Changing nutrient cycling in Lake Baikal, the world's oldest lake

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Lake Baikal, lying in a rift zone in southeastern Siberia, is the world’s oldest, deepest, and most voluminous lake that began to form over 30 million years ago. Cited as the “most outstanding example of a freshwater ecosystem” and designated a World Heritage Site in 1996 due to its high level of endemicity, the lake and its ecosystem have become increasingly threatened by both climate change and anthropogenic disturbance. Here, we present a record of nutrient cycling in the lake, derived from the silicon isotope composition of diatoms, which dominate aquatic primary productivity. Using historical records from the region, we assess the extent to which natural and anthropogenic factors have altered biogeochemical cycling in the lake over the last 2,000 y. We show that rates of nutrient supply from deep waters to the photic zone have dramatically increased since the mid-19th century in response to changing wind dynamics, reduced ice cover, and their associated impact on limnological processes in the lake. With stressors linked to untreated sewage and catchment development also now impacting the near-shore region of Lake Baikal, the resilience of the lake’s highly endemic ecosystem to ongoing and future disturbance is increasingly uncertain.

Significance

Lake Baikal (Siberia) is the world’s oldest and deepest lake and a UNESCO World Heritage Site. Containing an exceptionally high level of biodiversity and endemism, in addition to a fifth of global freshwater not stored in ice sheets, the lake has been cited by UNESCO as the “most outstanding example of a freshwater ecosystem.” Using geochemical and climate data, we demonstrate that rates of nutrient supply to the lake’s photic zone have risen to unprecedented levels in the last 2,000 y through the 20th and 21st centuries. Linked to increased in wind speed enhancing deep ventilation, we show that these changes are capable of altering lake primary production and community dynamics, including the balance between endemic and cosmopolitan species.

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Ancient lakes have long been associated with both high levels of biodiversity and endemism. However, they are also being threatened by anthropogenic forcings that have led to impacts ranging from the warming of lake waters (1), hydrological modifications (2), increases in aquatic toxicity (3), and declining endemic populations due to introductions of nonnative species (4). Global populations increasingly reliant on large and ancient lakes for ecosystem services, the biodiversity (5) and value of ecosystems (6) have become increasingly threatened by both climate change and anthropogenic modifications (2), increases in aquatic toxicity (3), and declining endemic populations due to introductions of nonnative species (4). With global populations increasingly reliant on large and ancient lakes for ecosystem services, the biodiversity (5) and value of ecosystems (6) have become increasingly threatened by both climate change and anthropogenic factors have altered biogeochemical cycling in the lake over the last 2,000 y. We show that rates of nutrient supply from deep waters to the photic zone have dramatically increased since the mid-19th century in response to changing wind dynamics, reduced ice cover, and their associated impact on limnological processes in the lake. With stressors linked to untreated sewage and catchment development also now impacting the near-shore region of Lake Baikal, the resilience of the lake’s highly endemic ecosystem to ongoing and future disturbance is increasingly uncertain.

Concerns exist over the future health of this unique ecosystem, amid evidence of extensive shoreline eutrophication (11, 12) and climate-induced shifts in primary productivity (13, 14). Together, these changes have impacted organisms ranging from sponges and gastropods to ciliates, flagellates, and algal communities (15). Given the likelihood of future anthropogenic disturbance on Lake Baikal, further disrupting productivity exchanges through the lake’s food web, there is a need to place these contemporary observations into their historical setting. In Lake Baikal, we have evidence that algal communities have undergone rapid multidecadal to multicientennial timescale changes over the last 2,000 y (16). However, there is a need to also gain a clearer insight into how biogeochemical and nutrient cycling has altered over the same timescale, both to contextualize natural and anthropogenic drivers of change and to understand the susceptibility of the lake’s ecosystem to further alteration under different climate states (17). Annual primary productivity in Lake Baikal is ultimately regulated by photic zone nutrient availability, in addition to ice/snow cover, which regulates light availability for photosynthesis (10, 18). Here, by analyzing the silicon isotope composition of diatom silica (δSi), we show that nutrient supply to the surface waters of Lake Baikal has rapidly increased through the 20th and 21st centuries coincident with increased wind-driven Ekman transport and reduced ice cover. These changes in photic zone nutrient availability have the potential to alter resource competition and prey–predator interactions across the lake (15, 19).
Results and Discussion

Our composite 30Siδdiatom record, from the south basin of Lake Baikal (Figs. 1 and 24), is controlled by changes in the rates at which nutrients (silicic acid [SiOH4]) are supplied to the photic zone and the rates at which the same nutrients are utilized by diatoms (unicellular siliceous algae, which dominate primary productivity in Lake Baikal). An increase (decrease) in δ30Siδdiatom could therefore be driven by the following: 1) an increase (decrease) in biogenic silicic acid utilization due to the isotope fractionation associated with this process; 2) a decrease (increase) in nutrient supply to the photic zone, which replenishes the pool of nutrients and their isotope composition; or 3) a combination of these two processes, with their relative magnitudes determining the direction of change in δ30Siδdiatom (e.g., increased rates of both nutrient utilization and supply). These two parameters can be constrained from δ30Siδdiatom using modern Lake Baikal values that account for the δ30Siδdiatom fractionation factor (20), the δ30Si composition of deep lake water that dominates intraannual and interannual nutrient supply to the photic zone (δ30Siδlake) (21), and biogenic silica (BSi) mass accumulation rates (MARs) to account for siliceous algal productivity.

For the past 2,000 y, changes in δ30Siδdiatom follow rates of silicic acid utilization, which predominantly varies from 70 to 90% (σ = 79%, 1σ = 6.7%). Rates in the 20th and 21st centuries (σ = 78%, 1σ = 5.0%) are lower than during the Little Ice Age (LIA) from 1180 to 1840 CE (σ = 5.8%) (P < 0.05) and Dark Ages Cold Period (DACP) from 500 to 750 CE (σ = 3.6%), but similar to the Medieval Climate Anomaly (MCA) from 880 to 960 CE (9, 23). Intraannual and interannual geochemical cycling in Lake Baikal is therefore primarily regulated by the vertical mixing of nutrient-rich deep waters into the photic zone (23), sustaining high levels of primary productivity within the lake. Due to thermal stratification, seiches and seasonal convective mixing in Lake Baikal do not extend below 300 m (10), while cyclonic induced upwelling is constrained to the upper 400 m of the water column (24). Instead, whole water column vertical mixing is primarily controlled by coastal downwelling, triggered by thermobaric instability in a process known as deep ventilation (9, 10, 25) and balanced by the upwelling of deep water rich in silicon, nitrogen, and phosphate to the photic zone (630 mmol SiO2·m−2·y−1; 93 mmol NO3−·m−2·y−1; 5 mmol P·m−2·y−1) (23).

In deep lakes across the world, thermobaric convection is resistant to direct surface water warming from anthropogenic climate change (26). Lake Baikal is no exception to this with deep ventilation from coastal downwelling believed to be resilient to constraining utilization as a ratio against BSi MAR from the same core samples, the 20th- and 21st-century decline in silicic acid utilization can be attributed to a progressive increase in the rates at which nutrients (silicic acid) are supplied to the photic zone, with a significant escalation after 1900 CE (P < 0.001) (Fig. 2 C and D). In other words, while absolute rates of silicic productivity and biomineralization increased (Fig. 2C), the rate of nutrient supply to the photic zone occurred at a faster rate than the same nutrients could be biomineralized, leading to the 20th- and 21st-century decrease in relative rates of nutrient utilization.

Nutrient Cycling in Lake Baikal. Due to the dissolution of diatoms and other organisms during sinking and the associated remineralization of nutrients into the water column, deep water nutrient, phosphate, and silicate nutrient concentrations are higher than the overlying waters in the epilimnion (9, 23). Intraannual and interannual geochemical cycling in Lake Baikal is therefore primarily regulated by the vertical mixing of nutrient-rich deep waters into the photic zone (23), sustaining high levels of primary productivity within the lake. Due to thermal stratification, seiches and seasonal convective mixing in Lake Baikal do not extend below 300 m (10), while cyclonic induced upwelling is constrained to the upper 400 m of the water column (24). Instead, whole water column vertical mixing is primarily controlled by coastal downwelling, triggered by thermobaric instability in a process known as deep ventilation (9, 10, 25) and balanced by the upwelling of deep water rich in silicon, nitrogen, and phosphate to the photic zone (630 mmol SiO2·m−2·y−1; 93 mmol NO3−·m−2·y−1; 5 mmol P·m−2·y−1) (23).

In deep lakes across the world, thermobaric convection is resistant to direct surface water warming from anthropogenic climate change (26). Lake Baikal is no exception to this with deep ventilation from coastal downwelling believed to be resilient to
past and predicted future changes in surface water temperature (SWT) (27–29) (Fig. 3A). Instead, deep ventilation in Lake Baikal is predominantly controlled by wind, through generating Ekman transport toward the coast, which is able to trigger thermobaric instability in the water column and thus deep ventilation (Fig. 3). Reduced ice cover and changing SWT dynamics over Lake Baikal, altering lake wind conditions and deep ventilation (Fig. 3). Reduced ice cover and changing SWT dynamics may also increase the period of time favorable for deep ventilation, which occurs when SWTs are below 4 °C and close to water temperatures at the lake bottom.

Rivers in the catchment (>350 rivers; ~540,000 km²) also supply nutrients to the lake, but due to the long residence time of both waters and nutrients in Lake Baikal these inputs represent only a fraction of all nutrients annually cycled within the lake (23). While deteriorations in river water quality have been observed (38), we have found no evidence that anthropogenic activity has altered the silicic acid concentrations or $\delta^{30}$Si (35, 36) (Fig. 3A, D, and E). While such a change is unlikely to have directly impacted deep water ventilation in Lake Baikal (25), research on Lake Superior has demonstrated that increasing SAT and shortening of the ice season both warmed SWT and destabilized the atmospheric boundary layer, increasing wind speeds above the lake (37). With winds over Lake Baikal chiefly controlled by local pressure phenomena due to differential heating between land and water (10), similar SAT, SWT, and ice cover changes in Lake Baikal may be triggering the same process over Lake Baikal, altering lake wind conditions and deep ventilation (Fig. 3). Reduced ice cover and changing SWT dynamics may also increase the period of time favorable for deep ventilation, which occurs when SWTs are below 4 °C and close to water temperatures at the lake bottom.

Drivers of silicic acid supply in Lake Baikal. (A) Mean surface water temperatures (SWTs) (May to October) from shoreline locations across Lake Baikal (29). (B) CERA-20C (32) and ERA5 (33) wind speed reanalysis data from the barycentre of Lake Baikal and modeled 5-yr running mean Ekman transport in Lake Baikal during the typical periods of downwelling (May to June and December to January). Both datasets are shown as anomalies relative to a baseline period of 1990 to 2000 CE. (C) Changes in photic zone silicic acid supply relative to a value of 100% at 2005 CE. Shaded region for $\delta^{30}$Si supply relative to a value of 100% at 2005 CE. Shaded region for $\delta^{30}$Si.

Fig. 2. Proxy records from Lake Baikal reflecting changes in silicon cycling in the lake. (A) $\delta^{30}$Si$_{diatom}$ from Lake Baikal. (B) Relative rates of photic zone silicic acid [Si(OH)$_4$] utilization. (C) Biogenic silica (BSi) mass accumulation rates (MARs) at core site BAIK13-1 (Fig. 1). (D) Changes in photic zone silicic acid supply relative to a value of 100% at 2005 CE. Shaded region for $\delta^{30}$Si$_{diatom}$ reflects the absolute analytical uncertainty ($2\sigma$) of the isotope analysis. Shaded polygons for silicic acid supply/utilization and BSi MAR reflect the 1σ uncertainty derived from Monte Carlo simulations (10,000 replicates). Age boundaries for the Little Ice Age (LIA) and Medieval Climate Anomaly (MCA) are based on diatom assemblage records of environmental change from Lake Baikal (22). Also shown are age boundaries for the Dark Ages Cold Period (DACP). Subplots in B and D document changes since 1900 CE.

Fig. 3. Drivers of silicic acid supply in Lake Baikal. (A) Mean surface water temperatures (SWTs) (May to October) from shoreline locations across Lake Baikal (29). (B) CERA-20C (32) and ERA5 (33) wind speed reanalysis data from the barycentre of Lake Baikal and modeled 5-yr running mean Ekman transport in Lake Baikal during the typical periods of downwelling (May to June and December to January). Both datasets are shown as anomalies relative to a baseline period of 1990 to 2000 CE. (C) Changes in photic zone silicic acid supply relative to a value of 100% at 2005 CE with the shaded polygon reflect the 1σ uncertainty derived from Monte Carlo simulations (10,000 replicates). (D) Annual mean surface air temperature (SAT) at Irkutsk (May 1990: 30710 [52°16′ N, 104°18′ E; elevation, 467 m]) (Fig. 1). (E) South basin annual ice cover duration. The black lines and gray confidence intervals on individual panels show a GAM fitted to each time series.

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composition of waters flowing into the lake, based on spatial and
temporal river measurement across the Selenga River drainage
basin that supplies 62% of all riverine inputs to Lake Baikal (21).

With instrumental records also showing interdecadal
variability but no long-term change in the flow of rivers draining
into Lake Baikal through the 20th and 21st centuries (39), it is
unlikely that natural or anthropogenic alterations to the catch-
ment have increased the supply of silicic acid to Lake Baikal.

Similarly, while anthropogenic activity from urbanization, mining,
and deforestation in the immediate vicinity of the lake has
resulted in significant volumes of wastewater entering the lake,
and even shoreline eutrophication (11, 12), this development
has largely occurred since the 1960s and so is incapable of
initiating the increase in silicic acid supply from the mid-19th
century onward. Therefore, we conclude that changes in deep
ventilation within Lake Baikal are the principal mechanism to
explain increases in photic zone nutrient supply during the 20th
and 21st centuries.

**Fig. 4.** Diatom community changes at core site BAIK13-7 (Fig. 1) (14, 16). (A) Changes in photic zone silicic acid supply (relative to a value of 100% at 2005 CE) together with the ratio of autumn/spring taxa, detrended canonical correspondence analysis (DCCA) axis 1 scores reflecting diatom composition turnover, principal-components analysis (PCA) axis 1 scores reflecting changing taxa composition, relative abundance of *U. acus* and *A. skvortzowi*, as well as mean surface water temperatures (SWTs) (May to October) from shoreline locations across Lake Baikal (29). (B) First derivatives and 95% simultaneous confidence intervals of GAMs fitted to each time series. Where the simultaneous interval does not include 0, the models detect significant temporal change in the proxy record.
Ecological Implications. Lake Baikal’s biodiversity and ecosystem functioning has been subject to abrupt and rapid change through the Holocene, including changes to carbon dynamics (40) and endemic diatom communities (22, 41). With pelagic communities in the lake known for their ability to rapidly respond to changing conditions (42), there is a need to assess the resilience of Lake Baikal and its high endemicity to anthropogenic forcings including changes in biogeochemical cycling. Increases in both endemic and non-endemic diatom taxa are observed from the end of the LIA in response to warmer climate conditions and reduced snow/ice cover on the lake, increasing turbulent mixing, light availability, and changes to the suspension of diatoms in the photic zone (16, 43). Simultaneous with this and the higher rates of Ekman transport driven nutrient supply to the photic zone (16, 43), significant relative decreases (increases) in autumn (spring) productivity, driven by declines in endemic taxa including *Ctenophora portula inconspicua* and *Cyclotella minuta* (Fig. 4).

Changes to the diatom community and compositional turnover—the change in species composition and relative abundances—continue through the 20th and 21st centuries (P = 0.004), with breakpoint analyses and generalized additive models (GAMs) indicating a significant escalation from the 1970s onward (Fig. 4). Community changes in Lake Baikal in the second half of the 20th century and the expansion and displacement of endemic taxa have previously been attributed to increased SWT and summer thermal stratification (14, 16) (Fig. 4). While it remains unclear to what extent these changes can also be attributed to the coincident increase in photic zone nutrient supply, redundancy analysis suggests that nutrient supply may account for almost one-quarter of diatom community variation. Furthermore, changes in community turnover are strongly associated with relative abundance increases in the endemic *Aulacoseira skvortzowii* (r = −0.68, P < 0.005) and cosmopolitan *Ulnaria acus* (r = −0.83; P < 0.005), trends that are mirrored elsewhere across the lake (14, 16, 22, 44) (Fig. 4). *U. acus* is a taxa associated with higher dissolved silica concentrations in the water column (22, 41), while cells of both *A. skvortzowii* and *U. acus* require strong winds/currents to be transported from their littoral region habitats to colonize pelagic waters (46). Strongly linked with anthropogenic processes (46) linked to high nutrient (silicic acid) supply and wind-driven Ekman transport, as well as warmer SWT, may be driving shifts in compositional turnover in Lake Baikal, especially during the past 50 y.

The potential impact of Ekman transport-driven nutrient supply on the diatom community highlights the ability for changes in deep ventilation to also increase other forms of primary productivity, reduce relative rates of nutrient utilization, and alter food–web interactions and nutrient resources in Lake Baikal (15). This, in turn, has the capability to exacerbate problems caused by the emergence of anthropogenic stressors through the 20th and 21st centuries. Climate change, primarily through reduced ice cover and higher SWT, as well as shoreline eutrophication, has impacted a range of autotrophic and heterotrophic organisms in littoral and pelagic regions across the lake (11–14, 42, 44). Future anthropogenic warming in the 21st century is predicted to shift primary productivity to less silicified, littoral diatoms and autotrophic picoplankton (15, 16, 22, 44, 47). While the combined impact of these changes on energy transfers and trophic cascades in Lake Baikal’s endemic ecosystem remains unresolved (19, 42), it is clear that as SWTs have increased, heavier pelagic diatoms are living at deeper depths in the photic zone, concurrent with upward shifts in many groups of zooplankton consumers, leading to an alteration in the spatial overlap between the grazers and their food (42).

Our results show that the 20th and 21st centuries have been characterized by a significant increase in deep ventilation in Lake Baikal, which increased the rates at which deep water nutrients are supplied to the photic zone. Combined with models showing the susceptibility of coastal downwelling to changes in wind strength (28), these findings highlight the need for robust estimates of future wind changes over Lake Baikal under Intergovernmental Panel on Climate Change Representative Concentration Pathway/Shared Socioeconomic Pathway scenarios. This is key to determining the vulnerability of Lake Baikal to future physicochemical alterations as well as aiding ongoing efforts to understand ecosystem functions in this World Heritage Site. Wind characteristics over Lake Baikal are complex and hard to predict (28), with recent observations outside the main wind ventilation season showing reductions in wind strength (29) rather than the increase forecast to occur with anthropogenic climate change (10). However, with indications that anthropogenic warming will continue to reduce annual ice cover over the lake (35, 36), further increases in wind activity over the lake in response to higher SWT and a destabilized atmospheric boundary layer seem assured (37). Together, these changes risk increasing turbulent mixing and deep ventilation-driven nutrient supply to the photic zone. Alongside shoreline eutrophication, this threatens the balance between endemic and cosmopolitan species across both littoral and pelagic regions of the lake (13, 22, 44), impacting feeding strategies of at least the lake’s primary consumers (42).

Materials and Methods

Methods. **Study site.** Sediment cores from site BAIK13-1 (51°46′ 04.2″ N, 104°24′ 58.6″ E; water depth, 1,360 m) and BAIK13-4 (51°41′ 33.8″ N, 104°18′ 00.1″ E; water depth, 1,360 m) were collected from the south basin of Lake Baikal in March 2013 using a UWITEC corer with PVC-liners (Ø 63 mm) that enabled undisturbed recovery of material at the sediment/water interface (Fig. 1). Cores therefore range from 0 to 90 cm of sediments. Subsamples from 10 to 90 cm of BAIK13-1C (50 cm) and 12.5 cm of BAIK13-4F (33 cm) were subsampled in the field at a resolution of 0.2 cm and transported to the United Kingdom. Both sites are located >120 km away from the Selenga Delta and other major river inflows/sources of nutrients to the lake (Fig. 1). **Chronologies.** Well-constrained 210Pb-derived age models for core BAIK13-1C and BAIK13-4F have previously been published covering the last ~150 y (48). To extend these age models to cover samples prior to 1850 CE, radiocarbon (14C) dating was completed on two samples at BAIK13-1C and one sample at BAIK13-4F. All 210Pb and calibrated 14C dates were then combined to create a new Bayesian radiocarbon age model for each site using Bacon **Isotope analysis.** Diatoms were extracted for isotope analysis with a combination of 5% HCl and 30% H2O2, alongside sodium polytungstate heavy liquid separation at specific gravities of ~2.2 g/mL, used to remove non-diatom contaminants (48). All samples were screened using a Zeiss Axiovert 40 C inverted microscope, scanning electron microscope, and X-ray fluorescence to confirm sample purity and the absence of nondiatom contaminants. Only samples with an Al:Si contamination <1% and that visibly demonstrated diatom-rich assemblages were analyzed. This quality control ultimately limits the final number of analyzed samples and so the resolution of the isotope record. Diatoms in the analyzed samples are dominated by planktonic taxa including *Aulacoseira baicalensis*, *Aulacoseira skvortzowii*, *Ctenophora portula inconspicua*, *Cyclotella minuta*, *Stephanodiscus meyerii*, and *Ulnaria acus*. Given the ecology of these species, our isotope record is interpreted as reflecting mean annual conditions within the photic zone in Lake Baikal, with a small bias toward spring months when diatom productivity peaks (47). Due to their close proximity and the strong age models for both sites, samples from each core are combined together to create a composite record for the south basin of Lake Baikal.

Alkaline fusion (NaOH) of cleaned diatom samples and subsequent cation exchange (Bio-Rad; AG50W-X12) followed existing methodologies (20). Samples were analyzed in wet-plasma mode using the high mass-resolution capability of a Thermo Fisher Neptune Plus MC-ICP-MS (multicollector inductively coupled plasma mass spectrometer) at the British Geological Survey. Full analytical methods, including practices applied to minimize instrument induced mass bias and drift, are detailed in refs. 20, 21. Full procedural blank compositions from MC-ICP-MS analyses were ~48 ng compared to typical sample amounts of ~3,900 ng. Using the worst-case scenario (i.e., calculated using the sample with the lowest Si concentration), this level of blank could result in a...
potential shift in sample composition by <0.03‰, which was insignificant relative to the typical <0.1% propagated sample uncertainties. All uncertainties are reported as 2σ absolute, and incorporate an excess variance derived from repeat analysis of the NBS 28 reference material, which was quadratically added to the analytical uncertainty of each measurement. Long-term (~2 y) reproducibility and machine accuracy are assessed via the analysis of the Diatomite secondary reference material, with data (+1.2‰ ± 0.18‰, 2n = 244) agreeing well with the published consensus value (+1.26‰ ± 0.2‰, 2n = 106).

BSI. In line with previous work on Lake Baikal, BSI concentrations were measured on samples from BAIK13-1C at 0.2-cm resolution using a single-step wet-alkaline digestion technique. Following digestion of 30 mg of freeze-dried sediment in a weak (1% Na2CO3) solution, designed to minimize dissolution of aluminosilicates, aliquots were taken after 5 h and analyzed for dissolved silica using colorimetric determination. Replicate analyses of a standard material indicated an analytical reproducibility of 0.49%. BSI MARs were then calculated using dry bulk density and sediment accumulation rates for the core.

Silicic acid utilization/supply. Lake Baikal is best characterized by an open system model (21) in which records of δ30SiDiatom are a function of the isotope composition of dissolved silicic acid ([Si(OH)4]0 supplied to the photic zone (δ30SiLake), the fraction of Si(OH)4 remaining in the water (f), and the enrichment factor between diatoms and silicic acid (ς):

\[ \delta^{30}\text{Si}_{\text{Diatom}} = \delta^{30}\text{Si}_{\text{Lake}} + \epsilon \times f \]  

[1]

From this, changes in the relative rate of photic zone silicic acid utilization (i.e., \(1 - f\)) can be obtained given that \(\delta^{30}\text{Si}_{\text{Lake}}\) and \(\epsilon\) have been constrained in Lake Baikal at 1.71‰ and ~1.61‰, respectively (20, 21):

\[ \text{Si(OH)}_{\text{utilisation}} = \left(1 - \frac{\delta^{30}\text{Si}_{\text{Diatom}} - 1.71}{1.61}\right) \times 100. \]  

[2]

While changes in silicic acid utilization will mirror changes in δ30SiDiatom (Fig. 2A and B), BSI MAR can be used as a measure of silicic productivity to account for the fact that variations in relative rates of nutrient utilization can occur due to changes in the following: 1) siliceous productivity; and/or 2) the rate of nutrient supply to the photic zone, altering \(f\) in Eq. 1. With this, changes in the supply of Si(OH)+ to the photic zone are calculated relative to the sample at 2005 CE:

\[ \text{Si(OH)}_{\text{supply}} = \frac{\text{BSI MAR}_{\text{sample}}}{\text{BSI MAR}_{\text{2005CE}}} \times \frac{\text{Si(OH)}_{\text{utilisation}}}{\text{Si(OH)}_{\text{utilisation}} - \text{Si(OH)}_{\text{2005CE}}} \]  

[3]

Ekman transport. Coastal deep ventilation in Lake Baikal is generated by winds aligned with the main axis of the lake, producing a net transport of surface water toward the lake coast to the right of the wind direction. This phenomenon, known as Ekman transport, is caused by the planetary rotation and is defined as follows:

\[ M = \tau \times \frac{R}{\rho_w} \]  

[4]

where \(\tau\) is the Coriolis frequency, \(\rho\) is the density of water, and \(s\) is the wind shear stress:

\[ \tau = \rho_a C_D W^2 \]  

[5]

in which \(\rho_a\) is the density of air, \(C_D\) is the drag coefficient, and \(W\) is the wind speed component parallel to Lake Baikal’s coast, which on average has a 24-hour wind profile of ~50° relative to the horizontal direction. Previous work has shown that winds from the northeast are the most favorable to generate Ekman transport and subsequent deep ventilation in Lake Baikal, due to their predominance and high speed as well as the bathymetry of the lake with steeper slopes at the northwest shore where these winds produce coastal downwelling (24, 29). Using CERA-20C (32) (resolution, 125 km) and ERAS (33) (resolution, 30 km) wind reanalysis data (height, 10 m) around the barycentre of the Lake Baikal (53.375°N, 108.125°E), Ekman transport generated by winds from northeast were evaluated in the months when deep ventilation occurs in Lake Baikal (May to June and December to January) and is used as a quantitative measure of the potential intensity of deep ventilation. Specifically, as persistent wind events are required to generate coastal downwelling, for each year \(i\) and downwelling season \(s\), the cumulative Ekman transport \((M_i)\) is calculated across periods when the wind blows from northeast and is interrupted by winds from other directions for less than 1 d, with values then averaged over each year and downwelling season \((\overline{M_i}(i, s))\), where the overbar indicates averaging. Ekman transport anomalies of a given year and downwelling season can then be calculated relative to the mean Ekman transport from 1990 to 2000 CE (SI Appendix):

\[ \text{Anomaly} \overline{M_i}(i, s) = \frac{\overline{M_i}(i, s) - \overline{M_i}(1990 - 2000, s)}{\overline{M_i}(1990 - 2000, s)} \]  

[6]

Statistical analyses. Data normality was checked using a Shapiro–Wilk test with comparisons between datasets then performed using either a Wilcoxon rank sum test or a t-test. The significance level was set at \(p = 0.05\). Data normality was checked using a Shapiro–Wilk test with comparisons between datasets then performed using either a Wilcoxon rank sum test or a t-test. The significance level was set at \(p = 0.05\).

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