Salinity impact on water flow and lake ice in Lake Vostok, Antarctica

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[1] Lake Vostok, isolated from direct exchange with the atmosphere for millions of years, provides a unique, so far inaccessible habitat. By using a numerical model, and recent geometry information, the lake circulation was investigated for different salinites. For freshwater, thermally driven circulation occurs, resulting from pressure-dependent melting point differences at the inclined ice ceiling. North to south ice pumping provides a steady supply of glacial water. The weak circulation is driven by very small density contrasts, but requires no unusual geothermal input. For low salinity conditions, however, circulation intensifies, occupying the entire lake. The maximum amplitudes of melting/freezing increase by about 50% and melting extends further south. For both conditions approximately 200 m of refrozen ice accumulates beneath Vostok Station. The lake habitat will be affected clearly by salinity. It is essential to establish the specific chemistry for comprehending this unique environment and planning in situ experiments. *INDEX TERMS:* 1878 Hydrology: Water/energy interactions; 1863 Hydrology: Snow and ice (1827); 4842 Oceanography: Biological and Chemical: Modeling; 1655 Global Change: Water cycles (1836); 9310 Information Related to Geographic Region: Antarctica. **Citation:** Mayer, C., K. Grosfeld, and M. J. Siegert, Salinity impact on water flow and lake ice in Lake Vostok, Antarctica, *Geophys. Res. Lett.*, *30*(14), 1767, doi:10.1029/2003GL017380, 2003.

1. Introduction

[2] The identification of Lake Vostok as a potential extreme habitat for life [*Karl et al.*, 1999, *Priscu et al.*, 1999] has led to significant interest in the physical properties of this environment. In absence of direct access, knowledge about the lake circulation and its interaction with the ice sheet can only be gained from numerical models.

[3] Recent investigations have proposed distinct zones of subglacial melting and freezing at the ice-water interface [*Mayer and Siegert*, 1999; *Siegert et al.*, 2000]. A 210 m thick layer of refrozen 'lake ice' beneath Vostok Station has been discovered [*Jouzel et al.*, 1999]. *Wüest and Carmack* [2000] described the principal physical environment and potential lake circulation. *Williams* [2001] applied a 3-d ocean circulation model to simulate water flow within the lake. The results show a weak circulation, driven by geothermal heat only, which depends highly on the chosen bathymetry. Here, we adapt this approach and simulate the conditions for different water compositions, using recent measurements of the lake geometry [*Tabacco et al.*, 2002].

[4] The chemistry of the accreted ice [*Siegert et al.*, 2001; *Souchez et al.*, 2000; *Christner et al.*, 2001] has been used to infer the water composition in the lake, which was found to comprise either fresh water or to be slightly saline. The purpose of this paper is to identify the effect that salinity will have on the circulation of water in Lake Vostok.

2. Model Geometry and Physical Conditions

[5] Our model lake has a length of 260 km, a maximum width of 80 km and a surface area of 14000 km^2 (Figure 1). Because of the unknown bathymetry, we use the few available seismic soundings [*Kapitsa et al.*, 1996] and evidence from radio echo sounding profiles [*Gorman and Siegert*, 1999] to construct a wedge-shaped cavity with a maximum water depth of 500 m below Vostok Station, where the ice thickness is 3.8 km. The ice thickness increases towards the north to 4.2 km, whereas the water depth decreases to only 30 m in the northernmost part of the lake. The lake-ceiling gradients are in agreement with hydrostatic equilibrium regarding the ice thickness, with a mean N-S gradient of 1.7^{-3} [*Tabacco et al.*, 2002]. W-E gradients are generally much smaller across the central lake. For modelling purposes a closed lake system is assumed, of water, which in reality might be over-simplified. For the energy exchange through the lake, a geothermal heat flux of 54 mW m^{-2} is assumed [*Siegert et al.*, 2000].

[6] Temperature, and thus density differences are created by melting and refreezing and geothermal heat. For saline conditions, the water density also depends on concentration variations, mainly affected by mass exchange with the ice sheet. For freshwater conditions, the circulation is governed by thermal processes only, and we used the equation of state for freshwater, for temperature and pressure dependent density calculations [*Millero and Poisson*, 1981; *UNESCO*, 1981]. The system basically reacts in dependence of the water temperature relative to the 'temperature of maximum density' T_{md} [*Cadwell*, 1978]. For temperatures cooler than T_{md} the density increases with temperature. For temperatures above T_{md} conditions are convective: cold melt water descends and warmed bottom water rises. Thus, the coldest water will be at pressure-melting point (T_{pmp}) of the ice

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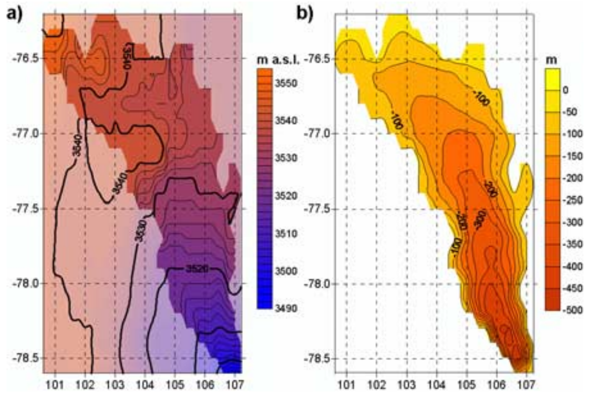

Figure 1. (a) Surface elevation and extent of Lake Vostok derived from airborne radar measurements of the lake edge and ice surface gradient transitions, (b) constructed water depth in the lake relative to the ice sheet base.

base, which for Lake Vostok is higher than T_{md} and a convective regime is expected.

[7] For saline conditions gradients are expected to be small (of the order of 1.2‰, *Souchez et al.* [2000]). Lake stratification depends no longer on temperature only and is expected to be more pronounced. Compared with the freshwater case the gradient of the density-temperature relation is steeper and T_{md} is reduced. T_{pmp} is still greater than T_{md} everywhere, and the system will be convective. Freshwater from melting reduces the salinity and, hence, the density close to the ice. During freezing salt rejection increases the density of the topmost water layer. If strong enough, this process induces convection and thus mixing in the vertical.

3. Numerical Model Setup

[8] Our circulation model has been developed from a well established 3-d Ocean General Circulation Model [*Gerdes*, 1993] and has been used previously to determine circulation beneath ice shelves [*Grosfeld et al.*, 1997] and in Lake Vostok [*Williams*, 2001]. It is adapted to the specific problems induced by inclined upper and/or lower boundaries. The horizontal resolution in this setup is 0.2° (E-W) by 0.1° (N-S). Ten vertical layers are used, with highest resolution at the ice ceiling and towards the lake floor. Sub-grid-scale processes are parameterized using a constant eddy viscosity (ν) and diffusivity (κ). Assuming that the fresh (or near fresh) water is not in a regime controlled by molecular processes, ν and κ are chosen to be equal and thus the turbulent Prandtl number is unity. Accounting for the different scaling properties and grid resolution in the horizontal (h) and vertical (v) the following coefficients are chosen: $\nu_h = \kappa_h = 50\ m^2 s^{-1}$ and $\nu_v = \kappa_v = 5 \cdot 10^{-5} m^2 s^{-1}$.

[9] The model is initialized with a homogenous temperature of -2.6°C and zero velocities, and integrated for 500 years to reach a quasi steady state. This time-span depends on the overturning time scale of the final result, which can be derived from the mean temperature evolution during integration. According to this analysis the 'spinning up' of the model reaches stationarity already after 100–150 years.

[10] We assume that the circulation is forced mainly by differences in heat flux at the ice/lake interface. The lake is expected to be nearly stationary with current speeds of the order of 10^{-4} m s^{-1} [*Wüest and Carmack*, 2000]. Thus a bulk formulation of the turbulent heat exchange coefficient is difficult to derive. We decided to use, as a lower limit, the molecular thermal diffusivity of freshwater ($1.35 \cdot 10^{-7}$ m^2 s^{-1}) for a laminar boundary layer (1 m thick). The velocity dependent bulk transfer coefficient γ^T for a smooth boundary [*Holland and Jenkins*, 1999] is used, if the velocity exceeds the friction velocity of 10^{-5} m s^{-1}.

[11] The heat flux at the ice-lake interface is directed from the lake to the ice base. It divides into a conductive heat flux through the ice column and a latent heat flux from melting/freezing at the ice base. The temperature-depth profile of the ice beneath Vostok Station is nearly linear, at least for the lowermost 2000 m [*Salamatin et al.*, 1998]. Thus, heat conduction through the ice sheet can be calculated from the temperature gradient to be 33 mW m^{-2}, i.e. about 2/3 of the heat available.

4. Results

[12] To investigate thermally driven circulation within the lake, and to evaluate the salinity influence, we have set up two model experiments: The first model run is performed with freshwater. In the second run the salt content is 1.2‰. as suggested by *Souchez et al.* [2000].

4.1. Fresh Water Circulation

[13] Similar to earlier work [*Williams*, 2001] we simulated the lake circulation for freshwater. While *Williams* [2001] derived principle patterns for different bedrock geometries (constant water column thickness and schematized realistic topography), our study is based on what we consider to be the most realistic bathymetry and ice sheet draft.

[14] The vertically integrated mass transport stream function (Figure 2a) shows a barotropic circulation pattern with anticyclonic flow of $\sim 4.5 \cdot 10^3$ m^3 s^{-1} in the northern and southern part of the lake, while a cyclonic gyre arises in the centre. It is caused by a weak, but well established advection with mean horizontal velocities of about $8 \cdot 10^{-2}$ cm s^{-1}. The northwestern, shallow part is occupied by cyclonic, weak transports. The flow direction is very sensitive to the density stratification, which strongly depends on mass exchange at the lakes's ice ceiling. The horizontal turnover time scale (lake volume versus volume flux) is about 20 years. This is far shorter than the time for ice to cross the central lake (i.e. $\sim$34,000 years at 77.5°S). The lake circulation is most probably in equilibrium with respect to ice flow. Our results are generally similar to earlier work [*Williams*, 2001]. Some differences arise due to our more realistic representation of geometry. While the horizontal transport is of similar magnitude, our results indicate almost barotropic flow. There is, in general, no shear within the velocity field, despite local topographic effects. Meridional overturning is of similar magnitude than the horizontal flow, but not uniform and characterized by a gyre-to-gyre exchange pattern. For a convective regime, melt water sinks due to its density. This is obvious in a temperature transect along 106°E (Figure 2c), where in a vertically well mixed lake temperatures increase from north to south. In the north, where the ice is thickest, water of -2.81°C mixes down the entire water column. In the south, the water temperature is only -2.73°C. Horizontal advection is too weak to break

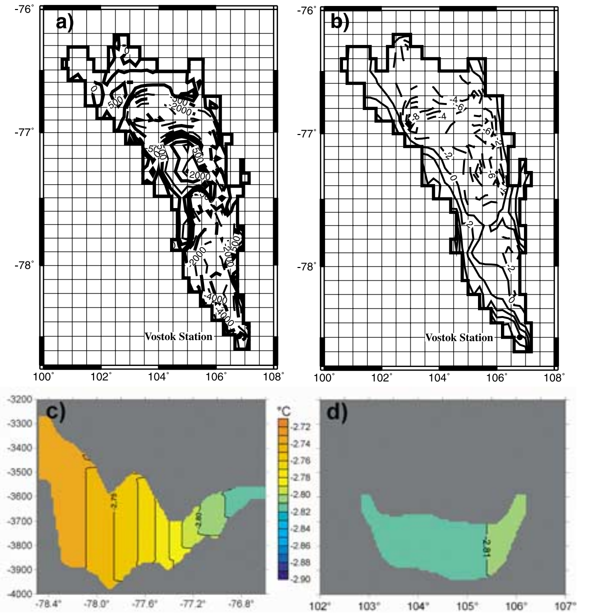

Figure 2. (a) Vertically integrated mass transport stream function (m^3 s^{-1}) for a freshwater lake. (b) Rates of basal melting (negative) and freezing (positive) (cm yr^{-1}). (c) Meridional potential temperature distribution along 106°E. (d) Zonal potential temperature distribution along 77°S. The vertical scale in (c) is about 330-fold, in (d) about 190-fold exaggerated.

this vertically well mixed structure. A zonal transect along 77°S (Figure 2d) shows much smaller gradients.

[15] The meridional temperature distribution generates freeze and melt regions. The water velocity at the lake ceiling indicates a heat exchange coefficient close to its minimum. Melting and freezing in the order of a few centimeters per year occur (Figure 2b). Investigations of internal radar layers and numerical ice-flow modelling indicate melting of the same order along the western lake margin, followed by refreezing [*Mayer and Siegert*, 1999; *Bell et al.*, 2002]. The refreezing area is well established in our results, whereas the narrow marginal melt zone cannot be resolved (Figure 2b). Maximum melt rates reach about 8 cm yr^{-1} in the north, while freezing rates as high as 6.8 cm yr^{-1} in the vicinity of Vostok Station are similar to earlier estimations [*Williams*, 2001; *Bell et al.*, 2002].

4.2. Circulation With Low Salinity Lake Water

[16] In the second experiment an initial salt content of 1.2 ‰ was chosen for the bulk lake water composition. Mass exchange at the ice sheet base will now have an additional impact on the stratification of the water column, because freshwater is injected or extracted from the system. The stream function now (Figure 3a) shows an enhanced anticyclonic gyre involving the whole lake. The maximum transport is nearly doubled ($8.8 \cdot 10^3$ m^3 s^{-1}), leading to a turnover time of only 11 years. Mean horizontal velocities of 0.12 cm s^{-1} are mainly oriented north-south with maximum amplitudes at the margins. The flow is again of barotropic nature. The reason for the changes is an additional freshwater flux, associated with freezing and melting. Besides temperature, freshwater from melting ice influences the stratification and, hence, provides a driving force for the circulation. This is discernible in the corresponding temperature section (Figure 3c). Unlike the vertically homogenous structure for freshwater, the lake is now stratified in the shallower northern part. Temperatures now increase from −2.88°C to −2.78°C across the lake (N-S). Melting ice decreases density and yields to upwelling of water along the ascending ice sheet base. Freezing in the south, associated with the release of heat and salt rejection, increases the density in the upper layers. The induced vertical convection homogenizes the water column. The zonal transect (Figure 3d) demonstrates the stratification effect of basal melting in the northern part of the lake and over its total width.

[17] Melting and freezing patterns (Figure 3b) complete the conditions of the lake system. Greatest melting (12 cm yr^{-1}) occurs along the eastern lake margin, and greatest freezing (up to 10 cm yr^{-1}) is found along the western grounding line. Melting now extends further into the southern part of the lake compared to the first experiment. The model retains the accretion of over 200 m of ice beneath Vostok Station. This suggests that saline conditions are at least possible, under the current knowledge. Clearly, potential life forms in the lake will be dependent on these environmental conditions. We need to resolve the issue of the lake's hydrochemistry in order to determine the final state of circulation conditions. The basal flux balance is negative and of the same order (−0.1 Gt yr^{-1}) for both scenarios. As our model is not coupled with ice dynamic reactions, an interpretation of this balance would be speculative.

5. Conclusions

[18] A 3-d fluid dynamics model is used to define principal characteristics of the water circulation in Lake Vostok, based on temperature and salinity variations. The latest available data have been used to simulate the lake conditions as realistic as possible. A more recently published lake geometry [*Studinger et al.*, 2003], would not

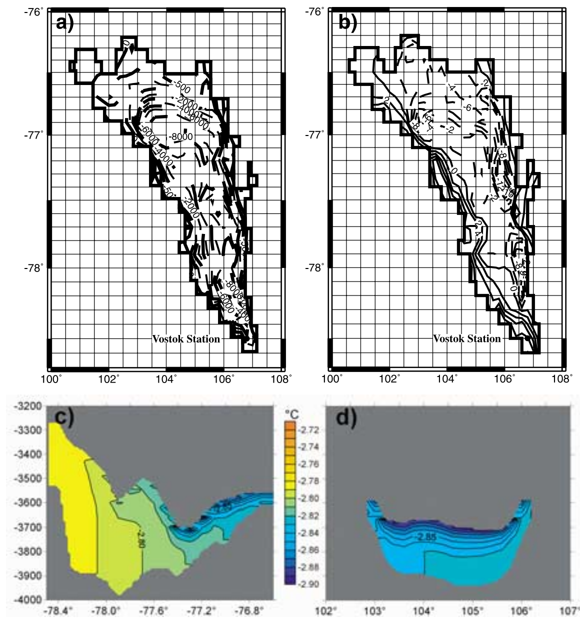

Figure 3. Results for a lake water salinity of 1.2‰. Captions as in Figure 2.

change our basic findings, as the differences in ice thickness only involve minor areas. Hence, we conclude:

[19] 1) For freshwater the circulation is very weak and driven by temperature induced density contrasts. The turnover time scale is around 20 years. The flow within the lake is barotropic, but vertical mass exchange and convection is sufficient to induce mixing over the whole water column. It is unlikely, therefore, to expect vertical gradients in particle concentration or dissolved nutrients. The exchange from north to south is modified by a gyre-to-gyre structure. There is, however, no reason to expect a significantly different geochemical signature of the water between south and north.

[20] 2) The existence of salt (nutrients) in the water reduces the overturning time scale to about 11 years. The circulation regime comprises the whole lake. The gain or loss of freshwater leads to an additional density contrast and, thus, enhanced driving force. The freshwater enables a pronounced vertical gradient in temperature in basal melt regions. There is an obvious north/south difference, which possibly influences the conditions for biogenic material. Most particles mixed into the topmost layer during melting probably remain there and become advected southward, where they can be sealed again during refreezing. Sensitivity studies showed an increase of horizontal circulation and mass exchange with increasing salinity, which cause enhanced stratification and a larger vertical temperature contrast in the lake.

[21] 3) The slope of the lake roof is maintained by a combination of ice flow and basal mass balance. The refrozen basal layer beneath Vostok Station is a result of ice-pumping and equals about 3000 years of accretion if the freezing rate is about 6.8 cm yr^{-1} (i.e. a refrozen basal ice of $\sim$204 m). The values are similar for the saline case (freezing of 8.3 cm yr^{-1} yields basal ice of $\sim$249 m). The required time is large compared with the lake overturning and there are no general differences between both experiments.

[22] 4) Meteoric ice is exposed to the lake water in the northern part only. The predominance of melting suggests the presence of sediment and biogenic material. Further south, debris in the glacier ice is soon sealed by lake ice, after the ice enters the lake from the west. Release of englacial material is therefore likely to be concentrated on the northern and westernmost part of the lake.

[23] 5) The lake regime is very likely to have been convective for almost its entire existence, because the overlying ice thickness needs to be less than 3000 m for enabling the lake to switch to a stable, stratified system. This holds for both freshwater and saline conditions.

[24] These results demonstrate the environmental envelope in which life may exist in Lake Vostok. Regardless of lake salinity, the pattern of melting and freezing seems to be very robust under present day conditions. In the saline case, environmental conditions in the north reveal a more isolated bottom regime than for freshwater, where the water column is much more homogenous and released glacial material is mixed to the bottom. The southern part of the lake seems to be similar in both experiments. Despite a homogenous vertical temperature distribution, weak density gradients from freshwater injection can lead, in the saline case, to a concentration of geochemical constituents in the upper boundary layer, while the main water column remains more pristine. For the deployment of instruments in the lake such a local difference of the environment should be taken into account. The environment and thus potential life within the lake will be very different compared with a fresh water situation. For the future it is imperative to derive more evidence about the true hydrochemistry of Lake Vostok.

[25] **Acknowledgments.** The contribution of M.J.S. was gratefully supported by the NERC grant NER/A/S/2000/01144.

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