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EFFECTS OF RESEARCH DIVING ON A STRATIFIED ANTARCTIC LAKE

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Abstract—Results are presented from a study into the effects of scuba diving on water column structure in perennially ice-covered Lake Fryxell, Antarctica. General theoretical predictions are compared with results, which assess potential impacts from diving activities on water quality parameters related to disruptions to water column stability and dissolved gas concentrations. Potential mechanisms of water column disturbance are considered including: (1) mixing due to diver motion, (2) mixing by diver-exhaled bubble plumes and (3) changes of water column gas concentrations due to dissolution of diver-exhaled gases. Data (temperature, dissolved oxygen, specific conductance, pH, dissolved organic carbon, salinity) were collected from two control holes and one dive hole immediately before and 2.5 d after dive activities. Variability in measured parameters did not differ significantly between sampling sites either before or after diving; and differences between control holes and dive hole observations, on a depth-by-depth basis, were within the range of expected statistical fluctuations. Pre- and post-dive virus-like particle, bacterial, ciliate, photo- and heterotrophic flagellate densities also did not differ significantly. An apparent lack of long-term trends indicative of water column destabilization over the past 18 ys of diving is discussed, along with recent evidence for deep mixing in this lake. Although all potentially affected parameters have not been considered, theoretical model results and an analysis of field data suggest that diving impacts on physicochemical properties and microbial distributions in a closed-basin, ice-covered lake occur at spatiotemporal scales other than those considered in this study.

Key words—scuba diving, impact assessment, disturbance, dissolved gases, water quality, Antarctica, polar lakes, stratification, stability

INTRODUCTION

The distribution of perennially ice-covered lakes is largely limited to Antarctica (Goldman, 1970). Lakes of the McMurdo Dry Valleys region of South Victoria Land have been studied in increasing detail over the past 30 yr (e.g. Green and Friedmann, 1993). These lakes are largely insulated from annual variations in air temperature by thick (2.8–6 m) ice covers (Wharton *et al*., 1993). Many of the lakes are remnants of larger glacial water bodies which, through repeated drying and filling events, have developed unique salinity profiles (Armitage and House, 1962; Hoare *et al*., 1965; Lawrence and Hendy, 1985; Spigel and Priscu, 1998). Ice covers on these lakes minimize wind-driven currents and, to a limited extent, the exchange of gases between the water column and the atmosphere. Although the historical processes which have led to observed density-stratified lakes are still being considered (e.g. Lyons *et al*., 1998a,b), this layering, combined with minimal turbulence, has major implications for the distribution of planktonic organisms (e.g. Vincent, 1981; Hawes, 1983; Kepner and Wharton, 1996; Lizotte *et al*., 1996; Laybourn-Parry *et al*., 1997; Priscu *et al*., in press).

The lakes of the McMurdo Dry Valleys have been studied since the International Geophysical Year of 1957. More recently, the Madrid Protocol of 1991 designated Antarctica as a natural reserve, devoted to peace and science. The Protocol sets out environmental principles, incorporates a conditional prohibition on mineral resources activities, and requires the conduct of Environmental Impact Assessments (EIAs) for proposed activities on the continent. Also, signatory nations have agreed to elaborate rules and procedures relating to legal and

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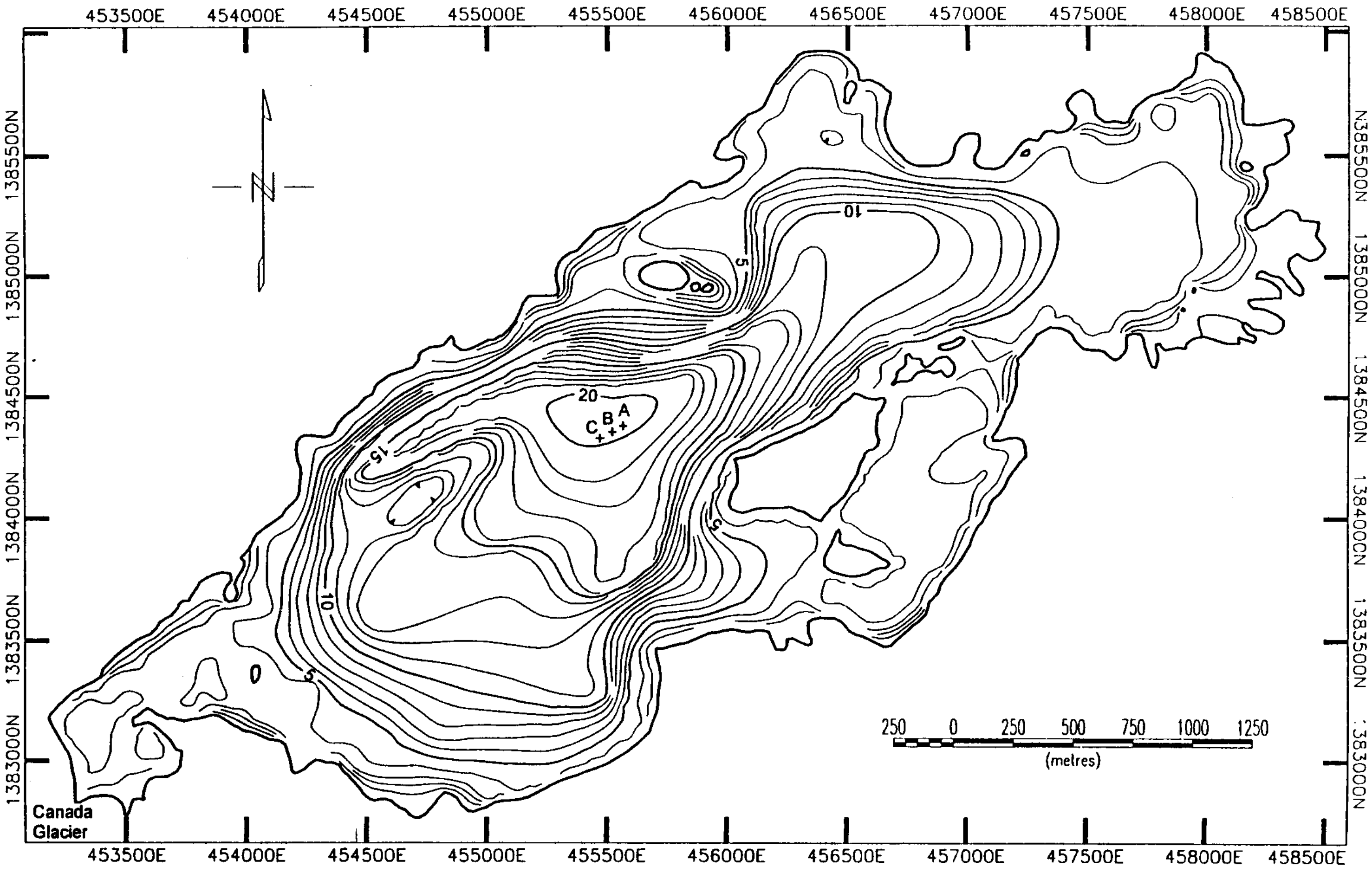

Fig. 1. Bathymetric map of perennially ice-covered Lake Fryxell showing the location of two control holes (A and B) and the dive hole (C). Contour intervals are 1 m. Modified from Doran *et al.* (1997).

practical responsibility for environmental damage arising from their activities. “Minor and transitory” are terms used in the Madrid Protocol to describe levels of effects proposed activities may have without requiring EIAs. These terms are not defined in the Protocol, yet it is important to evaluate the potential impacts of activities in Antarctica even in the absence of specific definitions. Given that lakes of the dry valleys are unique on Earth and have properties which are used as indicators of regional and global climate change, it behooves the scientific community and public at large to preserve their pristine nature to the maximum extent possible.

The present study has been prompted by concerns regarding environmental impacts (the terms impacts and effects are used here synonymously) of research activities within Antarctica’s pristine natural environments (e.g. Jezek and Tipton-Everett, 1995; Vincent, 1996). Research diving is one of many potentially disruptive activities requiring objective evaluation. A recently formulated Environmental Code of Conduct for researchers working in the McMurdo Dry Valleys (Vincent, 1996) states, “Avoid swimming or diving in the lakes if at all possible. These activities could contaminate the water body and physically disturb the water column, delicate microbial communities and sediments.” Research diving in lakes is currently considered to be a moderate, high or unacceptably high environmental impact activity, depending upon the scale and location of the activity (Vincent, 1996). This study has been conducted because an awareness of potential environmental impacts is prerequisite to the development of proper management strategies for this scientifically important region of Antarctica.

In this paper, we report the results from a theoretical analysis and field study designed to investigate effects of scuba diving on the stratified water column of an Antarctic lake. To our knowledge, this study represents the first attempt to quantify the potential impact of diving on any lake system.

SITE DESCRIPTION

Lake Fryxell is a perennially ice-covered, highly stratified, closed-basin lake located at the eastern end of Taylor Valley (77°37′S, 163°8′E) at an elevation of 18 m above mean sea level (Fig. 1). Several glacial meltwater streams drain the 230 km^2 watershed. These streams typically flow for 4–8 weeks during the austral summer. Depending upon summer air temperatures, a 1–10 m wide ice-free moat usually forms around much of the lake margin. This moat typically comprises $<3\%$ of the lake’s total surface area, hence the amount of wind energy available to directly mix the water column is negligible (Spigel and Priscu, 1998). For a given wind speed and area of open water, the energy flux into the water column can be estimated. The average 1 December through 31 January wind speed at Lake Fryxell is 3.6 ± 0.1 m s^{-1} (Doran, unpublished data). This would yield an approximate energy flux of 6.3×10^{-6} W m^{-2} to open moat water (Schladow and Fisher, 1995), meaning that an average of 4.5 W or 3.9×10^5 J d^{-1}, is deposited into Lake Fryxell for every 1% of the total lake surface that is ice-free. Assuming 30 d of entirely open moat per year, this works out to roughly 3.5×10^7 J yr^{-1} of wind-deposited energy.

The average annual influx of meltwater to Lake Fryxell between 1990 and 1995, excluding direct glacial input and non-gaged streams, was 1.3×10^6 m^3 (USGS unpublished data, see http://srvdwimdn.er.usgs.gov/hrhdocs). The liquid portion of Fryxell can be divided into two parts: (1) a low-salinity, oxygenated, low-dissolved organic carbon (DOC) epilimnion with a volume of 1.1×10^7 m^3 and (2) a saline, anaerobic, high-DOC hypolimnion lying below a depth of 8 m, with a volume of 1.4×10^7 m^3 (Doran *et al.*, 1997). By volume, the majority of water in the lake is actually ice, which covers the lake with a mean total thickness of approximately 5.5 m (Table 1). The water column below this ice is highly stable, with stabilities ranging from 0.5 to 1.0×10^{-3} m^{-1} (Spigel and Priscu, 1998). This is four to eight times higher than the stability of a typical freshwater thermocline (Spigel and Priscu, 1998).

In addressing possible effects of diving, we initially asked two questions. What is the equilibrium state of Lake Fryxell? That is, would a small perturbation of the system tend to be amplified or dissipated? If the equilibrium state were unstable, in the dynamical systems sense rather than the traditional limnological sense, then a relatively small perturbation might initiate cascading reactions causing the system to move toward a new equilibrium. By definition, a stable state would, upon being disturbed, tend to return to its initial state. If the system does in fact reside in a stable state, then are dive-related perturbations sufficient to push the system far enough from its equilibrium state to significantly affect the physical, chemical, and/or biological character of the lake?

In actuality, Lake Fryxell is not strictly in a state of static equilibrium (a state which would only be realized with uniform, unchanging, isothermal and isohaline profiles); a fact betrayed by its existing temperature gradient. Temperatures range from 0°C at the ice–water interface to approximately 2.7°C in midwater portions ($\approx$10–13 m) of the lake. The insulating quality of the thick ice cover, along with the immense thermal inertia of the ice–water system, virtually ensure that Fryxell exists in a *de facto* state of dynamic equilibrium in which the influx of solar radiation and continuous material and energy transfers between the atmosphere and underlying sediments lead to an approximate steady state in the lake. Although Lake Fryxell does not occupy a

Table 1. Morphometric data for Lake Fryxell (Doran *et al.*, 1997)

Maximum length	5.84 km	Surface area	7.08 km^2
Maximum breadth	2.06 km	Mean depth	7.60 m
Maximum depth[a]	20.0 m	Shore line development	2.20
Average ice thickness	5.50 m	Volume of liquid water	2.52×10^7 m^3
Average ice depth[a]	4.70 m	Volume of water as ice	2.83×10^7 m^3

[a] At piezometric water level in ice drill holes.

true static equilibrium state, its thermal profile appears to be stable from year to year and recent thermal profile data are similar to those obtained as much as 35 yr ago (e.g. see Hoare *et al.*, 1965). This is important because temperature acts as a nearly passive tracer of water column disturbance. Density and resulting stability gradients in Lake Fryxell are controlled almost entirely by the concentration of dissolved solids (i.e. "salinity", Spigel and Priscu, 1998). Perturbations introduced each summer during moat melting, meltwater inflow and scientific work do not appear to send the system cascading towards another, significantly different state. The density gradient associated with both salinity and temperature will cause any parcel of water moved a relatively small vertical distance from its equilibrium position to tend to migrate back to its original position rather than cause any kind of cascading destabilization effect. Nevertheless, during the movement of any water parcel, irreversible changes occur over a limited spatiotemporal range. If the frequency and spatial scale of observations do not match those at which these changes occur, we will observe a temporally stable density gradient in the lake.

Lake Fryxell's dissolved oxygen (DO) distribution also does not represent a state of static equilibrium, since there is a net flux of O_2 from supersaturated epilimnetic waters to O_2-depleted bottom waters. Previous work on nearby Lake Hoare (77°38′S, 162°53′E) has identified net sources and sinks for water column O_2 including: (1) the enrichment of DO near the surface by the seasonal formation of new ice, (2) downward transport of DO by diffusion to benthic microbial mats and anaerobic bottom waters and (3) lateral transport of O_2 (Wharton *et al.*, 1986, 1987; Craig *et al.*, 1992). Also, during autumnal moat freezing, solute-enriched water excluded from ice may sink as density currents to the bottom of the lake (Miller and Aiken, 1996), conceivably affecting gas concentrations.

Aiken *et al.* (1991) estimated the mixing potential of Lake Fryxell by calculating the stability of the water column (5–18 m) as a function of its density. Using the empirical relationship of Quay (1977), they obtained a vertical eddy diffusion coefficient (K_z), of $5.9 \times 10^{-5}\ cm^2\ s^{-1}$. The K_z is inversely related to water column stability. Lerman (1988) reported K_z values for stratified lakes ranging from 10^{-2} to $10^2\ cm^2\ s^{-1}$, at least three orders of magnitude higher than that calculated for Lake Fryxell. Other recent studies indicate that stability in Lake Fryxell is extremely high and that there appears to be little vertical mixing compared with other freshwater lakes (Hood *et al.*, 1998; Spigel and Priscu, 1998). This great stability, along with smooth temperature and salinity profiles, suggests that vertical transport of dissolved solutes is dominated by processes of molecular diffusion (Spigel and Priscu, 1998), although additional transport mechanisms have recently been suggested (Miller and Aiken, 1996; Tyler *et al.*, 1998).

THEORETICAL ANALYSIS

In this section, we analyze and evaluate the magnitude of three potential mechanisms by which research divers might impact the water column of Lake Fryxell. These include: (1) mixing due to diver motion, (2) mixing by diver-exhaled bubble plumes and (3) changes of water column gas concentrations due to dissolution of diver-exhaled gases. Considering Lake Fryxell as a relatively stable, dissipative system, methods have been chosen to limit uncertainties and simplifying assumptions have been made conservatively such that potential errors in analyses tend to overestimate the magnitude of diver impact.

Diver motion

A diver typically achieves forward momentum by pushing a volume of water backwards. This volume of water, although initially moving as a collective mass, soon dissipates into chaotic turbulent motion. A diver moves forward by converting stored chemical energy, through muscular activity, into random turbulent motion within the fluid, which is available to mix the stability profile of a water column through induced diffusive mechanisms. In the treatment that follows, it is assumed that the energy deposited into the fluid through propulsion is effective at destabilizing the water column with an efficiency of 1.0. We acknowledge that this assumption is a gross overestimate since mixing efficiencies are found to range between 0.05 and 0.25 (Imboden and Wüest, 1995).

Provided we know the force, $\vec{F}$, with which a diver is propelled, the amount of energy deposited into the water column is easy to calculate. The work performed by a force, acting over a distance, $\vec{s}$, is defined as

$$W = \int_s \vec{F}\, \mathrm{d}\vec{s}. \tag{1}$$

The force produced by a diver can either be estimated using Newtonian mechanics or measured directly. Sarich and Chatterton (1984) performed such measurements by towing a fully outfitted diver in a ship model towing tank. They found $0.5\ \mathrm{m\,s^{-1}}$ to be the practical upper limit on swimming speed, and an average diver would have to exert approximately 21 N to overcome drag forces at such a speed. Based on O_2 consumption data, Sterba (1990) reported that the optimal swimming speed for a dry suit diver in very cold water is $0.26\ \mathrm{m\,s^{-1}}$. Combined with the fact that, on average, $< 20\%$ of actual in-water time is spent actively swimming during a research dive, the average swimming speed during a typical dive in Lake Fryxell would be well below $0.5\ \mathrm{m\,s^{-1}}$. Nevertheless, we will use this high speed to insure that we are considering an extremum of energy deposition. Knowing the force, $\vec{F}$, the swimming speed, v, and the duration of a dive, t, equation (1) can be recast into a form that will yield the energy deposited by a single research dive:

$$W = Fvt. \tag{2}$$

Assuming that a dive lasts for about 45 min, the amount of work done during a typical research dive becomes

$$W = 21\ \mathrm{N} \times 0.5\ \mathrm{m\,s^{-1}} \times 2700\ \mathrm{s} = 2.8 \times 10^4\ \mathrm{J}$$

To assess the impact associated with deposition of this quantity of energy, we compare it to the total energy stored in the stratification of the water column. How does the energy produced by the diver compare to the total energy needed to adiabatically mix the water column? Consider the center of mass of a completely mixed isopycnal lake:

$$Z_{\mathrm{CM,M}} = \frac{\int_v z\,\mathrm{d}m}{\int_v \mathrm{d}m} = \frac{\int_v z\rho\,\mathrm{d}V}{\int_v \rho\,\mathrm{d}V} = \frac{\int_0^h zA(z)\,\mathrm{d}z}{\int_0^h A(z)\,\mathrm{d}z} = \frac{\int_0^h zA(z)\,\mathrm{d}z}{V} \tag{3}$$

where z is the lake depth, $\mathrm{d}m$ is a mass element, $\mathrm{d}V$ is a volume element, ρ is the density of water, $A(z)$ is the horizontal area of the lake as a function of depth and h is the maximum depth under consideration, in this case, the lake bottom. Further, the center of mass of a density-stratified lake is

$$Z_{\mathrm{CM,S}} = \frac{\int_v z\,\mathrm{d}m}{\int_v \mathrm{d}m} = \frac{\int_0^h z\rho(z)A(z)\,\mathrm{d}z}{\int_0^h \rho(z)A(z)\,\mathrm{d}z} = \frac{\int_0^h z\rho(z)A(z)\,\mathrm{d}z}{M} \tag{4}$$

where $\rho(z)$ is the depth-dependent water density and M is the total mass of water in the lake, with g being the acceleration due to gravity. The difference in potential energy between a mixed and stratified water column is

$$\Delta U = U_{\mathrm{M}} - U_{\mathrm{S}} = MgZ_{\mathrm{CM,M}} - MgZ_{\mathrm{CM,S}} \tag{5}$$

Substituting the explicit forms of $Z_{\mathrm{CM,M}}$ and $Z_{\mathrm{CM,S}}$ into equation (5) and reducing, yields

$$\Delta U = g\int_0^h [\bar{\rho} - \rho(z)]zA(z)\,\mathrm{d}z \tag{6}$$

where $(M/V) = \bar{\rho}$.

Using measured temperature and salinity profiles, together with hypsographic curves for Lake Fryxell, we calculate that the energy required to mix the entire lake is approximately 2.0×10^9 J. The energy required to mix a discrete cylinder of water with a radius of 50 m (the maximum extent of most tethered dives) and a depth of 18 m (the maximum depth of Lake Fryxell) is 1.1×10^7 J.

In comparison, one 45 min dive would impart $(2.8 \times 10^4\ \mathrm{J})/(2.0 \times 10^9\ \mathrm{J}) = 1.4 \times 10^{-5}$ or 0.0014% of the energy needed to mix the entire stratified lake. The same dive would impart $(2.8 \times 10^4\ \mathrm{J})/(1.1 \times 10^7\ \mathrm{J}) = 2.5 \times 10^{-3}$ or 0.25% of the energy needed to mix the previously described hypothetical cylinder of water, 50 m in radius. Additional comparisons can be made to the estimated 3.5×10^7 J of wind-deposited energy entering Lake Fryxell each year. We reiterate that our estimate of mixing effects due to diver motion is a gross overestimate because of assumptions regarding mixing efficiency and diver swimming speed.

Another means of estimating the effects of research diving on Lake Fryxell is to compare the natural vertical eddy diffusion rate, cited earlier as $5.9 \times 10^{-5}\ \mathrm{cm^2\,s^{-1}}$ (Aiken *et al.*, 1991), to the diffusion rate induced by the internal dissipation of the diver-deposited energy. Using a model introduced by Ozmidov (1965), Fischer *et al.* (1979) expressed the induced eddy diffusion coefficient, K_{zi}, as

$$K_{zi} = \frac{\alpha\Delta\rho gPh}{\Delta UN^2\rho_0} \tag{7}$$

where α is a diffusion efficiency, assumed to be no larger than 0.05 (Imberger and Hamblin, 1982), $\Delta\rho$ is the surface to bottom density difference ($6.7\ \mathrm{kg\,m^{-3}}$), P is the power input to the water column, N is the stratification frequency (integrating equation (A.5) of Appendix A over measured temperature and salinity profiles of Lake Fryxell gives $N = 0.088\ \mathrm{s}^{-1}$) and ρ_0 is a characteristic density of the water column. The maximum induced diffusion coefficient associated with the diver power input (i.e. $P = \vec{F} \times \vec{v} = 10\ \mathrm{W}$) is $K_{zi} = 3.4 \times 10^{-5}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$, which is on the same order of magnitude as the natural eddy diffusion coefficient. However, a more intense diving schedule might involve one 45 min dive per day, for which the energy input, averaged over a 24 h period, would be 320 mW. Given this scenario, the average induced diffusion coefficient would be $K_{zi} = 1.1 \times 10^{-6}$ or a factor of 50 below the naturally occurring diffusion coefficient.

Diver-exhaled bubble plumes

The second method we consider by which diving could perturb the stability profile of Lake Fryxell is through mixing due to the entrainment of water by bubble plumes from diver-exhaled gases. We employ the findings of Asaeda and Imberger (1993) who developed a double annular plume model applicable to stratified fluids with linear density profiles. A refinement of the equivalence strategy introduced by Lemckert and Imberger (1993) is used to extend Asaeda and Imberger's results to the realm of non-linear density profiles (Appendix A). Bubble plume behavior can be ascribed with the aid of two dimensionless parameters (Asaeda and Imberger, 1993). These include the effective buoyancy flux:

$$M_H = \frac{Q_0 g h_a}{4\pi\alpha^2 h^2 u_s^3} \tag{8}$$

and the reduced inverse intrusion length:

$$P_N = \frac{N^3 h^4 (h + h_a)}{Q_0 g h_a}, \tag{9}$$

where Q_0 is the rate of gas flow at 1 atm., g is acceleration due to gravity, h_a is the equivalent atmospheric pressure head (typically 10.2 m), h is the maximum water depth under consideration, in this case, the depth of the bubble source, u_s is the slip velocity between the rising bubble plume and the entrained water column, α is the entrainment coefficient and N is the buoyancy frequency as defined in Appendix A. Standard values for u_s and α are $0.3\ \mathrm{m\ s}^{-1}$ and 0.083, respectively (Schladow, 1992). Assuming an air consumption rate of $20\ \mathrm{l\ min}^{-1}$, as would be the case during continuous slow ($0.13\ \mathrm{m\ s}^{-1}$) swimming (Edmonds *et al.*, 1995), $Q_0 = 3.3 \times 10^{-4}\ \mathrm{m}^3\ \mathrm{s}^{-1}$. Integrating equation (A.5) of Appendix A over measured temperature and salinity profiles gives $N = 0.088\ \mathrm{s}^{-1}$. Resulting values for the effective buoyancy flux and the reduced inverse intrusion length are $M_H = 3.0 \times 10^{-2}$ and $P_N = 5.9 \times 10^4$, assuming a bubble source at a depth of 18 m.

Calculations by Asaeda and Imberger (1993) indicate that values of $M_H = 3.0 \times 10^{-2}$ and $P_N = 5.9 \times 10^4$ correspond to a plume efficiency, η, of approximately 0.08. The plume efficiency is defined as $\eta = \Delta E / (Q_0 \rho g h_a \ln(1 + h/h_a)\Delta t)$, where ΔE is the amount of buoyancy potential energy that is coupled into the fluid and $Q_0 \rho g h_a \ln(1 + h/h_a)$ is the power required to isothermally compress air from the pressure $\rho g h_a$ to the pressure $\rho g h$ at the rate Q_0. Given $\rho g h_a = 1$ atm and $\eta < 0.08$, this expression for η can be rearranged to give $\Delta E/\Delta t = 3.5\ \mathrm{J\ s}^{-1}$, or for one 45 min dive, $\Delta E = 9.5 \times 10^3$ J. This is roughly a factor of three below the energy input generated by the diver's locomotion (see above). Thus, mixing due to diver locomotion will be somewhat greater than mixing due to exhaled bubble plumes, although these two mechanisms will likely effect water column stratification to approximately the same order of magnitude.

Gas dissolution

By considering both high and low impact scenarios for potential gas concentration disruptions, we establish the possible range over which our model diver might impact gas concentrations through the dissolution of exhaled gases. We first consider the case with respect to O_2, an atmospheric gas that is strongly stratified in Lake Fryxell. Although released atmospheric gases differ in their behavior (e.g. due to differences in ambient concentrations, solubilities, absolute saturation values, etc.), we consider DO as a proxy for other dissolved atmospheric gases released by divers.

The highest impact scenario assumes that a diver's entire gas exhaust would be completely dissolved into one layer of deep, anaerobic water [e.g. the 17–18 m ($3.6 \times 10^4\ \mathrm{m}^3$) layer in Lake Fryxell]. Again assuming our model diver requires $20\ \mathrm{l\ min}^{-1}$ of air, 900 l would be used in one 45 min dive. Given that the fraction by weight of the atmosphere that is O_2 is approximately 0.231, a 45 min dive would require the inhalation of 0.27 kg of O_2. Dissolving this amount of O_2 completely into the 1 m thick layer of Fryxell bottom water would increase average DO in this layer by less than $0.01\ \mathrm{mg\ l}^{-1}$, thus allowing tens of hours of diving before detectable changes in DO could be observed. Of course, it is more realistic to assume that only a fraction of inhaled O_2 is actually exhaled and that even a smaller fraction of released O_2 would dissolve in lake bottom waters, thus increasing deep diving time to hundreds of hours before changes in DO could be detected.

A lower impact scenario results when we assume that diver-exhaled gas bubbles rise immediately to the ice–water interface while having little interaction with the water column. In this case there will be negligible change in the concentration of dissolved gases in the water column. We have observed that bubbles naturally migrate to, and exit from, the dive hole when divers are within approximately 10 m in any horizontal direction. Moreover, during the austral summer when diving activities occur, the ice is often porous and fractured, allowing exhaled gases to escape rapidly to the atmosphere through the ice (Andersen *et al.*, 1993; Wharton *et al.*, 1993). Thus, it is likely that the majority of diver-generated gases escape to the atmosphere within minutes or even seconds of release.

The small proportion of exhaled gas that does not escape through the diver access hole, or cracks in the ice, will collect under the ice. Here it will either dissolve into the water (unlikely in the case of O_2, considering supersaturated epilimnetic O_2 conditions), or under appropriate circumstances, freeze into the bottom of the ice. When freezing does occur, 40–70% of the gas located at the freezing front is incorporated into the bottom of the ice cover (Craig *et al.*, 1992). Water freezes at the bottom (ice/water interface) while continually ablating from the top of the ice cover. Similar to detached pieces of benthic microbial mat (Parker *et al.*, 1982), ice-incorporated gas bubbles will be gradually conveyed upwards. Assuming a steady-state ice cover thickness, an ablation rate of 30–40 cm yr^{-1} (Henderson *et al.*, 1965) and comparable mass loss by melting (Wharton *et al.*, 1992); diver-derived gases frozen into the overlying ice of Lake Fryxell would ultimately be released to the atmosphere within 4–8 yr, as previously described for Lake Hoare (Wharton *et al.*, 1992). In addition, gases that do dissolve in surface waters will have a relatively minor impact due to the large quantities of extant dissolved gases (e.g. Wharton *et al.*, 1986, 1987).

Although the majority of exhaust gas either quickly escapes to the atmosphere or is frozen into the ice cover (Craig *et al.*, 1992), we now consider O_2 dissolution into the upper 1 m layer. The mean DO concentration in this layer of water is approximately 14 mg l^{-1}. Assuming that exhaled air contains an O_2 concentration equivalent to that of the dry atmosphere (i.e. again neglecting O_2 consumed by the diver) and that all exhaled gas is dissolved completely in the 1 m surface layer of water, approximately 500 h of continuous diving would be required to increase this upper layer DO concentration by 0.1%.

To put these potential DO concentration changes into perspective, it is useful to compare diver-generated O_2 inputs to the average annual DO input to Lake Fryxell via meltwater streams. Assuming that the streams are saturated with atmospheric O_2, the average annual influx of meltwater delivers approximately 23,300 kg of O_2 to the lake. This is equivalent to the amount of O_2 which, under high impact circumstances, would be introduced during 65,170 h (2700 d) of continuous diving. This implies that, even if diver-generated gases could not escape the lake and were completely dissolved in the water column, several scuba divers diving continuously for an entire field season would have no large-scale impact on water column DO concentrations.

Although temporary (<8 yr), localized (10 to 50 m) increases in concentrations of specific gases in the overlying ice cover might be expected as a result of diving, these changes would be negligible at larger scales of consideration. Assuming that measured areal freezing rates and rates of O_2 incorporation into new ice on Lake Hoare (Craig *et al.*, 1992) apply to Lake Fryxell, we estimate that 9–12 MT of O_2 is frozen into the Fryxell ice cover on an annual basis. This is three orders of magnitude more O_2 than that potentially introduced in the form of diver-exhaled gas.

The effects of diving on trace gas concentrations have been addressed by considering data on current Lake Fryxell chlorofluorocarbon (CFC) concentrations (Tyler *et al.*, 1998). Using best-fit curves fitted to mean CFC concentrations collected at specific depths and the hypsographic curve for Lake Fryxell (Doran *et al.*, 1997), we estimated masses of CFCs 11, 12 and 113 on a whole-lake basis and compared them to amounts potentially released to the water column in diver-exhaled gas (Table 2). Calculations indicate that several hundred of years of continuous diving would be required to introduce the masses of CFCs currently present in Lake Fryxell. Based on this data, we conclude that diving constitutes a negligible source for water column CFCs.

FIELD ASSESSMENT

Materials and methods

In addition to the theoretical analysis described above, a field study was designed to assess the *direct* effects of dive activities, i.e. those potential effects which are observable at the same time and location in which diving takes place. Indirect effects which are potentially caused by diving, but which are manifested later in time or farther removed in space, were not addressed by our field study.

Three dives were conducted on 24 November, 1996 in Lake Fryxell, with under-ice dive times of 24, 28 and 30 min. Tethered drysuit divers were instructed to direct activities away from control holes following descent. During the dives, researchers descended through the chemocline (8–12 m) and collected benthic material (sediment cores and grab samples) before returning to the surface. A total of approximately 57 diver-min were spent in hypolimnetic (>10 m) waters, while 25 min were spent in the upper water column. Dives were conducted with no conscious bias and were meant to be representative of typical research dives in Antarctic lakes.

Profiles of temperature, DO, pH, specific conductance and salinity were obtained from three holes in Lake Fryxell before and after dives using a HydroLab Surveyor 2™ sensor array. According to manufacturer specifications, the temperature sensor is accurate to ±0.15°C, DO to ±0.2 mg l^{-1}, pH to ±0.2 standard units and specific conductance to 1% of the calibration range, this yields a precision in salinity measurements of ±0.20 ppt. Control sample holes (A and B in Fig. 1) were located at least

Table 2. Summary of analysis for potential contribution of SCUBA diver-exhaled gases to existing Lake Fryxell pools of three specific CFCs

	Lake Fryxell total mass (g)[a]	Assumed mean atm. (1978–1996) (pptv)[b]	Diver exhaled (μl h^{-1}@STP)	Dive time for turnover (yr)[c]
CFC-11	27.6	230	0.28	1830
CFC-12	11.9	375	0.47	543
CFC-113	5.0	25	0.03	2236

[a] Derived from data of Tyler *et al.* (1998).

[b] Parts per trillion by volume in the atmosphere.

[c] Continuous dive time necessary for introduction assuming complete dissolution, no degradation and diver-exhaled gas at 20 l min^{-1} as sole source for CFCs.

50 m from the dive hole (C in Fig. 1). Pre-dive profiles were obtained 3–6 h before diving and post-dive data were collected from all holes 60–64 h after completion of diving. For logistic reasons, this was the soonest that investigators could return to the study site. Water samples were also collected through these holes using a 2.0 l Niskin bottle and analyzed in the laboratory for dissolved organic carbon (DOC).

Duplicate samples from control hole B and the dive hole were collected at six depths to determine total bacterial and flagellate densities. Samples were fixed in 2% PO_4^{3-}-buffered glutaraldehyde and stored in the dark at 4°C. For bacterial counts, we used a modification of the method of Porter and Feig (1980). For bacteria, sample volumes of 1–2 ml were stained with 4′,6-diamidino-2-phenylindole (DAPI) and filtered onto black, 25-mm diameter, 0.2 μm pore size, polycarbonate membrane filters. Duplicate UV epifluorescent microscopic direct counts of 10 Whipple grids were obtained for each prepared filter. For heterotrophic and phototrophic nanoflagellate (HNAN and PNAN, respectively) counts, 20–50 ml of each preserved sample was filtered onto black, 25 mm diameter, 2.0 μm pore size polycarbonate membrane filters. Duplicate counts of 20 replicate Whipple grids were obtained using both UV and blue-light filter sets in order to distinguish between HNAN and PNAN based upon chlorophyll autofluorescence of PNAN. For ciliate counts, single samples of either 0.5 or 1.0 l were collected from the three sample holes and preserved in 1% acid Lugol's solution. Total ciliate densities were determined by Sedgewick-Rafter cell counts following sample concentration. Minimum detection limits for ciliates were either 1 or 2 l^{-1} depending upon sample volume concentrated, and for flagellates, ranged from 12 to 50 ml^{-1}, depending upon sample volume filtered and magnification used for examination of samples. Additional samples were collected from control hole A before and after diving as well as from the dive hole after diving. These samples were used for the determination of planktonic virus-like particle (VLP) densities according to the direct epifluorescence microscopy method of Hennes and Suttle (1995).

Statistical analyses

Hydrochemical profile data were tested univariately by comparing single dive hole observations with the mean of observations from the two control holes (Sokal and Rohlf, 1981), giving one degree of freedom. In dimensions other than the vertical, we assumed a relatively homogeneous water column in the absence of diving impacts. Since the diving treatment was unreplicated and water column depth must be treated as a blocking factor, we considered observations one depth at a time and assessed differences for pre- and post-dive data separately. Differences were considered related to diving only if statistical differences between control and dive hole data post-dive were greater than differences observed prior to diving on a depth-by-depth basis. In an alternative approach, data from a particular hole collected at a particular time were pooled and variances of these profile data were compared using *F*-tests. This approach could potentially indicate changes in the variability observed in profile data, possibly indicative of a diving impact.

Untransformed microbiological data were analyzed using Friedman's test, a nonparametric two-factor ANOVA equivalent. This test permits us to examine the primary effect of diving while considering depth as a blocking variable that is assumed not to interact with the primary factor. Friedman's *S* was calculated after obtaining mean bacterial, PNAN and HNAN densities from duplicate samples collected at each depth, both before and after diving. Samples obtained for ciliate and VLP densities were unreplicated and so Friedman's test was performed on raw data.

RESULTS AND DISCUSSION

Significant differences between control holes and dive hole observations of various water quality parameters, on a depth-by-depth basis, were rare. Only those significant differences occurring between holes post-diving can be attributed to dive activities. Of 84 total comparisons, only three were cases where post-dive differences between control and dive hole values were greater than pre-dive differences and were also statistically significant (i.e. $P < 0.05$, Table 3). This number of significant differences is less than the number expected based on random statistical variations alone. The anomalous points are easily seen in the profile data (Fig. 2). For example, the single significant temperature difference was due to an unusually high value obtained post-dive at 4 m in the dive hole [Fig. 2(A)], perhaps resulting from a failure to allow the thermistor to equilibrate for a sufficient amount of time. The unusual DOC value obtained post-dive at 10 m from one of the two control holes [Fig. 2(E)] remains unexplained. The single significant difference in DO occurred at a depth of 17 m, a depth where DO concentrations are so low (often negative values were obtained below 14 m) that measurements made with the HydroLab instrument may be unreliable. With the exception of these three observations, there were no differences in water column profiles between sampling holes and/or sampling times (Fig. 2).

Treating water column physicochemical observations at different depths as replicate measures for a given sample hole allowed us to test for differences between coefficients of variation from readings obtained both before and after diving. Equality

Table 3. Fraction of observations, on a parameter by parameter basis, for which statistically significant differences at various levels of probability were observed. Only cases in which differences between dive hole and mean control hole observations were greater after diving than before are considered

	Temperature	DO	Cond.	Salinity	pH	DOC	Total
$P < 0.20$	5/18	1/18	4/18	0/18	1/6	2/6	13/84
$P < 0.10$	4/18	1/18	2/18	0/18	1/6	2/6	10/84
$P < 0.05$	1/18	1/18	0/18	0/18	0/6	1/6	3/84

of variance tests were used to compare the variability obtained in the three sample holes both before and after diving. For all variables tested (i.e. temperature, DO, conductivity, salinity, DOC and pH) variances between holes were not significantly different (all *F*-test *P*-values > 0.20) either before or after diving. Maximum variability between the three sample holes decreased insignificantly (*P*'s > 0.20) after diving in the cases of DO, conductivity and pH and increased insignificantly (*P*'s > 0.20) in the cases of temperature, salinity and DOC. This even split in the variance responses of our measured parameters would be expected due to chance alone and in the absence of any significant impact.

Biological data also failed to indicate any impact of diving. Total bacterial densities were statistically indistinguishable (Friedman's $S = 1.00$, df = 3, $P = 0.801$), between hole B and C, both before and after diving [Fig. 3(A)]. The same conclusion was reached based upon our analyses of planktonic PNAN, HNAN, ciliate, and VLP distributions at holes A, B and C (Table 4). Microbial profile data therefore indicated that there was no significant difference among sampling hole/sampling time combinations. As with hydrochemical data, there appeared to be no impact of diving on the distribution of organisms within the water column of Lake Fryxell.

Based upon our comparisons of single observations with mean control values, we found that the number of observations for which statistically significant differences were observed was negligible. We are familiar with the argument that statistical significance can not be equated with biological significance and also realize that potentially sensitive parameters remain unmeasured. Additionally, so-called indirect effects, far removed in space (i.e. > 100 m) and/or time (i.e. > 60 h) from the actual dive activity, have not and likely can not be experimentally assessed. This is true not only for diving effects, but also for the effects of other human activities in this relatively pristine region. Nevertheless, evidence from our field survey indicates that there is no substantial impact of diving on measured parameters at the spatiotemporal scale considered in this study.

To date, there is no evidence of any cumulative or chronic impact on water quality due to research diving. Divers first entered Lake Fryxell during the 1978–1979 austral summer. Since then, United States Antarctic Program (USAP) participants have made dives in the lake during eight of the past 18 field seasons. We estimate that divers have spent a total of 150–200 h in the waters of Lake Fryxell during this time. This has amounted to approximately 10 h yr^{-1} of diving since diving began. As has been described, Lake Fryxell remains both thermally and chemically stratified, with water chemistry profiles remaining broadly similar over the past 35 yr (e.g. see data in Angino *et al.*, 1962; Hoare *et al.*, 1965; Lawrence and Hendy, 1985; Torii, 1994; Spigel and Priscu, 1998). Minor differences in pre- and post-1978 hydrochemical profiles appear to be as much a result of differences in measurement techniques and changing lake surface level reference points as actual changes in water chemistry (Lyons *et al.*, 1998a,b).

However, it has been suggested that the water columns of ice-covered, dry valley lakes are not as stable as has been previously thought. For example, the presence of CFCs in Fryxell bottom waters (Tyler *et al.*, 1998) together with descriptions of tritium (^{3}H) in these deeper waters (Miller and Aiken, 1996) provide evidence of deep circulation in this lake. Measurable CFCs in excess of those predicted based on molecular diffusive transport suggest that Fryxell waters may circulate on a time scale of less than 50 yr (Tyler *et al.*, 1998). Again, this is an indication that these lakes are not static systems and that any potential diver-induced effects take place against a background of dynamic materials and energy flows.

Of further relevance to the question of diver impact, Tyler *et al.* (1998) have considered the

Table 4. Friedman's test results for microbial density data

Parameter	Comparisons	S_{test}	df	*P*
PNAN	all	10.53	5	0.063
HNAN	all	9.01	5	0.110
Ciliates	all	8.32	5	0.141
Bacteria	B and C	1.00	3	0.801
VLP	A and post-C	0.25	2	0.883

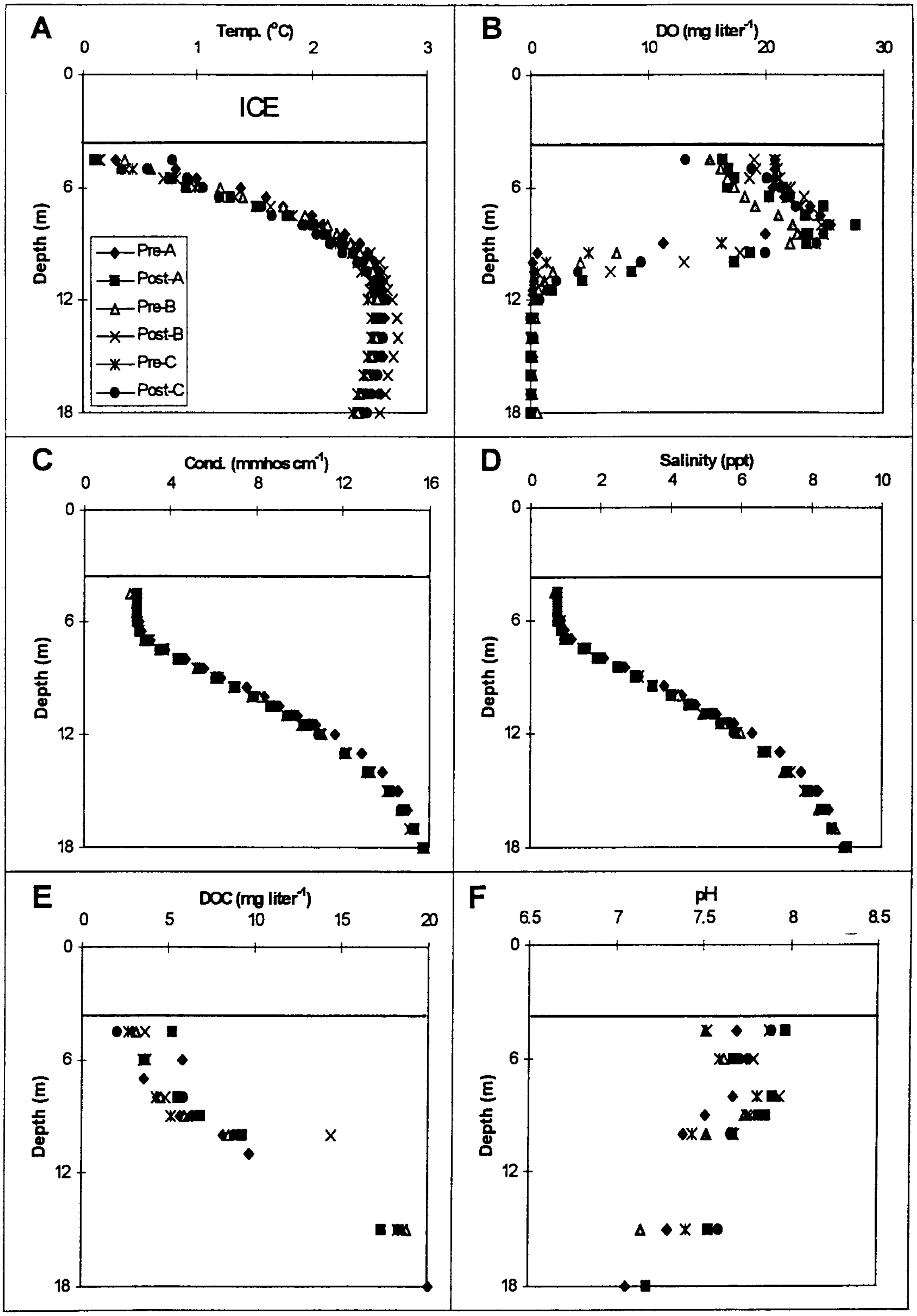

Fig. 2. (A) Temperature (Temp.), (B) dissolved oxygen (DO), (C) specific conductance (Cond.), (D) salinity, (E) dissolved organic carbon (DOC) and (F) pH profiles from a dive hole (C) and two control holes (A and B), collected 3–6 h before (PRE-) and 60–63 h after (POST-) diving in Lake Fryxell.

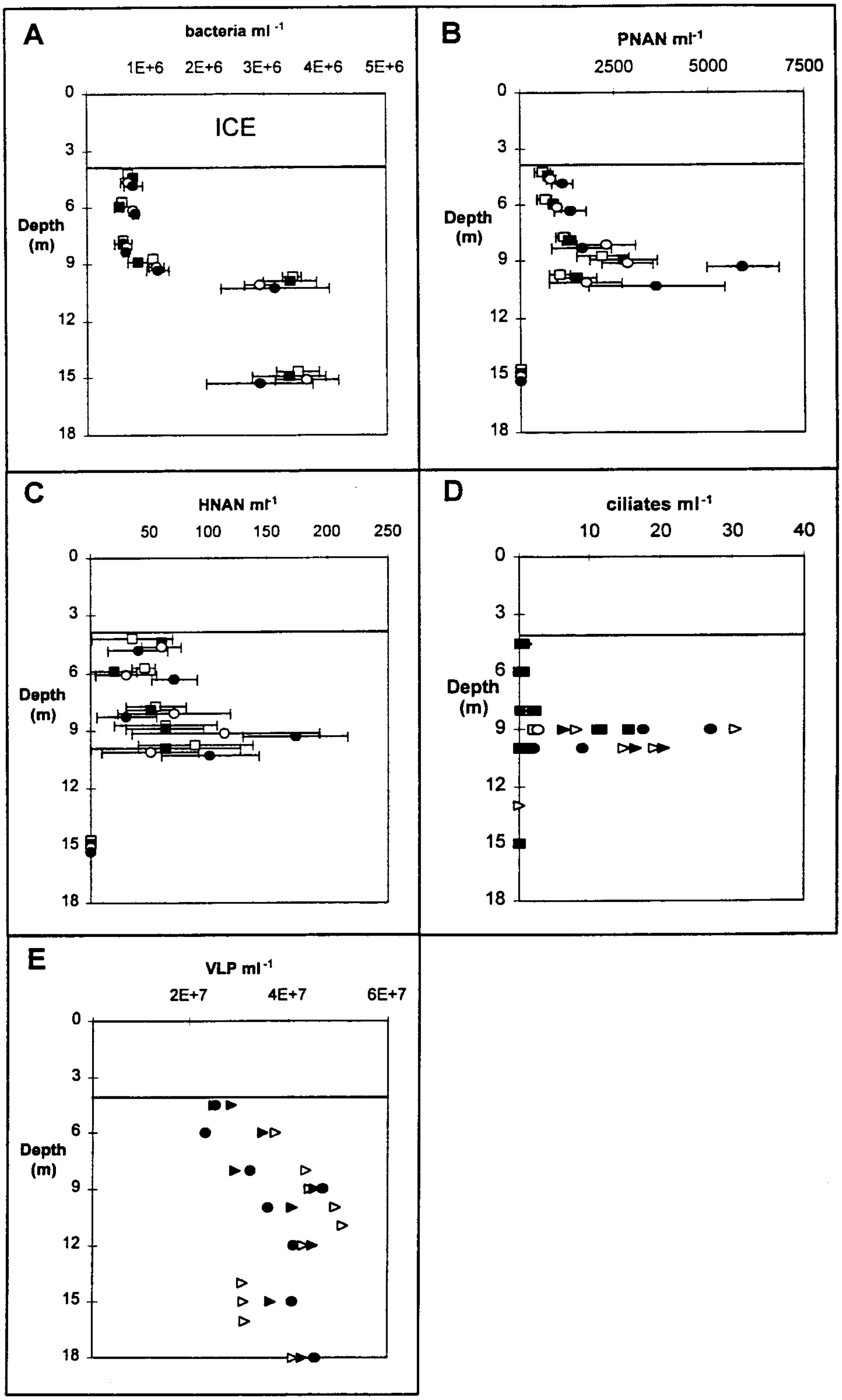

Fig. 3. Means (±S.D.) for total bacterial (A), PNAN (B) and HNAN (C) densities and single observations of ciliate (D) and VLP (E) densities with depth at two control (squares and triangles) and a dive access (circles) hole, both before (open symbols) and after (closed symbols) diving.

possibility that deep-water CFCs in nearby Lake Hoare are a diver-introduced contaminant. Since CFC-113 rapidly increased in the atmosphere relative to other CFCs beginning in the late 1970s, diver exhalations since that time would have introduced this gas to the water column. However, the CFC-113 ratios in the water column of Lake Hoare are not those expected from modern air (Tyler *et al.*, 1998). Taken together with our calculations for Lake Fryxell (see above), this implies that scuba activities are a negligible source of CFCs in both Hoare and Fryxell.

CONCLUSION

Considering one of several of the perennially ice-covered lakes of Antarctica's McMurdo Dry Valleys, our calculations indicate that the impact of diver-exhaled gases on dissolved gas (e.g. DO and CFC) concentrations in the water column is negligible. Of somewhat greater potential importance are physical mixing effects due to both diver motion and the upwelling of water due to diver-exhaled bubbles. Despite these potential limited impacts, physicochemical and biological data from this study yielded no evidence of water column disruption within 2.5 d of diving activities in Lake Fryxell.

Theoretical model results, together with field data, indicate that diving impacts on physicochemical properties and microbial distributions in a closed-basin, ice-covered lake do not occur at the spatial and temporal scales addressed in this study. Not all potentially affected parameters have been monitored, nor have all potential impacts of dive activities been addressed in this study. For example, the localized disturbance of benthic communities by diver activities has not been considered. Nevertheless, we conclude that research dives, as currently conducted, do not appear to have a long-term, large-scale impact on measured water column properties.

Based upon our theoretical analysis and typical level of diving activities, the intensity of diving required to measurably impact the water column of Lake Fryxell has not, and in all likelihood will not, occur. Data have yet to be presented which would suggest anything other than minor and transitory (i.e. short-lived and highly-localized) impacts to lakes resulting from research diving. Environmental drivers (e.g. stream inputs, wind energy) have been shown to have a much greater effect on the Lake Fryxell water column than diving. Whereas diving in dry valleys lakes has been classified as having a relatively moderate to unacceptably high level of environmental impact (Vincent, 1996), our findings indicate that research diving is best classified, both spatially and temporally, as a low to moderate impact activity.

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APPENDIX A. IMPROVED DERIVATION OF EQUIVALENT LINEAR STRATIFICATION

The goal of this appendix is to refine Lemckert and Imberger's (1993) method of extending the double annular bubble plume model to non-linear density stratifications. In particular, we introduce a more consistent definition of potential energy and derive a form of the model linear density distribution that is more general and, we believe, better able to produce an accurate equivalent linear stratification.

The necessity of arriving at an equivalent linear stratification arises from how the buoyancy frequency is defined in annular plume models (e.g. see Schladow, 1992; Asaeda and Imberger, 1993; Lemckert and Imberger, 1993), in which

$$N = \left(- \frac{g}{\rho'} \frac{\Delta\rho}{\Delta z} \right)^{1/2} \tag{A.1}$$

where ρ' is some characteristic density of the water column and $(\Delta\rho/\Delta z)$ is the density gradient that is required to be a constant. Lemckert and Imberger's extension involves calculating the potential energy per unit area of the water column with respect to the surface, $U_{surface} = \int_0^h g\rho(z)\,\mathrm{d}z$, where $\rho(r)$ is the depth-dependent density function for a non-linear stratification; a value for

N is then chosen that corresponds to a water column with a linear density distribution, but with a potential energy equivalent to U_{surface}.

In our approach, N is redefined in terms of a quantity that better describes the degree of stratification than does U_{surface}, since gauge invariant properties of potential energy render U_{surface} an inaccurate measure of stratification. Just such a quantity is ΔU from equation (6), which is the amount of energy required to completely mix a stratified water column, in other words, ΔU is a direct measure of stratification strength.

We model the linear stratification by decomposing the linear density function into two terms:

$$\rho(z) = \rho_0 + \frac{\Delta\rho}{\Delta z}(z - z_0), \tag{A.2}$$

Thus, we have a constant term ρ_0 and a linearly varying gradient $(\Delta\rho/\Delta z)(z - z_0)$, where ρ_0 takes on the value ρ_0 at $z = z_0$. Substituting equation (A.2) into equation (6) and integrating, we find

$$\Delta U = -g\left[\frac{1}{2}(\bar{\rho} - \rho_0)h^2 - \frac{\Delta\rho}{\Delta z}\left(\frac{1}{3}h^3 - \frac{1}{2}z_0h^2\right)\right]. \tag{A.3}$$

Equation (A.1) is then used to eliminate $(\Delta\rho/\Delta z)$ from equation (A.3). Solving for N^2 gives

$$N^2 = \frac{\Delta U - (1/2)g(\bar{\rho} - \rho_0)h^2}{\rho'\big((1/3)h^3 - (1/2)z_0h^2\big)}. \tag{A.4}$$

This is a functional form of the buoyancy frequency for the equivalent linear stratification. An examination of equation (A.4) reveals that N is sensitive to the exact definition of the linear stratification, equation (A.2), and arriving at an accurate value for N will depend upon making a wise choice for this definition. We thus choose $\rho_0 = \rho' = \bar{\rho}$, i.e. we select both the constant density term of equation (A.2) and the characteristic density of equation (A.1) to be the average density of the non-linear water column. Further, a choice of $z_0\frac{1}{2}h$ is required by the necessity that the mid-point of a linear density profile is equal to the average density. Given these choices equation (A.4) simplifies to

$$N^2 = -\frac{12\Delta U}{\bar{\rho}h^3}. \tag{A.5}$$