Hydrobiologia (2006) 568(S):253–257
G. Coulter, O. Timoshkin, L. Timoshkina & K. Martens (eds), Species and Speciation in Ancient Lakes
DOI 10.1007/s10750-006-0306-x


# Hydrophysical processes in Lake Baikal in its transition from subtropical to modern climates

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*Key words:* Lake Baikal, climate, subtropical, deep water, convection, convective mixing, water exchange

## Abstract

During the past 5 million years significant changes have taken place in the Lake Baikal ecosystem. The climate changed from subtropical, with average annual air temperatures ($T_{air}$) of 15–10 °C, to a moderate one with $T_{air}$ of ~0 °C. The modern hydrophysical regime of the lake has been formed with increase in depth, and gradual cooling of the water body from deepwater temperatures ($T_{dw}$) of 15–10 °C to below 4 °C. The processes of cooling of Lake Baikal water in its transition from subtropical climate with deep temperatures greater than those of maximal density ($T_{md}$) are similar to modern processes of deepwater cooling of the Mediterranean type of MEDOC convection. Such intensive mechanisms of vertical exchange (MVE) are similar to autumn homothermy in Lake Baikal. However, they are higher than $T_{md}$. Inverse thermal stratification began to occur in surface layers in cold periods of the year after the deep water had cooled to $T_{md}$. The character of water exchange also changed; instead of a monomictic lake with warm water from surface to bottom, the lake has become dimictic with lower water below 4 °C, i.e. vertical mixing now occurs not once but twice a year. Winter ice cover began about a million years ago.

## Introduction

For the last 5 million years, the history of Lake Baikal has been rich in geological, climatic, hydrophysical and biological events. A subtropical climate, characterized for 10 million years by high average annual air temperature ($T_{air}$) around 20 °C, was replaced by a cooler (moderate) climate with intervening periods of great glaciations until it gained the features of the modern climate (Yasamanov, 1985; Vorobieva et al., 1995; Kuz'min et al., 1997).

## Materials and methods

### *Brief theory*

During the transitional period from subtropical to modern climate, three stages in Lake Baikal can be discerned: (1) subtropical stage, (2) transitional stage and (3) moderate climate.

These stages are characterized by the formation of various hydrophysical processes corresponding to qualitative and quantitative features of convective mixing and water exchange.

### *The subtropical climate*

The subtropical climate at the beginning of the transitional regime had average annual air temperatures about 15 °C with significant intra-annual seasonal changes (Fig. 1a). However, subzero temperatures did not occur. The maximum monthly temperature probably reached 18 °C in June–July, falling to an annual minimum of 12 °C. Such benign minimal temperatures existed until a systematic drop of average annual air temperatures in the Early Pliocene (5 my ago) in the Tertiary Period (Haq Bilalu & van Eysinga, 1994).

Annual surface water temperatures $T_{sw}$ followed air temperature $T_{air}$ with some delay, as water possesses high heat inertia. During autumn

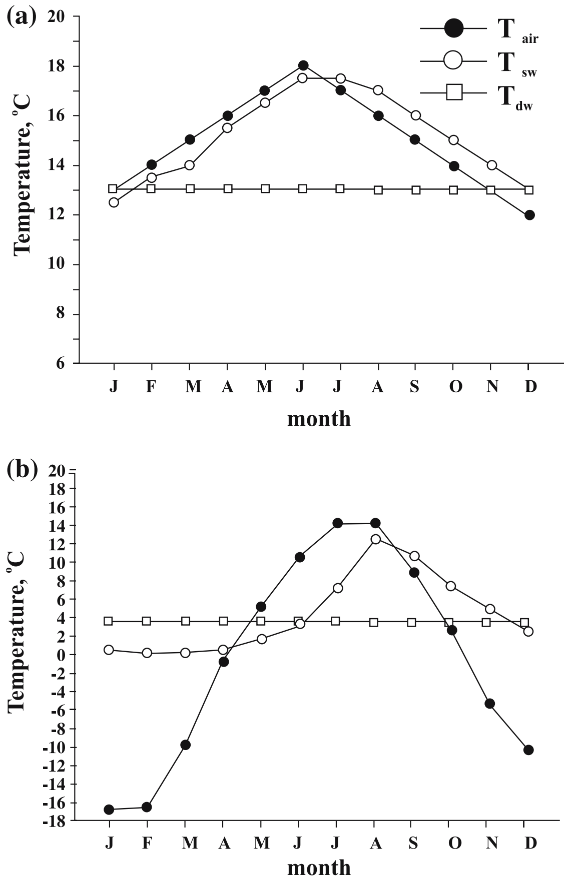


*Figure 1.* Annual variation of $T_{air}$, $T_{sw}$ and $T_{dw}$ (depth about 500 m). (a) for the subtropical climate (data of Vorobieva et al., 1995): $T_{air}$~15 °C, (b) for the moderate modern climate: $T_{air}$~0 °C for Southern Baikal (Kuimova & Sherstyankin, 1998), $T_{sw}$ – Verbolov's data, 1964, $T_{dw}$ for depth of about 500 m.

cooling, $T_{sw}$ was higher, but during spring warming it was below $T_{air}$.

Daily convection takes part in the formation of hydrophysical regimes. It has always existed and is caused by daily fluctuations of $T_{air}$ and, accordingly, by $T_w$. The beginning of daily convection in lakes is characterized by threshold density changes corresponding to changes of water temperature $\Delta T_w(\rho)$, which depend on $T_w$ values according to parabolic law (Table 1). $\Delta\rho$ changes highly disproportionately with temperature change; e.g. a fall in water temperature of 0.5 °C causes density to increase from 2.3 ($10^{-6}$ g/cm$^3$) to 94 ($10^{-6}$ g/cm$^3$), i.e. more than 50 times. Under the same conditions, the intensity of convection should also increase correspondingly.

An appropriate analog may be the winter regime of the Mediterranean Sea where strong winds (the "Mistral") cause cooling of the water mass. The mechanism of cooling is known as MEDOC convection (abbreviation – oceanic convection of the Mediterranean Sea) and has been well studied.

The main peculiarities of MEDOC convection are that the processes in the water column occur at temperatures different from those of maximal density: $T_w$ about 13 °C and $T_{md} \approx 4$ °C below zero (Oceanographic Tables, 1975, p. 165). Temperature decrease of 0.14 °C in the frontal zone where the main processes of convection take place leads to the decrease of water density by about 20 $\mu$g per cm$^3$or 20 g per m$^3$ (Table 1).

In winter, MEDOC convection is the main process in the formation and descent of deep layers and consists of three phases: a preliminary phase in an area with low water temperatures, high salinity and density and with vertical gravitation stability; a phase of strong mixing accompanied by stormy winds (30 m/s) where central mixed regions appear in the form of a narrow belt oriented parallel to the shore; a phase of descent and distribution (intrusion of new deep water) reaching near-bottom waters, the density characteristics of which are similar to each other (Lacombe et al., 1970).

Severe conditions of vertical mixing can arise with strong cooling of upper water layers and MEDOC convection with descending vertical velocities of water reaching 10–12 km a day (Lacombe et al., 1970).

In Lake Baikal, the daily convection cycle determines the levels of water layers with different physical, chemical, biological and microbiological characteristics (Sherstyankin et al., 1972).

Except for daily synoptic changes of temperature (from some days to several months), there were annual changes of $T_{air}$ and $T_w$ when minimal input of solar radiation occurred during winter solstice. The coldest period of the year was from November to February with strong winds. The intensification of vertical water mixing occurred once a year. Such types of water bodies are monomictic.

In order to understand former hydrophysical processes in Baikal it is necessary to imagine that the periods of cooling were of hundreds and thou-

*Table 1.* Deficit of water density $\Delta\rho$ at $T_{sw}$ changes

| $T_w$, °C | $-\Delta\rho$, $10^6$ g/cm$^3$ | $T_w$, °C | $-\Delta\rho$, $10^6$ g/cm$^3$ | $T_w$, °C | $-\Delta\rho$, $10^6$ g/cm$^3$ | $T_w$, °C | $-\Delta\rho$, $10^6$ g/cm$^3$ |
|---|---|---|---|---|---|---|---|
| 23.5 | 2558 | 18.5 | 1474 | 13.5 | 662 | 8.5 | 157.1 |
| 23.0 | 2438 | 18.0 | 1380 | 13.0 | 597 | 8.0 | 125.0 |
| 22.5 | 2321 | 17.5 | 1289 | 12.5 | 536 | 7.5 | 96.3 |
| 22.0 | 2206 | 17.0 | 1201 | 12.0 | 476 | 7.0 | 63.6 |
| 21.5 | 2094 | 16.5 | 1115 | 11.5 | 421 | 6.5 | 50.1 |
| ***21.0*** | ***1984*** | 16.0 | 1032 | 11.0 | 369 | 6.0 | 32.4 |
| ***20.5*** | ***1877*** | 15.5 | 953 | 10.5 | 320 | 5.5 | 18.6 |
| 20.0 | 1772 | 15.0 | 876 | 10.0 | 274 | 5.0 | 8.5 |
| 19.5 | 1670 | 14.5 | 802 | 9.5 | 231 | ***4.5*** | ***2.3*** |
| 19.0 | 1571 | 14.0 | 731 | 9.0 | 193 | ***4.0*** | ***0.0*** |

Bold and italic types mark MEDOC convection within the range of 20.5 and 21 °C taking into account $T_{md}$ (~−4 °C at salinity $S$~38‰); within the range of 4 and 4.5 °C – the autumn convection in Lake Baikal.

sands of years. During the transition to a modern climate, warming periods occurred when average annual temperatures of air and surface water increased. However, temperatures of deep waters remained constant. Processes of rapid cooling of deep waters are known (MEDOC convection), but those of fast warming are unknown. Inertia of warming is much greater than that of cooling.

Inter-annual and long-term climatic changes were characterized by systematic $T_{air}$ decrease. In the uppermost layers, $T_w$ was ~4 °C (temperature of maximal water density $T_{md}$).

The temperature pycnocline was established in the surface layers, the depth of which increased in a cold period. It could disappear completely during storms. At that time $T_{dw}$ decrease also occurred.

The temperature differences of surface and deep waters decreased in dynamically active areas (convergent zones) and reduced to zero, while the pycnocline of temperature and density deepened significantly or disappeared completely.

The transition from subtropical climate was completed in Lake Baikal when $T_{sw}$ was about 4 °C or lower, and inverse temperature stratification occurred in the upper layers.

*Transitional stage*

The decrease of average annual air temperatures occurred mainly because of winter temperature decrease. In modern times, the average annual temperature for Southern Baikal is about 0 °C, whereas $T_{air}$ in January and February can reach 17 °C below zero (Fig. 1b).

How do changes of average annual and monthly temperatures influence the main hydrophysical processes, namely the processes of convection which cause vertical mixing and water exchange?

During cold periods in surface layers, inverse temperature stratification is sustained and the mesothermic temperature maximum occurs. $T_{dw}$ is below 4 °C nevertheless higher than $T_{md}$ in corresponding layers.

With the appearance of inverse temperature stratification, spring homothermy is observed, i.e. the type of water body changes from monomictic to dimictic (Hutchinson, 1957).

*The modern climate*

The modern climate began with the appearance of stable ice cover, mesothermic maximum in winter, and with the development of spring homothermy.

All the hydrophysical processes in the water column gradually gained their modern characteristics. Intensification of vertical mixing occurs now twice a year, during $T_{sw}$ transition through 4 °C ($T_{md}$) with increase in spring and decrease in autumn.

## Results and discussion

*The subtropical climate*

Before the origin of modern Lake Baikal, $T_{air}$ was about 20 °C. Lake Tanganyika is an analog, where the average annual surface water temperature is about 26 °C with only small seasonal change. The surface water (epilimnion) in Tanganyika varies at most only about 3 °C in the year. The metalimnion density/temperature drop in this lake is located at depths of 100–200 m, below which the column is anoxic. Vertical mixing in upper layers (above the pycnocline of density), which provides proper distribution and mixing of oxygen necessary for biota, is caused by daily convection and slight cooling of water due to seasonal and trade winds. The dense convection reaches 400 m because of seasonal winds. Seasonal changes cause vertical mixing to take place above this discontinuity, but below it the anoxic layer is permanent (Edmond et al., 1993).

Such phenomena did not occur in Lake Baikal during the subtropical phase because of low $T_{air}$ and $T_{sw}$ during winter and considerably greater daily convection than occurs in Lake Tanganyika. Systematic fall of average annual $T_{air}$, $T_{sw}$ and $T_{dw}$ caused convection intensification.

Approximate annual variation of $T_{air}$, $T_{sw}$ and $T_{dw}$ is shown in Figure 1a. Hydrophysical processes were governed by the fact that temperatures of air and water were not lower than 10 °C.

The temperature difference between surface and deep water decreased, and in dynamically active regions (convergent zones) disappeared (as in modern autumn homothermy in Lake Baikal and its analog – MEDOC convection in the Mediterranean Sea) (Lacombe et al., 1970). Temperature and density discontinuities deepened considerably or disappeared entirely. In vertical water mixing the role of $T_w$ dominates, and T-type mixing results (Sherstyankin et al., 1995).

*The transitional period*

was relatively short (from ~2.6 to 2.4 my ago) in the Middle Upper Pliocene between successive paleomagnetic epochs; the Matuyama replaced the Gauss. For about 200 thousand years (Vorobieva et al., 1995; Bezrukova et al., 2004), $T_{air}$ had been changing from 9–10 °C above zero to 4–10 °C below zero. The $T_{air}$ decrease was accompanied by astronomic (orbital effects, increase of planetary albedo, etc.) and planetary events (long storms and dust storms, changes of current systems in the World Ocean, changes of types of circulations, etc.), and by geological activity (mountain formation, increase of depth in Baikal by 1000 m and deeper, earthquakes, etc.).

The impact upon biota was great, especially its warm-loving species (rhinoceros, thermophilic vegetation; see exhibits of the Baikal Museum).

Intensive MEDOC type convection developed with drastic decrease of $T_{air}$ in the polar regions of the World Ocean, and deep water in Lake Baikal cooled rapidly. $T_{air}$ reached 0 °C, but since seasonal temperature fluctuated widely $T_{sw}$ reached 4 °C and lower, and the first ice phenomena appeared.

*Establishment of modern climate*

(2.4 my ago – till present time) occurred relatively fast while Lake Baikal gained its present features (Mats, 1995; Logachev et al., 1996; Popova et al., 1989).

Paleoclimates of the Baikal region beginning in the Pliocene (5 my ago) (Haq Bilalu & van Eysinga, 1994) are clearly distinguished in paleosoils (Vorobieva et al., 1995). Taking into account changes in Baikal region paleoclimates in the Late Cenozoic (Vorobieva et al., 1995), the first stable transition of $T_{air}$ to negative values occurred in the Upper Pliocene about 2.4 my ago (Fig. 2). However, the most significant cooling, when permanent ice phenomena appeared on Baikal, took place in the Upper Eopleistocene about 0.9 my ago (Vorobieva et al., 1995). About the same time, constant ice cover appeared in the Arctic (Khusid et al., 1993). In the Late Pleistocene, characterized by lower $T_{air}$, annual ice periods occurred on Baikal (Shimaraev et al., 1995). The period of open water may have shortened to 3–2 months, and during the coldest years the ice cover was probably broken into ice fields and porridge-like ice in Northern Baikal where average $T_{air}$ was 4 °C lower than in Southern Baikal. However, a period of ice break up and open water occurred every year (Kuimova & Sherstyankin, 1998).

Inverse temperature stratification strongly retards water from freezing; for example, Lake Vostok in the Antarctic, though surrounded by ice has not frozen so far (Zotikov, 2000). Lake Baikal has never been covered with ice for the whole year.

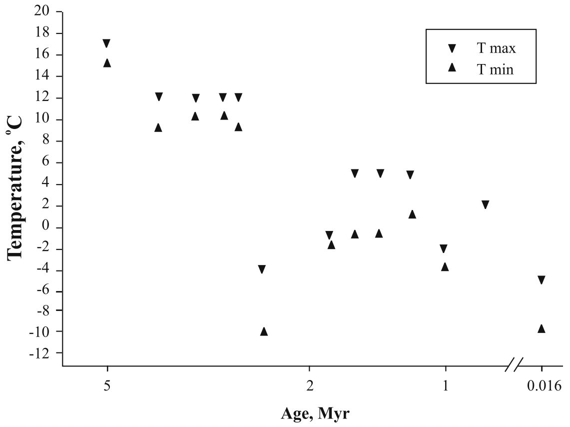


*Figure 2.* $T_{air}$ of the Baikal region for the last 5 million years (data of Vorobieva et al., 1995).

## Conclusion

The following sequences appear to have taken place in the Lake Baikal water column during its transition from subtropical to modern climates:

1. Cooling intensity gradually exceeded warming intensity.
2. Cooling of deep waters was of seasonal character and occurred only during the cold period of year.
3. MEDOC convection with $T_w$ significantly exceeding $T_{md}$, analogous to autumn homothermy on Lake Baikal.
4. With gradual cooling of climate, Lake Baikal changed from a warm monomictic water body into a dimictic one, characterized by convective overturn twice a year – in spring and autumn.

## Acknowledgements

This work was supported by the Russian Foundation of Basic Research, Grant No.01-05-65097 and 02-05-65345, 05-05-64375 and 06-05-64685. The authors offer their thanks to Professor George W. Coulter for the revision of the English version of this manuscript and his valuable remarks.

## References

Bezrukova, E., A. Bukharov & V. Bychinsky, 2004. High-resolution sedimentary record in a new BDP-99 core from Posolsk Bank in Lake Baikal. Geologiya Geofizika 45: 163–193 (in Russian).

Edmond, J. M., R. F. Stallard & H. Craig et al. 1993. Nutrient chemistry of the water column of Lake Tanganyika. Limnology and Oceanography 38: 725–738.

Haq Bilalu, U. & F. W. B. van Eysinga, 1994. Geological Time Table, (4th edn.) Elsevier.

Hutchinson G. E., 1957. A Treatise on Limnology, 1st edn. Willey, New York; Chapman and Hall, London, 1015 pp.

Khusid, T. A., V. N. Belyaeva & I. I. Burmistrova, 1993. On the history of deep Arctic Ocean. Oceanologiya 33: 930–934 (in Russian).

Kuimova, L. N. & P. P. Sherstyankin, 1998. Climate change and extreme hydrological events on Lake Baikal during the last 250,000 years. The Second International Conference on Climate and Water. Espoo, Finland, 17–20 August 1998, Vol. 3, 1197–1204 pp.

Kuz'min, M. I., M. A. Grachev, D. Wil'yams, T. Kawai, Sh. Horie & X. Oberhensli, 1997. The continuous annals paleoclimates last 4,5 millions years from Lake Baikal (first information). Geologiya Geofizika 38: 1021–1023 (in Russian).

Logachev, N. A., S. V. Rasskazov, & A. V. Ivanov, et al. 1996. Cenozoic rift genesis in continental lithosphere. In Litosfera tsentral'noi Asii, 57–80 (in Russian).

Mats, V. D., 1995. Development of the Baikal depression: chronology of the transformation of zoogeographic barriers. The Second Vereshchagin Baikal Conference, October 5–10, 1995. Abstracts. Irkutsk, 131 pp.

MEDOC group, 1969, 1970. Observation of formation of deep water in the mediterranean sea. Nature 227: 1037–1040.

Oceanographic tables 1975. Gidrometeoizdat, Leningrad (in Russian) 377 pp.

Popova, S. M., V. D. Mats & G. P. Chernyaeva et al. 1989. Paleolimnological reconstructions (In: The Baikal rift zone). Novosibirsk, "Nauka" (in Russian) 112 pp.

Sherstyankin, P. P., V. S. Kaplin & Maksimov, 1972. Vertical distribution of a transparency in under ice period on Lake Baikal and its connection with biological parameters. Idrobiologiska Journal 8: 65–68 (in Russian).

Sherstyankin, P. P., L. N. Kuimova & M. N. Shimaraev, 1995. On Paleothermohaline Regime of Lake Baikal. The Second Vereshchagin Baikal Conference, October 5–10, 1995. Abstrs Irkutsk, 231 pp.

Shimaraev, M. N., N. G. Granin & L. N. Kuimova, 1995. Experience of reconstruction of hydrophysical conditions in Baikal in Late Pleistocene and Holocene. Geologiya Geofizika 36: 97–102 (in Russian).

Verbolov, V. I., 1964. Temperature regime of Bay Listvenichnyi on Lake Baikal. In Elements of a hydrometeorological Regime of Lake Baikal. Nauka, Moskva – Leningrad, pp. 38–51 (in Russian).

Vorobieva, G. A., V. D. Mats & M. K. Shimaraeva, 1995. Late-Cenozoic paleoclimates in the Baikal region. Geologiya Geofizika 36: 82–96 (in Russian).

Yasamanov, N. A., 1985. Ancient Climates of the Earth. Gidrometeoizdat, Leningrad (in Russian) 295 pp.

Zotikov, 2000. On genesis of the Vostok Lake (Antarctica). Doklady Akademii Nauk 374: 824–626 (in Russian).