

## A review of the physics and ecological implications of the thermal bar circulation

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### Abstract

Following recent applications of numerical modelling and remote sensing to the thermal bar phenomenon, this paper seeks to review the current state of knowledge on the effect of its circulation on lacustrine plankton ecosystems. After summarising the literature on thermal bar hydrodynamics, a thorough review is made of all plankton observations taken in the presence of a thermal bar. Two distinct plankton growth regimes are found, one with production favoured throughout the inshore region and another with a maximum in plankton biomass near the position of the thermal bar. Possible explanations for the observed distributions are then discussed, with reference to numerical modelling studies, and the scope for future study of this interdisciplinary topic is outlined.

**Key words:** Cabbeling – lake dynamics – marine ecology – numerical modelling – plankton – thermal bar

### Introduction

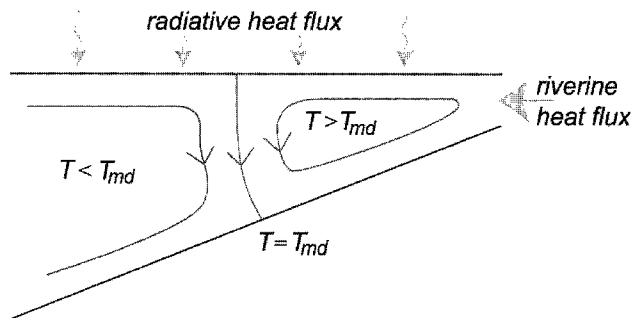
The thermal bar is a downwelling plume of fresh water at the local temperature of maximum density ( $T_{md}$ ) and is formed in temperate lakes in Spring and Autumn when waters on either side of the  $T_{md}$  mix. This either results from the confluence of a river and lake on opposing sides of the  $T_{md}$  or is due to preferential warming or cooling of shallow areas (Fig. 1).

As the surface heat flux continues after the initial formation of the thermal bar, it propagates out into the lake until stable stratification prevails everywhere. In this way all temperate lakes have a twice-yearly ventilation of lower waters from these downwelling episodes between the Summer and Winter stratified periods. The Autumnal cabbeling (contraction on mixing) is generally less clearly-defined than the Spring thermal bar due to

the stronger wind-stirring and weaker temperature gradients present at that time of year (ULLMAN et al. 1998).

The sinking vertical motion associated with the thermal bar generates converging flows at the thermal front, ensuring that transport perpendicular to the shore is extremely limited (GBAH & MURTHY 1998), particularly in comparison with the relatively strong alongshore transport. This means that the volume of water available for dilution of substances released inshore of the thermal bar will be far smaller than would otherwise be the case. The descending water column also mixes substances vertically, potentially delaying their flushing from the lake (CARMACK et al. 1979). These factors have important implications for such issues as anthropogenic effluent release, leaching nutrients in land runoff, dispersion of polluted river plumes and plankton and fisheries ecology.

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**Fig. 1.** Schematic diagram of the Spring thermal bar in the absence of rotational effects, caused by a river inflow and/or preferential heating of shallow areas.

Due to the non-monotonicity of the equation of state, the thermal bar forms an interface between stably stratified shallow waters and the well-mixed open lake in both Spring and Autumn. The suppression of vertical motions inshore of the thermal bar traps any shore- or river-released substances near the surface (HOLLAND et al. 2001), compounding the eutrophication problems associated with high nutrient loading and limited horizontal mixing.

As the thermal bar greatly affects the flow and thermal characteristics of most temperate lakes, it follows that it has a considerable influence on their ecological functioning (MOLL & BRAHCE 1986; BOLGRIEN et al. 1995; BONDARENKO et al. 1996; GOLDMAN et al. 1996; BUDD et al. 1999). This effect is extremely important, since a proper understanding of an ecosystem's interaction with relevant fluid phenomena is required to correctly determine minimum-impact nutrient loading levels for a lake (CARMACK et al. 1979; LEAN et al. 1987; ULLMAN et al. 1998). At the base of a lake's food chain, the maintenance of a balanced plankton ecosystem is of fundamental importance to all biota in the freshwater system. A comprehensive view of the spatial distributions of plankton populations also has the potential to allow the inference of useful climate information from sedimentation trends, particularly in the ancient, 6 km-thick sediments of Lake Baikal (KOZHOVA & IZMEST'EVA 1998). A final motivation for the investigation of ecosystem effects is that the presence of biomass may inhibit light penetration, reducing the surface heat flux and thus potentially altering the regime of the thermal bar itself (FRANKE et al. 1999).

With regard to concern over global warming, the thermal bar is a prime example of how a small change in climate could result in a much larger shift in the functioning of delicately-balanced ecosystems. The gradual warming of freshwater ecosystems predicted by current climate models (IPCC 2001) may have a strong influence on the thermal bar circulation, which is formed by temperature variations of just a few degrees Celsius.

Changing surface fluxes of heat and momentum could thereby affect the timing of Spring and Autumn overturn and wreak potentially devastating consequences on indigenous lake species.

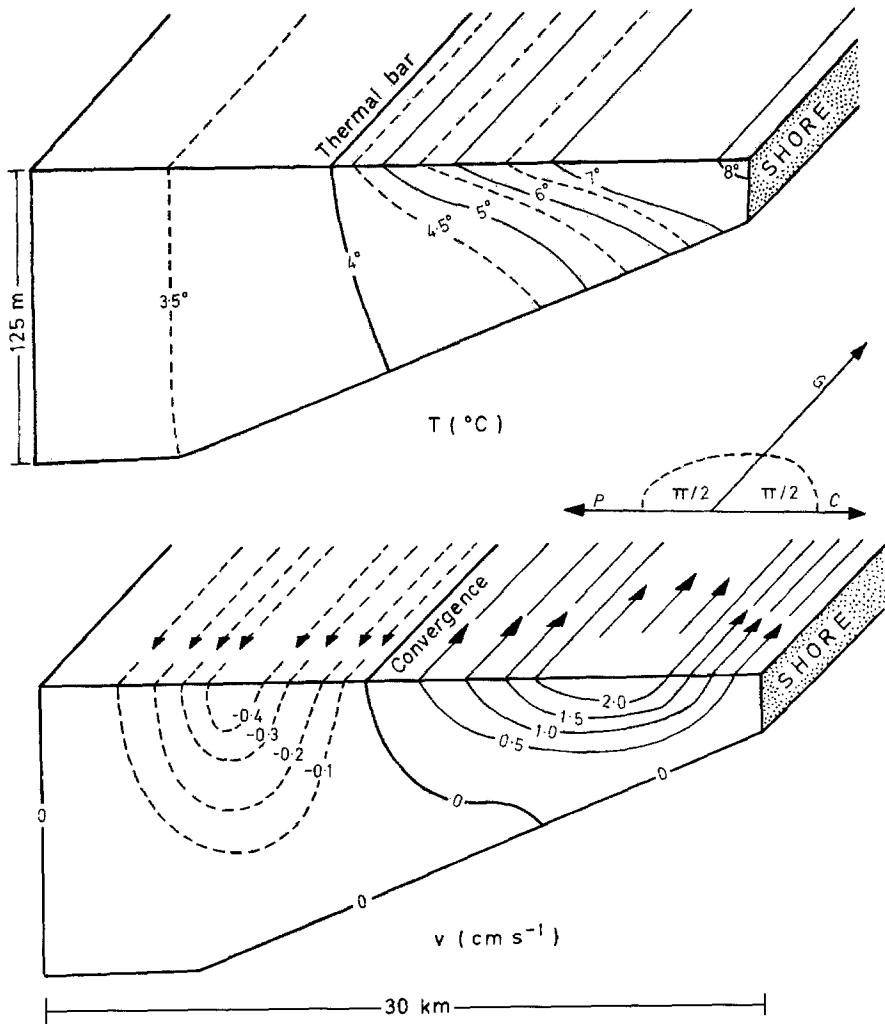
The hydrodynamics of the thermal bar circulation have been the subject of a relatively large number of studies, but only recently have researchers considered in detail the effect of these motions on lacustrine plankton populations. This new work arises from improved data collection, advances in remote sensing, and first trials of horizontally-varying numerical plankton modelling applied to lakes. It is the intention of this review to summarise these works, detailing both the hydrodynamics and ecology of the thermal bar, and to attempt to explain the processes governing the plankton distributions. The remaining questions in this relatively young, interdisciplinary problem are then discussed for the benefit of future researchers.

## Hydrodynamics

The vernal thermal front was first measured by FOREL (1880) in Lake Geneva, who called it the *barre thermique* (thermal bar) as it forms a barrier between waters warmer and cooler than the  $T_{md}$ . More recent measurements showing the existence of a thermal bar were made in Lake Ladoga by TIKHOMIROV (1963) and in the Laurentian Great Lakes by RODGERS (1965).

Observations of the non-riverine thermal bar, referred to below as the 'classical' case, have been made in most large temperate lakes, including Lakes Baikal (SHIMARAEV et al. 1993; PARFENOVA et al. 2000), Superior (HUBBARD & SPAIN 1973), Huron (MOLL et al. 1980), Michigan (HUANG 1972; BOLGRIEN & BROOKS 1992; MOLL et al. 1993), Ontario (CSANADY 1971; GBAH & MURTHY 1998), and Ladoga and Onega (NAUMENKO 1994; AVINSKY et al. 1999). Also, laboratory-scale models of the laminar thermal bar in a non-rotating frame have been studied (ELLIOTT & ELLIOTT 1969, 1970; KREIMAN 1989), and small-scale idealised tank experiments have increased our understanding of the basic processes involved in the cabbelling instability (MARMOUSH et al. 1984; INABA & FUKUDA 1986; LANKFORD & BEJAN 1986; IVEY & HAMBLIN 1989).

Under a geostrophic balance, the converging pressure gradients on either side of the surface  $T_{md}$  will generate 'thermal wind' flows in the alongshore direction, parallel to the thermal front (Fig. 2). These flows consist of a strong ( $O(10^{-1})$  m s<sup>-1</sup>) cyclonic circulation inshore of the thermal bar (as a result of the relatively steep temperature gradients there) and a weaker anticyclonic circulation offshore. Under the influence of Coriolis forces, the thermal bar therefore acts as a barrier between parallel horizontal flows in exactly opposing directions.



**Fig. 2.** Schematic diagram of the Spring thermal bar in a rotating frame; Geostrophy causes a flow parallel to the thermal front [from HENDERSON-SELLERS (1984)].

Flows converging at the thermal bar suppress most cross-frontal exchange so that it forms a barrier to horizontal mixing despite the lateral shear in longshore flows (GBAH & MURTHY 1998). Flows perpendicular to the shoreline are of order  $10^{-2} \text{ m s}^{-1}$ , yielding mid-latitude Rossby numbers of  $O(10^{-1})$  based on a bar width scale of 1 km. The strongest motion in the thermal bar circulation is therefore the thermal wind which runs parallel to the thermal front (HUANG 1971, 1972).

Water within the thermal bar plume sinks at a rate of  $1-30 \times 10^{-4} \text{ m s}^{-1}$  until it reaches a depth where it is no longer denser than the surrounding fluid. This may happen for several reasons, such as entrainment of lower density water into the plume or varying thermal characteristics of the surrounding water. Importantly, thermobaricity, or the decrease of the  $T_{md}$  with depth (pressure), may also suppress the downwelling motion of the thermal bar in exceptionally deep lakes (CARMACK & WEISS 1991; HOLLAND et al. 2001).

A review of the observational work referenced above highlights the strong sensitivity of the thermal bar circu-

lation to the particular bathymetry, wind stress, and surface heat flux of the lake under consideration. The thermal bar is described as a large (1 km wide), long-lived density front which emerges during May or June and persists for one to two months. The frontal propagation rate fluctuates due to the effects of wind, which may totally outweigh the buoyancy-driven circulation in the short term (HUBBARD & SPAIN 1973; GBAH & MURTHY 1998).

HUANG (1969) was the first to attempt a mathematical description of the thermal bar, balancing Coriolis and buoyancy forces in steady-state to yield the relevant temperature and flow fields. CSANADY (1971) later achieved similar results with a two-dimensional numerical model. Transient features were then resolved by assuming a balance between vertical shear and horizontal pressure gradients, using a two-dimensional model driven by a one-dimensional temperature equation in the absence of horizontal convection (ELLIOTT 1970, 1971; ELLIOTT & ELLIOTT 1970). This yielded the thermal bar position as a function of time (agreeing well with field ob-

servations (ELLIOTT & ELLIOTT 1969, 1970)) and revealed that the cabbelling plume may be inclined to the vertical.

Rotational effects were introduced into two-dimensional numerical models by BENNETT (1971) and HUANG (1971, 1972) who employed a third, longshore coordinate in which no gradients were permitted. These studies showed that the thermal wind is the dominant flow of the thermal bar in large lakes, a result which is in agreement with the asymptotics of BROOKS & LICK (1972), who studied a rotating rectangular channel under a horizontally-varying surface heat flux.

The first model to incorporate a surface wind stress was that of SCAVIA & BENNETT (1980), who concluded that the thermal bar is highly susceptible to this forcing. ZILITINKEVITCH et al. (1992) then refined the horizontal propagation rate estimates of ELLIOTT & ELLIOTT (1970) by elucidating the effects of horizontal heat advection. The numerical and asymptotic results of FARROW (1995a, b) on the non-rotating case then showed that the downwelling plume may become separated from the thermal front due to inertial effects, a feature not yet noticed in the field. FARROW & McDONALD (2002) then examined the rotating case, finding that inertial oscillations in the circulation of the thermal bar should be sufficiently powerful to increase its overall propagation rate. This was in contrast to the non-rotating analysis, in which inertial effects slowed the propagation. Both effects were more marked in deeper water where viscous effects are less important.

In a departure from heat-balance or general circulation models, KAY et al. (1995) obtained plume velocity and temperature gradient predictions as a function of the Prandtl number by analysing the thermal bar as a free-convection boundary layer. MALM (1995) then carried out a comprehensive numerical study of thermal bars under a range of wind and bathymetric conditions, finding that the wind sensitivity is highly dependent upon slope bathymetry, which strongly affects flow speeds even in the absence of a wind forcing.

GBAH et al. (1998) were the first authors to adopt a higher-order turbulence closure in the study of the thermal bar, producing reasonable estimates of the bar formation and migration timescales under a range of wind forcings. TSVETOVA (1995, 1999) made significant advances with the first thermobaricity-resolving (and fully compressible) model of the thermal bar in Lake Baikal but unfortunately failed to fully explore the details of thermobaric control of the sinking plume. More recently, BOTTE & KAY (2000) briefly investigated thermobaricity as part of their plankton population modelling study in the vicinity of a Spring thermal bar in Lake Baikal, and have also examined the balance of wind, Coriolis, and buoyancy forcings (BOTTE & KAY 2002).

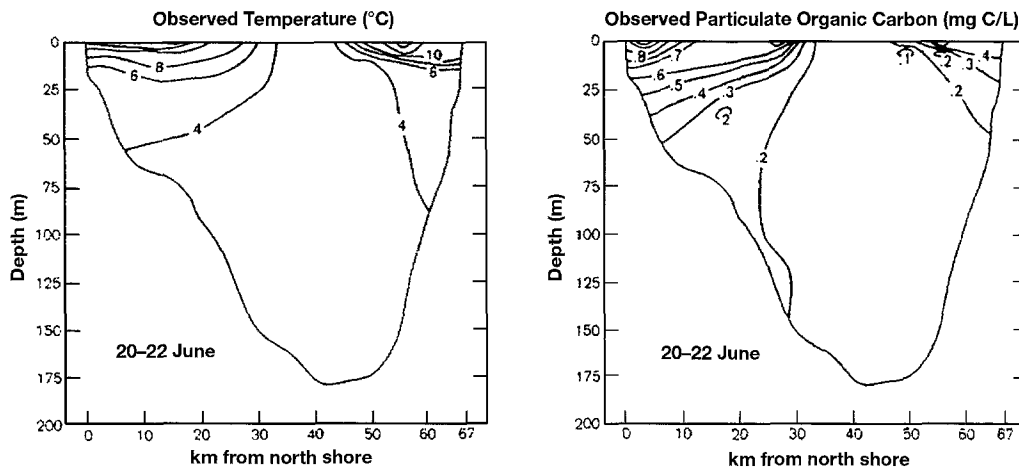
The Autumn thermal bar is a far less distinctive feature than its Spring counterpart, as it tends to be obscured by the storms and wind-induced turbulence common in Autumn (BUDD et al. 1999). Also the strength of inshore stratification and thermal gradients is limited by the maximum 4 °C gap between maximum density and freezing point. To the knowledge of the authors, the modelling work of BELETSKY & SCHWAB (2001) is currently the only study to generate a specifically Autumn thermal bar. However, their year-long model covers a mild winter when the thermal bar was extremely weak, even for the Autumn case, and the coarseness of their grid leads to a rather poorly-defined thermal bar.

The main difference between classical and riverine thermal bars is caused by the influx of salinity from the river. Detailed observations of predominantly-riverine thermal bars are only available for a few Canadian lakes, of which those of Kamloops Lake are by far the most comprehensive (ST. JOHN et al. 1976; CARMACK 1979; CARMACK et al. 1979, 1986; WIEGAND & CARMACK 1981). The only authors to model the hydrodynamics of the riverine case in detail are HOLLAND (2001) and HOLLAND et al. (2001), who showed that the riverine thermal bar may overcome thermobaric resistance and ventilate deeper lake waters as a result of riverine salinity in the plume. Examining the sensitivity of a riverine thermal bar in a smaller lake, they also elucidated the relative importance of Coriolis forcing, the surface heat flux and a realistic river delta section (HOLLAND et al. 2003).

## Plankton

While it has been known since the studies of STOERMER (1968) and MORTIMER (1974) that the thermal bar circulation influences lacustrine plankton distributions, it is only relatively recently that insight has been gained into the precise nature of these effects. Early studies found that plankton growth was promoted inshore of the thermal bar (e.g. Fig. 3), with populations increasing towards the shoreline and having a sharp concentration gradient at the  $T_{md}$  due to the converging flows (MOLL et al. 1980; SCAVIA & BENNETT 1980). Amongst other studies, remote sensing confirms that this effect is prevalent in lakes worldwide (BOLGRIEN & BROOKS 1992; GOLDMAN et al. 1996; BUDD et al. 1999). The aim of this section is to describe recent results from in-depth field and modelling studies, which both explain this classical observation and describe other less intuitive distributions of biomass which are found in the presence of the thermal bar.

In lakes, plankton growth mainly takes place during the Spring bloom, when insolation and water temperature are increasing and nutrient levels are still high from the reduced primary productivity over Winter. The discussion in this section is limited to the thermal bar which



**Fig. 3.** Observations of the temperature and particulate organic carbon in Lake Ontario on 20th - 22nd June 1972 [from SCAVIA & BENNETT (1980)].

forms during this period, as studies of the weak Autumn thermal bar are rare.

The Spring domination of growth provides a simple explanation of why waters trapped inshore of the  $T_{md}$  are richer in life; since plankton growth is commonly temperature-dependant (*e.g.* AVINSKY et al. 1999), the warmer inshore waters will usually support a larger in-situ productivity. However, the explanation of steep biomass gradients observed at the  $T_{md}$  is not necessarily so simple. Many ecological studies have emphasised the importance of stability considerations to the growth of plankton in open water, as the restriction of vertical mixing by static stability prevents the removal of biomass from the euphotic zone and thus permits continued growth (JASPER et al. 1983; SCAVIA & FAHNENSTIEL 1987). As the Spring thermal bar plume forms a boundary between stratified shallow waters and near-isothermal deep waters, the effects of stability support the notion that the thermal bar divides areas of favourable and less favourable physical conditions for growth (BOLGRIEN et al. 1995; GOLDMAN et al. 1996; BOTTE & KAY 2000).

The horizontal difference in plankton growth may also be influenced by the relative nutrient richness of inshore waters, due to leaching, point-source pollution and river inflow (BONDARENKO et al. 1996; MOLL et al. 1993). This added input could produce large increases in total annual growth inshore of the thermal bar by delaying nutrient limitation until mid or even late Summer (HOLLAND 2001). It follows that the highest growth will be immediately adjacent to the shore, where nutrient concentrations and temperature are both largest.

Combined with the growth-impeding effects of turbidity, the contribution of river-borne nutrients means that the influence of the specifically riverine thermal bar

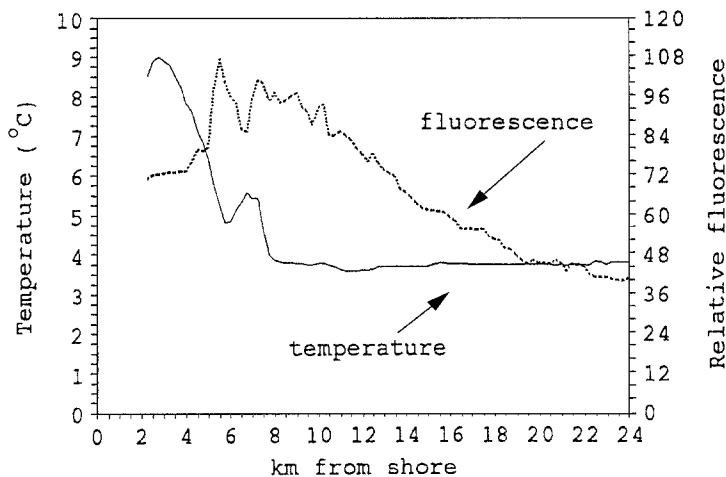
on ecosystem function may be of greater consequence than that of the classical case. Depending upon the exact balance of the river in question, its extra turbidity and nutrient influx could either promote or curtail plankton growth inshore of and at the thermal front (JASPER et al. 1983; ULLMAN et al. 1998; BUDD et al. 1999; AVINSKY et al. 1999).

Apart from physical and chemical considerations relating to in-situ growth rates, the structure of lacustrine plankton ecosystems may be affected by new populations which are carried by an inflowing river. For example, these populations could seed a new plankton bloom inshore of the thermal bar (MOLL et al. 1993; LIKHOSHWAY et al. 1996) or increase predation (AVINSKY et al. 1999), depending upon the particular species and physical conditions in question. However, riverine plankton concentrations are often lower than those in lakes because rivers have higher turbidities and are mixed more thoroughly and flushed more rapidly (SOBALLE & KIMMEL 1987; REYNOLDS 1994; AKOPIAN et al. 1999; WELKER & WALZ 1999). This means that, although conditions inshore of the  $T_{md}$  are generally favourable for plankton growth, there may be a significant influx of plankton-free water to dilute or displace the in-situ production (SOBALLE & KIMMEL 1987; AVINSKY et al. 1999; WELKER & WALZ 1999).

In contrast to the simple picture described above, some observations indicate that the thermal bar does not always form a straightforward boundary between regions of high and low biomass. The horizontal flows converging at the surface  $T_{md}$  signature may accumulate plankton, other organisms and debris nearby, forming a local population maximum (STOERMER 1968; MORTIMER 1974; MOLL et al. 1993; BOLGRIEN et al. 1995; LIKHOSHWAY et al. 1996). This maximum is generally slightly in-

**Table 1.** Vertical distribution of water temperature (°C), chloride (Cl<sup>-</sup>), soluble reactive silica (SiO<sub>2</sub>) and chlorophyll (Chl) in and around the thermal bar of Lake Michigan on 29th April 1998 [from MOLL et al. (1993)].

Depth	1 km Inshore				At Front				1 km Offshore			
	Temp (°C)	Cl <sup>-</sup> (mg l <sup>-1</sup> )	SiO <sub>2</sub> (mg l <sup>-1</sup> )	Chl (mg l <sup>-1</sup> )	Temp (°C)	Cl <sup>-</sup> (mg l <sup>-1</sup> )	SiO <sub>2</sub> (mg l <sup>-1</sup> )	Chl (mg l <sup>-1</sup> )	Temp (°C)	Cl <sup>-</sup> (mg l <sup>-1</sup> )	SiO <sub>2</sub> (mg l <sup>-1</sup> )	Chl (mg l <sup>-1</sup> )
1 m	4.45	9.95	0.84	2.05	4.4	10.7	0.99	2.35	3.22	9.69	0.87	1.82
5 m	4.44	9.95	0.85	2.23	4.34	10.7	1.05	2.12	3.19	9.85	0.91	2.04
10 m	4.43	9.95	0.86	2.17	4.27	10.6	0.98	2.42	3.2	9.81	0.89	1.69

**Fig. 4.** Surface temperature and chlorophyll fluorescence transect collected in Lake Baikal's Northern basin in early July, 1990 [figure from BOLGRIEN et al. (1995), data from GRANIN et al. (1991)].

shore of the thermal bar, but may also be at the position of the  $T_{md}$  (e.g. Table 1 and Fig. 4).

BOTTE & KAY (2000) showed that this localised bloom relies upon the incoming flows of the thermal bar circulation to maintain nutrient levels and thus avoid limitation of feeding, and it therefore follows the progression of the  $T_{md}$  into deeper waters as the surface heat flux continues. Currently the only authors to model the effects of the classical thermal bar on a plankton ecosystem, they used a simple Nutrient-Phytoplankton-Zooplankton model to produce a reasonable fit to LIKHOSHWAY et al.'s (1996) observations of a localised phytoplankton bloom following the Spring thermal bar in Lake Baikal. Their study shows that the bloom is mainly supported by primary production at the position of the thermal bar, rather than simple advection of biomass into the  $T_{md}$  zone, and emphasises the importance of water-column stability to the growth patterns observed.

Studying two separate models of ecosystem dynamics, HOLLAND et al. (2003) then extended this work to the case of the riverine thermal bar, finding that plankton growth was predicted to be more prolific than in the classical case. This is partly due to increased near-shore

stability, but the maintenance of nutrient levels by the riverine nutrient influx is also influential. Unfortunately, this work is limited by a lack of riverine data and a demonstrated oversimplification of the plankton models, and the authors conclude that much more work is necessary to arrive at a truly realistic model of lake plankton in the presence of any thermal bar.

Vertical motions associated with the thermal bar circulation may also be of considerable importance to lacustrine plankton populations. The downward transport of organic matter leads to increased microbial activity at depth (PARFENOVA et al. 2000) and creates more and less favourable times for the release of pollutants into a lake. CARMACK et al. (1979) showed that, due to deep mixing by the thermal bar, the dilution of effluents released into Kamloops Lake can be 20 times more effective in the Spring freshet than in Winter.

The thermal bar plume is compensated by rising water on both sides, generating an upwelling of deep nutrient supplies which may be crucial to the maintenance of surface productivity (LEAN et al. 1987), particularly when the bloom localised at the  $T_{md}$  is present (BOTTE & KAY 2000). There is some evidence that these flows sup-

port a particular species composition, as certain types of plankton (particularly diatoms) have significant sinking rates and therefore require upwelling motions to keep them in the euphotic zone (REYNOLDS 1994; KELLEY 1997). As a consequence of the stronger horizontal gradients and limited vertical extent on the inshore side of the thermal bar, the asymmetry of this vertical circulation provides another explanation for preferential growth rates on the shoreward side of the  $T_{md}$ .

In lakes wider than the local Rossby radius, the strong alongshore flows associated with a persistent thermal bar may cause localised plankton growth (*e.g.* near a river inflow) to spread rapidly around the shores while the deeper interior is still relatively unproductive (LIKHOSHWAY *et al.* 1996). In comparison to lake shallows in the absence of a thermal bar, this means that ecological effects will spread more widely along the shoreline, which may have important consequences in the presence of a localised change in ecological conditions, such as a pollution event or the onset of nutrient limitation of growth (MOLL *et al.* 1993; BUDD *et al.* 1999).

## Discussion and suggested further studies

The results summarised in this review show that the thermal bar circulation has been the subject of a significant quantity of scientific attention over recent decades. While the hydrodynamics of the thermal bar are far better understood than its ecological influence, both facets of this fascinating phenomenon still pose significant challenges for the interested researcher. The purpose of this final section is to briefly summarise this paper's discussion and outline some of the many open questions which remain.

Physical models of the thermal bar currently provide a comprehensive view of its hydrodynamics under a broad range of forcings and bathymetric conditions. Over the years, researchers have deduced a detailed understanding of many of its features, from flow and propagation rates to scalar transport patterns and its resilience to wind forcing. Other authors have concentrated on explaining the features of special cases of the thermal bar, such as its riverine and thermobaricity-controlled forms.

Opportunities for further developments to the understanding of the classical thermal bar are fairly limited; apart from the modelling of particular lake case studies to address local questions, the only major potential advance lies in significant improvement to the simple turbulence models so far employed. In this respect, a high-resolution study of thermal bars improving on the study of MALM (1995) may be appropriate, either adopting a more complex calculation of turbulent diffusivities or using a Large-Eddy Simulation.

Theoretically the rarely-studied Autumn thermal bar ought to have the same dynamics as a slowly-warmed and wind-disturbed Spring thermal bar, but there is some justification for a separate study of the cabbelling plume caused by a negative heat flux. Perhaps the best way to perform such a study would be to compare the Spring and Autumn thermal bar circulations on the same lake bathymetry under realistic seasonal surface fluxes of heat and momentum. In this way, or by performing high-resolution studies of the entire annual cycle of a slope-sided lake, the quantitative difference in circulation patterns and water renewal rates between Spring and Autumn might be surmised.

There is more scope for further analysis of the riverine thermal bar because it has so far only been modelled by HOLLAND *et al.* (2001, 2003), who were significantly limited by available computing power. Better-equipped investigators might numerically model an idealised river delta section under a range of (surface and riverine) thermal, haline and turbidity forcings, including both positive and negative heat fluxes to simulate Spring and Autumn conditions. Such a model could also include a study of the effects of wind. A three-dimensional domain would permit an improved understanding of the effect of Coriolis forces and topography, for instance allowing a comparison of dynamics for the riverine thermal bar in a long, narrow lake (such as Kamloops Lake) and a broad lake (such as Lake Baikal). A particularly interesting study would be an investigation of the importance of delta slope compared with river heat influx, determining the conditions under which a riverine thermal bar becomes dominated by surface heating. The riverine case would also benefit from a better representation of turbulent mixing and detailed sets of field data.

The state of knowledge on the ecology of the thermal bar is not so well advanced. There are several field studies which present observations of plankton populations in the vicinity of the thermal bar, but a deficiency in coverage and resolution prevents a general picture from emerging. Due to the complexity and lake-specific nature of plankton populations, modelling studies of these results are in their infancy.

The most enigmatic question arising from these field studies is why some temperate lakes experience a Spring bloom which is localised at or near the position of the  $T_{md}$  while other lakes support a more uniform or spatially monotonic growth profile inshore of the cabbelling plume. There are series of field studies showing examples of both types of plankton distribution, and there is enough published evidence to reject the possibility that such observations are a feature of the resolution or sampling strategy of each study (SCAVIA & BENNETT 1980; MOLL & BRAHCE 1986; MOLL *et al.* 1993; PAFENOVA *et al.* 2000).

The existence of a localised bloom is clearly due to a combination of physical and biological factors, but seems to be fundamentally controlled by the density structure of the near-shore region. Given strong, uniform stratification and weak horizontal converging flows (implying density gradients which are shallow in the horizontal and steep in the vertical) growth will be uniform inshore of the thermal bar, while weak stratification and strong downwelling at the  $T_{md}$  seems to cause a local plankton population maximum there. As a result, it is likely that the formation of a localised bloom is strongly related to the Winter state and Spring fluxes (through surface and shoreline) pertinent to the individual lake under scrutiny.

Although these physical factors have been shown to play a crucial role in the formation of the localised bloom, several other influences are likely to be important, such as the growth rates and preferences of the plankton populations in a particular lake. For example, the results of LIKHOSHWAY et al. (1996) show that certain species of phytoplankton congregate at the Spring thermal bar of Lake Baikal while overall plankton concentrations are found to increase monotonically towards the shore. Hydrochemical conditions will also affect plankton distributions by determining the spatial dynamics of nutrient limitation. Without dedicated in-situ studies of all physical and biological parameters at once it is impossible to deduce the relative importance of these effects.

Modelling efforts and the understanding of plankton populations in the vicinity of a thermal bar are seriously limited by a lack of spatially and temporally high-resolution field studies. Indeed, it is the opinion of the authors that further modelling work is difficult to justify in the absence of new data. In particular, understanding the factors leading to the generation of a localised bloom as opposed to blanket growth inshore of the  $T_{md}$  will require the collection of high-resolution data in a range of lakes encompassing a variety of trophic statuses and forcing conditions. Only after these data have been collected may it be possible to determine a set of conditions under which the localised bloom can be expected to appear.

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