside the range developed for the correction equation.

2.3.3.3 Respiration measurements

Pelagic epilimnetic respiration was estimated by measuring changes in O_2 concentration over time during dark incubations (24 h at 20 °C). At four different time points during the 24 h period, respiration was stopped by adding mercuric chloride ($HgCl_2$) to triplicate sets of 7 mL glass tubes filled with incubated water taken. Then tubes were stoppered and conserved in a water container to limit air exchange (Guillemette and del Giorgio 2011). This protocol permits O_2 levels to remain high enough (>2 mg L^{-1}) during the incubation so as to not alter bacterial processes (Berggren, Lapierre and del Giorgio 2012). The concentration of O_2 in each sample was measured with a MIMS (Membrane Inlet Mass Spectrometer) (Kana et al. 2001). The slope of the oxygen decline through time was then used to calculate the respiration rate (Guillemette and del Giorgio 2011).

2.3.4 Statistical analyses

The BACI protocol (Before-After-Control-Impact) was used to analyze the experimental results. This protocol allows us to compare results from before and after a manipulation while taking into account any differences between the experimental control sites, thereby isolating the effect of the experimental manipulation (Stewart-Oaten, Murdoch and Parker 1986). In the present experiment, the difference between the mixed and deepened basin (B3) and the control basin (B1) represents the variation caused by a deepened thermocline accompanied by a mixed epilimnion (B3-B1). The difference between the deepened basin (B2) and the control basin (B1) is the variation caused by only a deepened thermocline (B2-B1). Finally, the difference between the mixed and deepened basin (B3) and the deepened basin (B2) represents mostly the variation caused by an increase of mixing of the epilimnion (B3-B2). Annual differences were assessed using paired t-tests, and for each year of the experiment, differences between basins were observed using analysis of variance (ANOVA) (Underwood 1997), however only BACI statistical results are showed in this paper.

2.4 Results

2.4.1 Heat content, stability and stratification

The impact of the experimental manipulation on the temperature stratification are described in details in Mercier-Blais, Beisner and Prairie (chap. 1) but are summarized here to place the biogeochemical response in their proper context. Meteological conditions (from May 1st to September 28th) for both experimental (2010) and control (2011) years where respectively similar (BACI test; $p>0,05$) for temperature (16.22 and 16.25 °C), wind speed (1.97 and 2.12 m s^{-1}) and precipitation (613 and 595 mm), so any variation in basins between years could mainly be attributed to our experimental manipulation.

An important increase in the thermocline depth was observed following the experimental manipulation (Mercier-Blais, Beisner and Prairie chap. 1). In the mixed and deepened basin (B3), the thermocline and the bottom of the epilimnion were deepened by -2.7 m and -1.9 m respectively, with a concurrent decrease in the thickness of the metalimnion (-0.9 m) and hypolimnion (-1.1 m) (Figure 2.2). This modified basin thus had lower water column stability, and four-time higher vertical diffusivity (K_z) in the experimental year (2010). Similarly, the thermocline in B2 was lowered by an intermediate value of -1 m relative to the control. Despite higher vertical diffusivity, no major change in water column stability was observed in this deepened basin, nor was there any significant change in depth of the thermal strata in B2. Surprisingly, these changes in stratification did not result in any major differences in the average heat content between years compared to the control basin. Because the temperature data were collected continuously (every 20 minutes) for the two summers, the sample size (n) was necessarily very high and thus all results were deemed statistically significant, though not necessarily biologically relevant. We considered temperature differences between basins greater than 0.5 °C as ecologically significant. In the epilimnion, the mean and temporal evolution of summer temperatures also showed no biologically significant variation, with remaining comparable at around 20 °C in all basins and years. The most significant treatment difference occurred in the temperature of the hypolimnion, which increased by +1.5 °C in B3 (mixed and deepened basin), while it decreased by -0.9 °C in B2 (deepened basin). The temperature of the metalimnion increased only slightly (+0.2 °C and +0.3 °C) in both experimental basins.

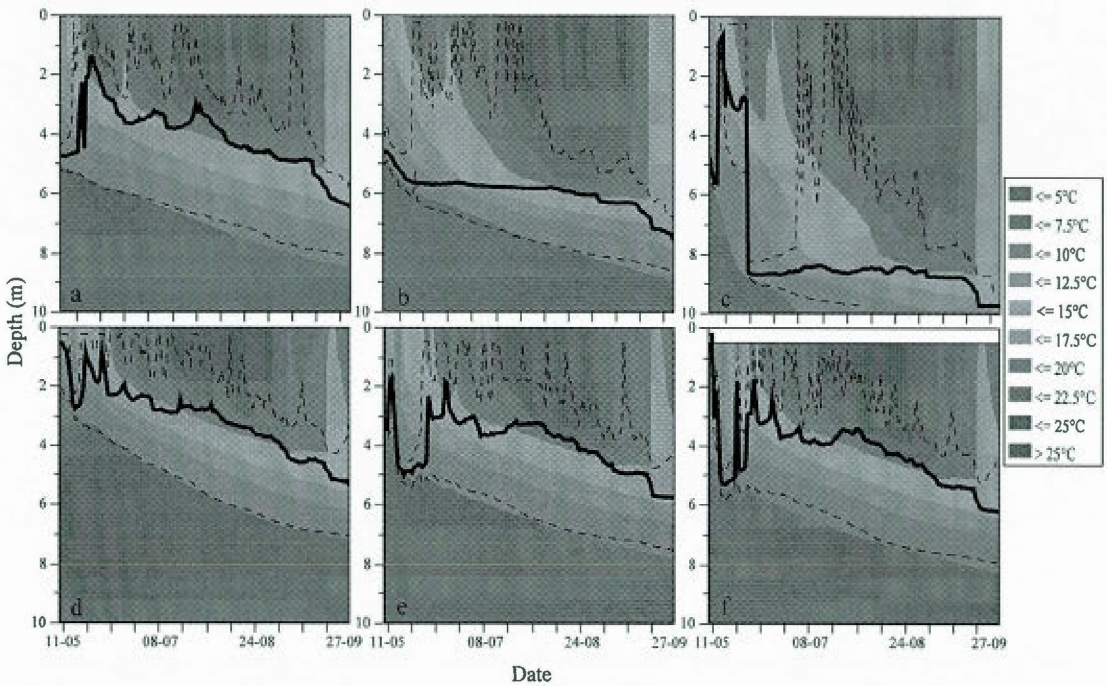

Figure 2.2 Temperature profile (in °C) of surface water to 10 m from May 10th to September 27th for (a) the experimental year for the control basin with a mean thermocline at 4.2 m, (b) the experimental year for the deepened basin with a mean thermocline at 6.0 m and (c) the experimental year for the mixed and deepened basin with a mean thermocline at 8.1 m ; (d) the control year for the control basin with a mean thermocline at 3.2 m, (e) the control year for the deepened basin with a mean thermocline at 4.0 m and (f) the control year for the mixed and deepened basin with a mean thermocline at 4.3 m. Solid lines represent the thermocline and dashed lines represent the limits of the metalimnion.

2.4.2 Environmental variables

While there was significant inter-annual variation in C-DOM and DOC and hence in the light attenuation coefficient (*Kd*) (Table 1), we found no evidence of significant changes in these variables induced by the experimental manipulation (BACI test; $p>0.05$). The exception was a modest but highly significant accumulation of DOC in the hypolimnion of the deepened basin (+0.5 mg L^{-1}, $p<0.0001$, n=39).

A similar lack of effect of the experimental manipulation was observed with respect to nutrients although somewhat uncoupled with associated measures of productivity. No significant changes in phosphorus were observed ($p>0.05$) except for a localized decrease in the TP concentration in the hypolimnion of the mixed and deepened basin (-3.6 μg L^{-1}, p=0.0026, n=38). Surprisingly, despite the absence of an effect on nutrients, Chl-*a* levels increased significantly by over 50 % in both B2 and B3 (+1.2 μg $L^{-1}$and +1.6 μg L^{-1}, respectively) above mean background levels in B1 of 2.2 μg L^{-1}. Similarly, primary production increased two-fold (+17.9 mgC m^{-3} d^{-1}, $p<0.0001$, n=32) in the mixed and deepened B3, and by +6.9 mgC m^{-3} d^{-1} (p=0.0027, n=32) in the deepened basin B2. During the experimental year, mixing and deepening in B3 affected the dissolved oxygen (DO) profile. There was an important increase in the overall concentration of DO of +0.89 mg L^{-1} (p=0.02, n=42) above those observed in B1 occurring mainly in the epilimnion (+0.8 mg L^{-1}, p=0.21, n=39) (Table 1).

Table 2.1 Average water chemistry variables for the control (B1), the deepened (B2) and the mixed and deepened (B3) basins for the experimental (2010) and the control (2011) years.

			Experimental year			Control year		
Variables	Units	n	Control	Deepened	Mixed + deepened	Control	Deepened	Mixed + deepened
DOC epilimnion	mg L^{-1}	40	4.4	4.5	4.6	4.4	4.6	4.8
DOC metalimnion	mg L^{-1}	40	4.3	4.7	4.7	4.4	4.6	4.8
DOC hypolimnion	mg L^{-1}	39	4.4	5.0	4.5	4.7	4.8	5.1
Total DOC	mg L^{-1}	40	4.3	4.6	4.6	4.5	4.6	4.8
C-DOM (A440)	m^{-1}	38	0.9	1.0	1.0	0.8	0.9	1.0
Light attenuation coefficient (*Kd*)	m^{-1}	38	3.2	3.2	3.1	2.7	2.7	2.8
Total phosphorus epilimnion	ug L^{-1}	38	4.9	6.4	8.6	3.7	5.0	5.3
Total phosphorus metalimnion	ug L^{-1}	39	6.7	9.0	7.9	5.4	7.1	7.3
Total phosphorus hypolimnion	ug L^{-1}	38	10.0	8.5	5.5	12.5	11.8	11.7
Total phosphorus	ug L^{-1}	41	6.2	7.2	7.9	5.9	6.0	6.4
Chlorophyll epilimnion	ug L^{-1}	38	1.5	2.3	3.1	1.3	1.7	1.7
Chlorophyll metalimnion	ug L^{-1}	39	2.0	2.8	2.5	2.8	2.5	2.5
Chlorophyll hypolimnion	ug L^{-1}	30	1.9	1.6	1.6	4.2	2.1	1.6
Total chlorophyll	ug L^{-1}	42	1.9	2.5	3.0	2.6	2.1	2.1
Primary production	mgC m^{-3} d^{-1}	38	16.3	28.2	39.6	13.9	19.0	19.4
Dissolved oxygen epilimnion	mg L^{-1}	42	8.6	8.5	7.7	8.5	8.7	6.8
Dissolved oxygenmetalimnion	mg L^{-1}	41	9.0	7.5	5.3	9.1	7.5	5.1
Dissolved oxygen hypolimnion	mg L^{-1}	42	4.1	2.9	2.8	3.5	2.4	1.7
Total dissolved oxygen	mg L^{-1}	42	8.4	8.1	7.3	8.0	7.9	6.0

2.4.3 Carbon transformation: pCO_2 and CO_2 evasion rates

The deepening of the thermocline induced a clear increase in the epilimnetic pCO_2 of the manipulated basins from an average of about 550 μatm in the control year and basin to about 1120 μatm ($p<0.0001$, $n=37$) in B3 during experimentation and to a more modest elevated level in B2 (average of 640 μatm, $p=0.22$, $n=37$) (Figure 2.3 a and b). Because we did not observe any changes in the gas exchange velocities among basins and years (Mercier-Blais, Beisner and Prairie chap. 1), the increased partial pressure led to correspondingly elevated CO_2 emissions to the atmosphere in those basins (Figure 2.3 c and d). We observed a significant increase in the evasion of CO_2 to the atmosphere only in the mixed and deepened basin (+129 mgC m^{-2} d^{-1}, $p=0.0018$, $n=38$).

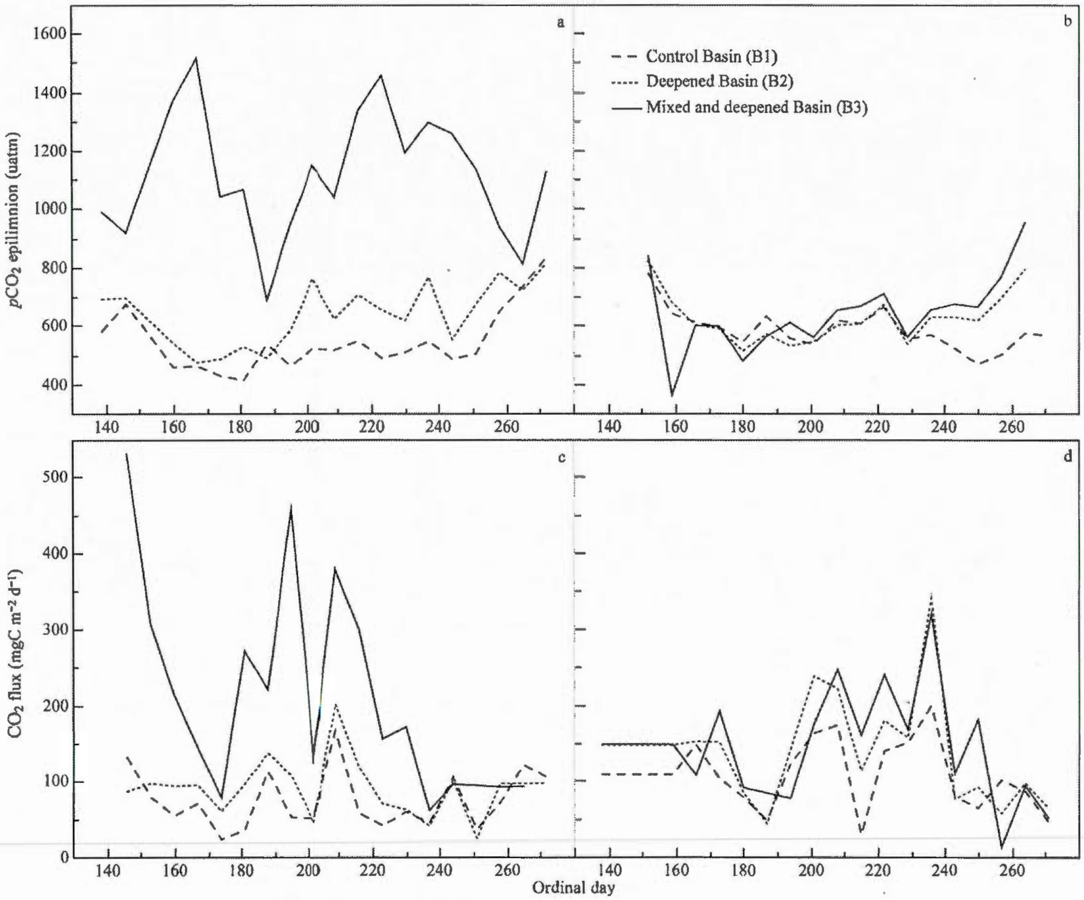

Figure 2.3 *p*CO2 in epilimnion (*u*atm) and CO_2 flux (mgC m^{-2} d^{-1}) from May 19th to September 29th for the control (dashed line), the deepened (dotted line) and the mixed and deepened (solid line) basins for the experimental (a and c) and the control (b and d) years. Significant variation in pCO_2 was observed for the deepened (B2) and the mixed and deepened (B3) basins during the experimental year, while a significant variation in CO_2 flux was only observed in the mixed and deepened basin (B3) (using data transformed with the BACI protocol).

We examined whether the differences among the basins were the result of metabolic changes or of a simple vertical redistribution of the processes generating the carbon dioxide. To this end, we calculated the net CO_2 production rate for the whole basin as well as for each stratum as

$$\text{Net } CO_2 \text{ production} = \Delta \text{ storage} + \text{Evasion} - \text{Import from adjacent strata}$$

These rates correspond to the net balance of all the processes generating and consuming CO_2 including respiration, photosynthesis, allochthonous CO_2 inputs, calcite dissolution, etc. Figure 2.4 clearly shows that thermocline deepening induced a significantly higher net CO_2 production when the whole water column is considered, but that these changes are largely confined to the epilimnion and hypolimnion, after taking into account the natural differences that existed among basins (i.e. BACI analyses). The increase in net CO_2 production of the epilimnion averaged 187 mgC m^{-2} d^{-1} ($p=0.0007$, $n=10$) over the season in the mixed and deepened basin (B3), in part because of the larger volume of the epilimnion but mainly because of the magnitude of respiratory processes. Volumetric respiration rates in epilimnetic waters increased by 31 mgC m^{-3} d^{-1} ($p=0.0007$, $n=10$). For an epilimnion experiencing no thermocline deepening (stable at 4.2 m) but a change in respiration rate, this represents an increase of 131.5 mgC m^{-2} d^{-1} in epilimnetic pelagic respiration. When only considering a larger volume of water due to a deepening of the thermocline (i.e. assuming no change in volumetric respiration), this transformation would have increased the respiration by 16.4 mgC m^{-2} d^{-1} (Figure 2.4, Epilimnion net CO_2 production for the experimental year). Thus, our results indicate that the higher pCO_2 and evasion rates observed in B3 are largely due to the intensification of metabolic processes.

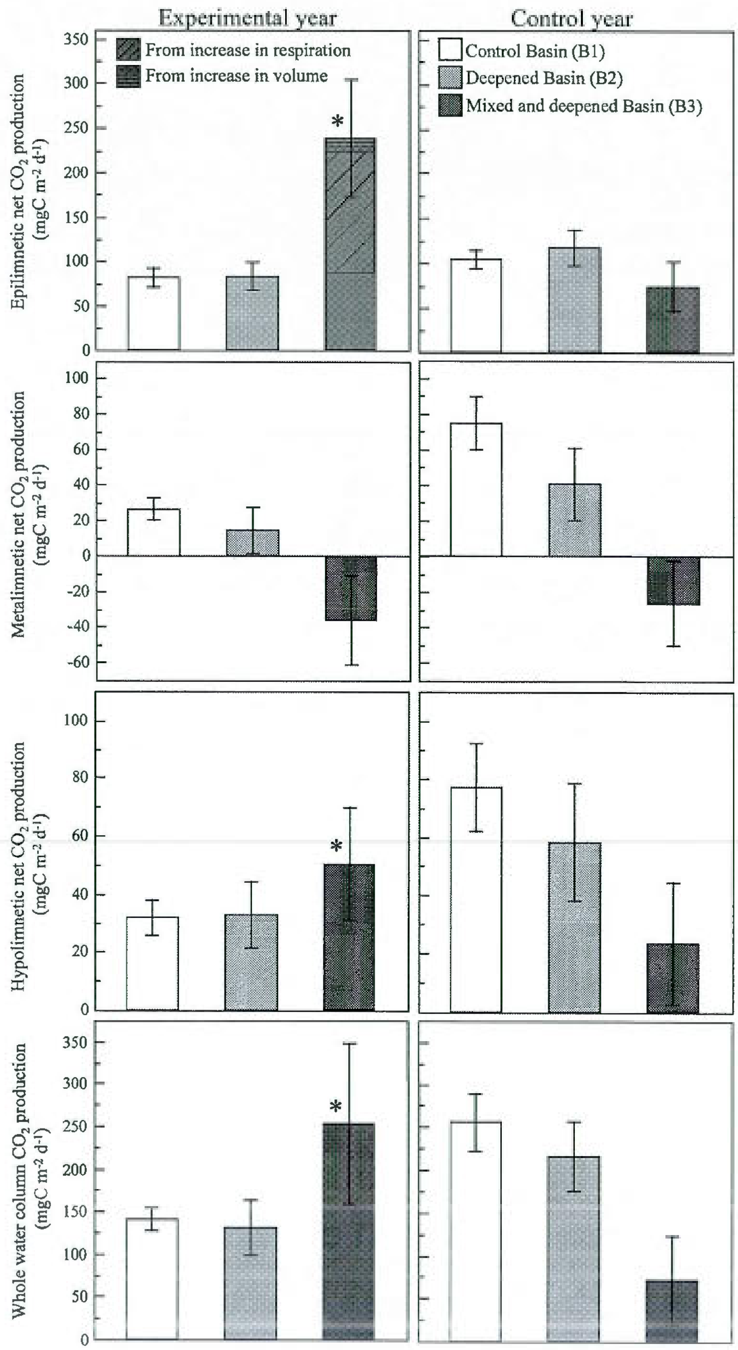

Figure 2.4 Net CO_2 production for the epilimnion, the metalimnion, the hypolimnion and the whole water column of the control (white), the deepened (light grey) and the mixed and deepened (dark grey) basins for the experimental and the control years. Asterisks show the significant variation caused by the manipulation tested with data transformed with the BACI protocol.

2.5 Discussion

We experimentally altered the vertical thermal structure of a lake to simulate the impact of a change in wind regime and explored its consequences for the carbon dynamics at a whole-lake scale. The two experimental basins (both with deepened thermoclines, but with and without active mixing) did not respond in the same way to the manipulation (Mercier-Blais, Beisner and Prairie chap. 1). The mixed and deepened basin (B3), with its general loss of stability and associated greater heat transfer to the hypolimnion, represents the closest approximation of a lake impacted by a greater wind regime. However, the second experimental basin (deeper thermocline but not induced by greater mixing, B2), is probably more akin to the expected changes resulting from an increase in water clarity (hence deeper light penetration; Snucins and Gunn 2000) without necessarily increased winds. For example, climate induced modified hydrological regimes with reduced colored DOC loading would lead to such a scenario. Thus, our two experimental basins can be interpreted as representing separate responses to climate change. However, because the goal of this study was to assess the impact of change in wind regime on lake, we focus our analysis on the response of the mixed and deepened basin (B3).

2.5.1 CO_2 dynamics with altered thermal stratification

The physical deepening of the epilimnetic stratum was expected to increase pCO_2 and CO_2 flux even without any changes in bacterial metabolic rates. This is because gas exchange with the atmosphere is confined to the same surface area, whereas the overall production of CO_2 is increased because of the greater volume of the epilimnion. At steady-state, the net epilimnetic CO_2 production, expressed on an areal basis, must match gas efflux to the atmosphere and this will be achieved only when water pCO_2 has reached sufficiently high levels, particularly given that the gas exchange velocity was not altered (Mercier-Blais, Beisner and Prairie chap. 1). Given the bathymetric shape of L. Croche, the increased depth of the epilimnion corresponds to a modest 20 % increase in the volume and therefore in the expected flux.

The two-fold rise in C evasion to the atmosphere (Figure 2.3) induced by our manipulation far exceeds this expected flux and hence requires an additional net source of

CO_2 to be maintained. Indeed, our calculations of net CO_2 production for the basin as a whole but particularly for the epilimnetic stratum (Figure 2.4), confirm that the metabolic processes were also much altered with the manipulation. Our independent measurements of pelagic respiration also showed a significant increase in the manipulated B3 basin, from 40 to 80 μg L^{-1} d^{-1}. Interestingly, we also observed a significant concurrent increase in chlorophyll and primary production in B3 (Table 2.1) that should have instead reduced the net CO_2 production of that stratum. Clearly, altering the thermal structure of the lake induced a shift towards a more pronounced net heterotrophic balance within the epilimnion. As the observed increase in chlorophyll was not induced by changes in nutrient loading or concentration ($p>0.05$), we suggest that the increase in the epilimnetic pCO_2 of the epilimnion may be the most likely explanation. According to a recent study (Jansson, Karlsson and Jonsson 2012), phytoplankton primary production is limited by nutrients but also by the degree to which a lake is supersaturated with carbon dioxide. Combining all our data from the 3 basins to expand the range of *p*CO2 observed, figure 2.5 shows that Chl-*a* and pCO_2 are tightly and significantly coupled, albeit non-linearly. This relation suggests that, at least in our experimental context, the degree of supersaturation in CO_2 is driving the concentration of chlorophyll and not the opposite as generally thought. Although some studies have begun exploring this relation (Low-Décarie, Fussmann and Bell 2011; Jansson, Karlsson and Jonsson 2012; Verschoor et al. 2013) in laboratory experiments, further study will be required to better unravel the direct and indirect drivers of this surprisingly strong relationship.

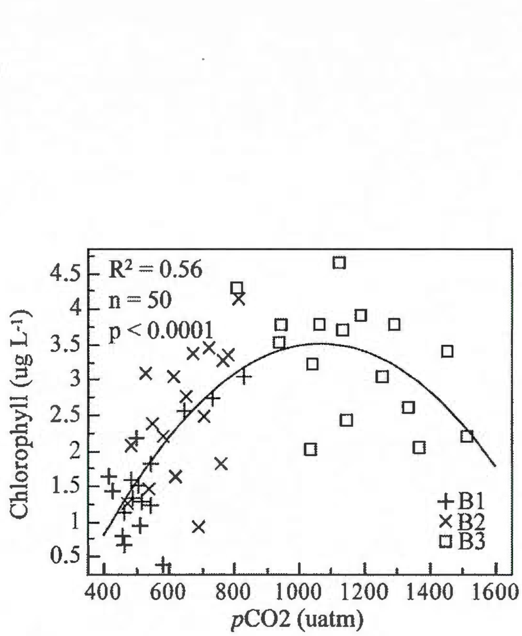

Figure 2.5: Quadratic regression (Chla = 0.23 + 0.0035 * pCO_2 – 6.08e-6 * (pCO_2-775.52)^2) showing the relationship between Chla (mg L^{-1}) and pCO_2 ($u$atm) in the epilimnion of all three basins during the experimental year.

Given that we did not directly measure all the other components of the CO_2 production/consumption processes, such as benthic respiration, and/or photo-oxidation, a complete carbon mass-balance of epilimnetic processes following our experimental manipulation therefore remains poorly constrained. Nevertheless, it remains useful in identifying other likely impacts created by a change in vertical thermal structure.

The reasons for the increase in pelagic water respiration rates observed are not obvious. Given that we did not observe any significant changes in water temperature or in the DOC concentration of the manipulated B3 basin, increased respiration suggests either a new source of labile DOC or a change in the lability of the existing pool. The increase in primary productivity/biomass and its well-known association to pelagic respiration (del Giorgio and Peters 1993, Pace and Prairie 2004) can explain a portion of the observed increase in respiration but cannot account for the increase in the net CO_2 production. One of the major impacts of the thermocline lowering is to expose nominally hypolimnetic sediments to much warmer temperatures, thereby enhancing benthic metabolism (Pace and Prairie 2004) and directly releasing CO_2 in epilimnetic waters. In addition, we suggest that these same sediments can also release labile DOC to the water column, a mechanism that has been shown to be significant in a recently flooded freshwater reservoir (Brothers et al. 2012). As no apparent change in DOC concentration was visible in the water column, we can only assume that the increased amount of DOC released by the sediment is roughly equivalent to the amount of C consumed as water column respiration. From the total net CO_2 production data, this reasoning would suggest a DOC release rate from the sediments on the order of 240 mgC m^{-2} d^{-1}. This estimate is within the range of values found in the literature (from 3 to 417 mgC m^{-2} d^{-1}) for unmanipulated systems (Hanson et al. 2003; Downing et al. 2008) and is thus entirely plausible for sediments having never experienced warm temperatures previously.

2.5.2 Shift in the net carbon balance following thermocline deepening

Temperate lakes typically play a dual role in the carbon balance of the landscape in that they simultaneously act as a permanent carbon sink (in the sediments) and a consistent carbon source to the atmosphere. These two components are functionally linked in that, all else being equal, a reduction in one must lead to an increase in the other. As no change in carbon loading from the watershed was present in this study, the increased net CO_2 production and flux to the atmosphere we observe necessarily implies the consumption of an additional organic carbon pool normally mineralized at lower efficiency. This significant shift in the net carbon economy of the ecosystem has important consequences, not only with regard to its own functioning under a climate change scenario, but also with respect to the role of lakes in the landscape. While our study cannot fully constrain which carbon pool is being preferentially consumed, the lack of any detectable DOC concentration changes in the water column following our experimental manipulation suggests that the major change occurs predominantly from the sediments either as CO_2 directly diffusing out or as DOC release which is then respired within the water column. As part of a different study of the same lake, Ferland et al. (In prep) quantified the net annual accumulation of carbon in the sediments to be about 2 gC m^{-2} yr^{-1}. Considering only the stratified period, the excess catabolism we observed following thermocline deepening amounts to the much larger value of about 55 gC m^{-2} yr^{-1}. This suggests that the stock of organic sedimentary carbon in the altered lake basin may now be declining instead of accruing. Whether this large shift in the net sink/source carbon balance represents only a short-term response following a sudden change in experimental thermal stratification is speculative but it could represent an important and largely unforeseen consequence of altered wind regimes. Ultimately, the depletion of sedimentary labile carbon cannot be sustained indefinitely at such a high metabolic rate. An important extension of this work would thus be to quantify the extent to which previously hypolimnetic sedimentary carbon pool can be metabolized once exposed to higher temperatures.

2.5.3 Lake carbon dynamics and climate change: the predominant influence of wind and a preliminary regional estimate of increased CO_2 evasion for the Laurentian region

While our study focused on the influence of a change in strong wind regimes, the known temperature dependence of pelagic respiration can be used to evaluate the relative importance of these two anticipated effects of climate change. Using the relationship of Pace and Prairie (2004), an increase of 2 °C in surface temperature caused by climate change without any change in thermocline depth would lead to a very small and likely insignificant change in epilimnetic pelagic respiration (from 183 to 187 mgC m^{-2} d^{-1}) while our results based on thermocline deepening (which corresponded to an increase in strong winds from 7 to 13 m s^{-1}) yielded a two-fold increase net CO_2 production. Even if the anticipated wind increase is smaller than predicted, it is clear from our work that the indirect effect of an altered wind regime on lake metabolism will have a much greater impact than the likely change in surface water temperature.

The effects of altered thermal structure we saw in L. Croche are likely to occur in other lakes experiencing similar physical transformations, with necessary consequences on the net carbon balance of the combined terrestrial-aquatic landscape. However, the extent to which individual lakes will respond will depend on the bathymetric shape of each system as the net CO_2 production was related to the release of C from sediment in contact with warmer temperatures. In our experimental lake, a deepening of the thermocline of 4 m led to a 46 % increase of the sediment surface area in contact with the surface mixed layer. This physical transformation yielded an increase of 75 % in the total CO_2 production of the lake (Figure 2.4). Assuming the increase in net CO_2 production is directly proportional to extent of newly exposed sediment surface, we developed a simple model predicting the change in net production ($\Delta\ CO_{2prod}$) as a function of the change in thermocline depth ($\Delta\ Z_{therm}$) based on the bathymetric model of Imboden (1973; $A_Z = A_0\ (1 - Z{:}Z_{max})^q$, where q is 1.43 for L.

Croche). This model, illustrated in figure 2.6, suggests that the net carbon balance of aquatic ecosystems is particularly sensitive to the depth of the thermocline. Considering that the bathymetric shape parameter *q* of L. Croche (1.43) is similar to the average of a sample of 229 Laurentian lakes (Adam Heathcote, UQAM, 2013, unpubl. data), we suggest that the magnitude of the response observed in L. Croche is likely representative of other lakes in the region. If this is the case, the future may well bring a generalized shift in the sink/source carbon balance of lakes with the implication that the landscape as a whole would lose significant portion of its capacity as a carbon sink.

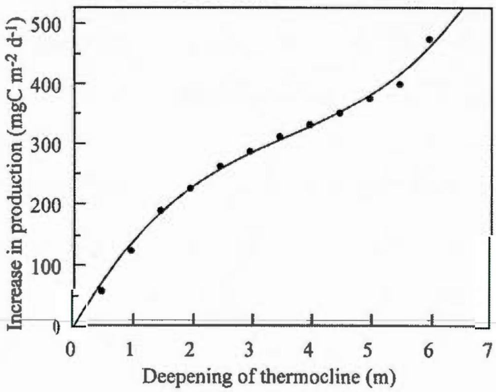

Figure 2.6 Cubic polynomial regression (Increase in CO_2 production= 139.30 + 47.74 * Deepening – 6.63 * (Deepening-3)^2 + 3.42 * (Deepening-3)^3) representing the variation in CO_2 production in L. Croche epilimnion caused by different scenarios of deepening of the thermocline.

2.6 Acknoledgements

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CONCLUSION

Les changements climatiques et les altérations anthropiques exercent actuellement des pressions importantes sur de nombreux écosystèmes. Des changements au niveau de la température atmosphérique, des précipitations et dans le régime des vents risquent de générer des transformations majeures sur la stratification thermique des lacs. Le projet TIMEX (Thermocline Induced Mixing EXperiment) avait pour objectif de mieux comprendre l'effet spécifique de l'augmentation des vents forts sur la stratification thermique d'un petit lac de la zone Nord Tempérée du Québec. Ce projet initié en 2007 au Lac Croche (St-Hippolyte, Québec, Canada) regroupait des limnologistes de différentes spécialités dans le but d'avoir une meilleure compréhension globale des transformations physiques, biogéochimiques et biologiques ayant lieu suite à une telle altération du régime thermique d'un lac (Cantin et al. 2011, Sastri et al. In press, Gauthier et al. In press, Gillespie et al. In prep, Perron et al. Submitted, Ouellet Jobin et al. Submitted et différents autres articles en préparation).

Mon projet de maîtrise vient plus spécifiquement répondre aux questions sur les changements physiques dans la colonne d'eau et sur la dynamique de transformation du carbone du lac. Des données récoltées toutes les semaines durant les années 2010 (année expérimentale) et 2011 (année contrôle) ont été utilisées pour répondre aux différentes questions de mon projet. Le premier objectif de celui-ci était de caractériser le cadre physique du projet TIMEX dans le but de mieux comprendre les changements physiques ayant lieu dans chacune des strates de la colonne d'eau suite à une augmentation du mélange de la couche d'eau de surface ainsi qu'à un abaissement de la thermocline. Par la suite, la seconde partie de mon projet de maîtrise s'intéressait aux transformations de carbone dans le lac suite à une telle altération de la stratification. Les objectifs de cette section étaient de déterminer les changements au niveau de la production nette de CO_2 dans la colonne d'eau pour par la suite évaluer les impacts d'un changement de régime thermique sur les émissions de CO_2 de la surface du lac vers l'atmosphère.

Dans le but de répondre à ces deux questions, un des trois bassins naturels du L. Croche a été expérimentalement altéré à l'aide d'une éolienne aquatique afin de simuler un abaissement de la profondeur de la thermocline. Un second bassin avec une thermocline partiellement altérée a aussi été utilisé durant le projet, alors que le troisième bassin est resté intact en tant que bassin contrôle (Figure 0.2)

En premier lieu, le calcul de différents paramètres de la stabilité de la colonne d'eau à l'aide des données de température (HOBO) a permis d'observer une perte importante de stabilité de la colonne d'eau dans le bassin mélangé et abaissé (B3). De plus, cette perte de stabilité a engendré une augmentation du transport vertical (quatre fois plus élevé) de chaleur, de matière et de gaz dissous. La principale conséquence de ce transport intensifié se situait dans l'hypolimnion de ce bassin, qui s'est réchauffé de 1.5 °C en moyenne au courant de la saison libre de glace de l'année expérimentale. Malgré aucun changement dans la température de l'eau de surface, le volume représentant cette eau chaude ainsi que l'aire de sédiment en contact avec celle-ci a été grandement augmenté (20 et 45 % respectivement).

Dans la deuxième section de mon projet de maîtrise, les résultats obtenus ont permis d'observer une augmentation importante dans la production de CO_2 dans un lac avec une structure thermique altérée, ce qui a résulté en une émission deux fois plus élevée de CO_2 de la surface du lac vers l'atmosphère. Cette production nette de CO_2 était principalement visible dans l'épilimnion et reliée à une augmentation importante des sédiments en contact avec l'eau réchauffée par un régime des vents intensifié. En effet, le changement physique observé dans la couche de surface causerait un relargage de C important des sédiments en direction de la colonne d'eau. Le carbone issu de ce relarguage serait alors en mesure de soutenir l'importante augmentation dans le métabolisme du lac, diminuant ainsi le stockage de carbone dans les sédiments en augmentant les émissions vers l'atmosphère.

Étant donné que les changements climatiques représentent des influences sur les écosystèmes complexes et susceptibles à de nombreuses variations au niveau temporel et spatial, il serait important de conduire plus d'études à long terme permettant d'établir leurs effets sur les lacs. Malgré l'importance de comprendre de manière individuelle les impacts de chaque changement possible dans le climat, il faut aussi prendre en considération les interactions entre les différents changements climatiques. Également, les scénarios climatiques émis par le GIEC au niveau du régime des vents prédisent une augmentation des évènements de vents forts et des tempêtes et non de la vitesse moyenne des vents (IPCC 2007). Dans le but de refléter de manière plus réalistique ces évènements périodiques, l'expérimentation pourrait être répétée, mais cette fois en laissant agir l'éolienne aquatique seulement durant de courtes périodes de temps.

De plus, il serait intéressant d'effectuer le même genre de projet expérimental sur des lacs ayant des caractéristiques physiques et chimiques différentes. Étant donné que les concentrations en COD ont une grande importance dans la dynamique du carbone, obtenir un gradient de COD dans les lacs à l'étude permettrait d'obtenir plus d'information sur la dynamique réelle du carbone. Ensuite, la respiration benthique représente une part importante de la production totale de CO_2 dans les lacs et n'a pas été mesurée dans le présent projet. En plus, il serait intéressant d'évaluer l'impact simultané d'un abaissement de la thermocline avec une augmentation des apports en carbone du bassin versant, une situation représentative de ce qui arriverait dans le cas d'une déforestation du territoire entourant le lac.

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