

Numerical model of the thermal bar and its ecological consequences in a river-dominated lake

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1 Introduction

There have been numerous theoretical and experimental studies of thermal bars formed in lakes when radiative heating or cooling causes the surface temperature to pass through the temperature of maximum density ($T_{md} \approx 4^\circ\text{C}$). Less attention has been paid to the riverine thermal bar, which appears when a lake and an inflowing river have temperatures on opposite sides of T_{md} . The only source of field data on the latter phenomenon appears to be from an experimental campaign in Kamloops Lake in the 1970's (Carmack, 1979; Carmack et al., 1979), while the only theoretical study has been that by Holland et al. (2001) (hereafter HKB) who used a greatly simplified numerical model for a deep lake. The first aim of the present work is to produce a more realistic model of the hydrodynamics of the riverine thermal bar, using the shallower ($< 200\text{m}$) bathymetry of Kamloops Lake which will allow more accurate representation of physical processes with the same computational resources.

It is well established that the presence of a thermal bar can have a profound effect on the distribution of dissolved or suspended matter, in two ways: firstly, the double-cell circulation can lead to a concentration of floating matter due to surface convergence and an impediment to mixing of effluent from the shoreline into the deeper parts of the lake; secondly, the thermal bar is a boundary between regions of stable and unstable stratification, with vertical mixing being hindered in the stable region. In particular, plankton and the nutrients on which they feed will be subject to these effects. An experimental study of plankton distributions in Lake Baikal was performed by Likhoshway et al. (1996) and their results were qualitatively reproduced in a computational study by Botte & Kay (2000). The second aim of the present work is to extend the computational results to the case of a riverine thermal bar, using firstly the same simple plankton population model used by Botte & Kay (2000), and then comparing with a more sophisticated ecological model.

2 The mathematical models

The hydrodynamical model is based on Navier-Stokes equations for flow in three dimensions, including all components of planetary rotation. However, the model is two-dimensional in the sense that all variables are assumed to be independent of the alongshore coordinate; this simplification is subject to the criticism that Kamloops Lake is rather narrow, but will nevertheless allow an assessment of the effects of coriolis forces even though the lake geometry will not be fully represented. The horizontal eddy viscosity is set to a constant value, while

the vertical eddy viscosity is constant in unstable conditions but decreases with increasing stability in stable stratification. Water densities are calculated from the equation of state of Chen & Millero (1986).

Scalar quantities (temperature, salinity and components of the ecological model) are governed by convection-diffusion equations, with eddy diffusivities set equal to the corresponding eddy viscosities. The equations for ecological components also include source/sink terms, representing the processes of photosynthesis, grazing and mortality, but formulated differently in the models of Franks et al. (1986) and of Parker (1991), hereafter referred to as models F and P, respectively. In particular, model P includes a detritus (D) component in addition to the nutrients, phytoplankton and zooplankton (N - P - Z) of model F; photosynthesis is dependent on light levels, and hence on depth, but model P also includes the effects of diurnal variations and self-shading by plankton; all processes are temperature-dependent in model P, but this factor is ignored in model F.

The computational domain includes a sloping river delta down to a maximum depth of 150 m. Boundary conditions include a surface heat flux of $170\text{W}\cdot\text{m}^{-2}$ as well as the usual hydrodynamic conditions at solid boundaries and the free surface. The lake is initially at 2.4°C and the river at 3.6°C , and the river is subsequently warmed at $0.2^\circ\text{C}\cdot\text{day}^{-1}$, conditions which approximate those measured in Kamloops Lake during Spring 1975. The lake is assumed initially to be in its nutrient-rich, low-biomass, Winter condition, with N - P - Z (- D) = 4-1-1(-1) mmol N m^{-3} . The ecological components in the river are taken to remain constant, at values equal to the initial conditions in the lake.

Full details of all the hydrodynamical and ecological model equations and initial and boundary conditions are given by Holland et al. (2003).

3 Results: Hydrodynamics

A thermal bar forms on day 3 of the simulation and for the next few days its circulation is confined to a region within 2 km of the river mouth, with a strong plume descending towards the lake bed (figure 1(a)). Any river-borne materials entering the lake at this stage would thus be conveyed towards the bed and could be expected to have a long residence time in the lake but minimal influence on biological processes in the euphotic zone. However, as the river temperature continues to rise, the river water becomes lighter than the lake water and forms a surface gravity current which extends across the lake until mixing has created sufficient water of maximum density to produce a descending thermal bar plume (figure 1(b)). This configuration allows river-borne materials to have a much greater influence on the euphotic zone, and constitutes an intermediate stage in the succession towards the Summer condition in which river water remains close to the lake surface from inflow to outflow.

Sensitivity analyses have been performed with regard to features of the present model that were omitted from the earlier model by HKB. Firstly, compared to a simulation in which the only heat input to the lake is from the river, the inclusion of a surface heat flux hastens the progression from boundary plume to surface overflow: by warming the lake towards the temperature of maximum density, it increases the density contrast between lake and river water and so strengthens the surface gravity current. Secondly, replacing the sloping delta

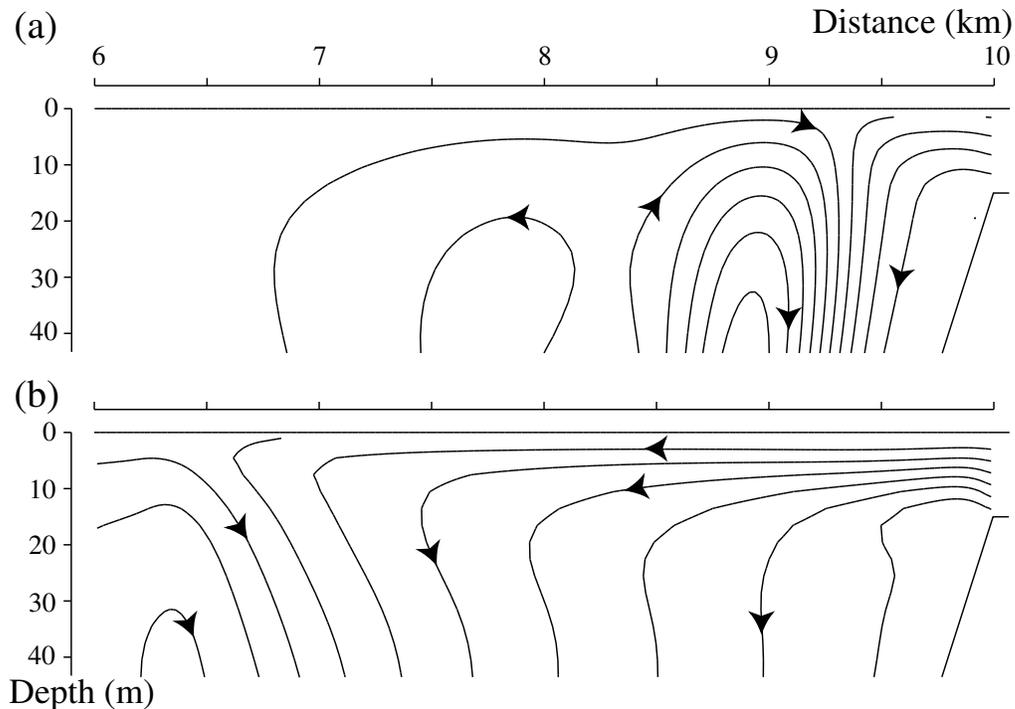


Figure 1: Progression of the flow-field at different stages of the simulation: (a) 8 days, (b) 24 days. The river inflow is on the right.

with a vertical boundary as used by HKB has very little effect on the behaviour of the thermal bar. Finally, the inclusion of the coriolis force is found to be the most important of the model refinements in the present study: in a non-rotating frame the thermal bar constantly accelerates, due to a strong return flow initially retarding its progress whereas in the later stages the gravity current propels it offshore; the effect of coriolis force is to weaken these flow components by turning them parallel to the thermal bar, thus smoothing its progress to a nearly constant speed.

4 Results: Plankton Ecology

Using ecological model F in conjunction with the hydrodynamical model yields the results illustrated in figure 2. A phytoplankton bloom has appeared at the location of the thermal bar within 16 days, accompanied by significant nutrient depletion and a small rise in the zooplankton population. At this stage the converging flow at the thermal bar appears to be the dominant influence on the plankton ecology. However, at 24 days a double bloom structure has appeared, with the outer bloom still located at the thermal bar (compare figure 1(b), which is on a different scale), but with an inner bloom which is found to be where the stability is at a maximum, preventing downward diffusion of nutrients and plankton. The dip in phytoplankton levels between the two blooms is clearly attributable to a combination of nutrient depletion and grazing by zooplankton.

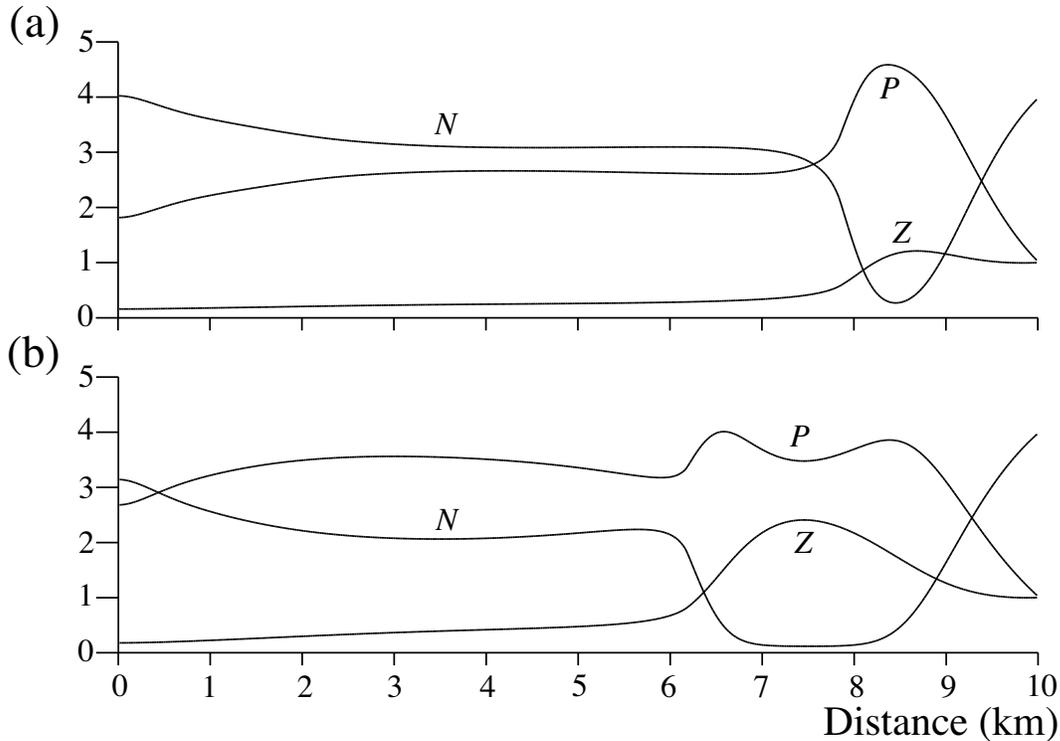


Figure 2: Horizontal profiles of all ecological components at 5m depth, using model F: (a) 16 days, (b) 24 days.

These findings do not concur with the experimental observations of St. John et al. (1976), who found a much steadier development of plankton populations in Kamloops Lake; in particular, there was no evidence of a double bloom structure ever appearing. There are several factors omitted from model F which would tend to moderate the plankton productivity: these include temperature-dependence, self-shading and the presence of a detritus component (which delays the recycling of dead plankton into the nutrient pool), all of which are included in model P. Some results from a simulation using model P are shown in figure 3, in which the intense double bloom of figure 2 (b) is replaced by a more modest phytoplankton bloom located in the stable region inshore of the thermal bar. This in turn results in only a partial depletion of nutrients and is insufficient to support any significant growth of zooplankton at this stage. Sensitivity analyses show that these differences are principally due to the temperature-dependence in model P, which leads to a general decrease in the rates of all biological interactions due to the cool temperatures in Spring, and also combines with stability effects to shift the bloom towards the warmer river water. Self-shading also has a significant effect in reducing phytoplankton growth.

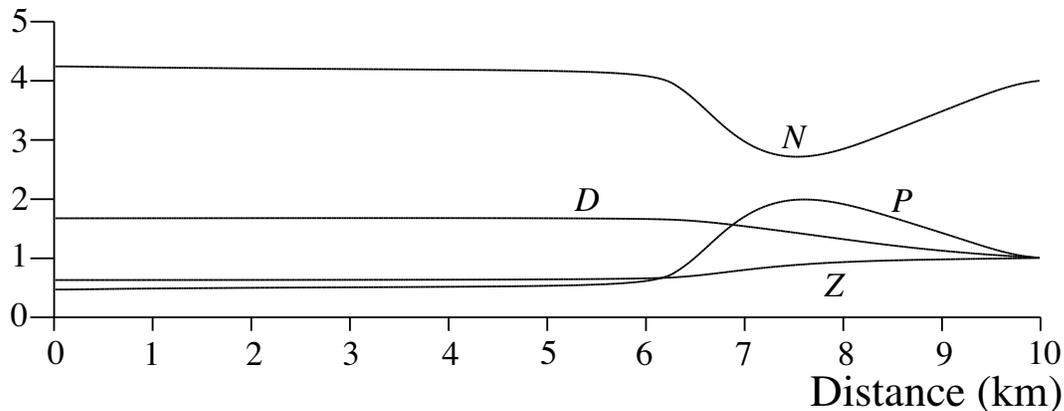


Figure 3: Horizontal profiles of all components at 5m depth, using model P, at 24 days.

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