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Observational evidence on the stability of the hydro-glaciological regime of subglacial Lake Vostok

A. Richter,[1] S. V. Popov,[2] R. Dietrich,[1] V. V. Lukin,[3] M. Fritsche,[1] V. Y. Lipenkov,[3] A. Y. Matveev,[4] J. Wendt,[5] A. V. Yuskevich,[4] and V. N. Masolov[2]

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[1] Combined geodetic, geophysical and glaciological in situ measurements are interpreted regarding surface height changes over subglacial Lake Vostok and the local mass balance of the ice sheet at Vostok station. Repeated GPS observations spanning 5 years and long-term surface accumulation data show that the height of the lake surface has not changed over the observation period. The application of the mass conservation equation to purely observational data yields an ice mass balance for Vostok station close to equilibrium. **Citation:** Richter, A., S. V. Popov, R. Dietrich, V. V. Lukin, M. Fritsche, V. Y. Lipenkov, A. Y. Matveev, J. Wendt, A. V. Yuskevich, and V. N. Masolov (2008), Observational evidence on the stability of the hydro-glaciological regime of subglacial Lake Vostok, *Geophys. Res. Lett.*, *35*, L11502, doi:10.1029/2008GL033397.

1. Introduction

[2] Subglacial lakes are a main focus of current research in Antarctica [*Masolov et al.*, 1999; *Kennicutt*, 2005; *Siegert et al.*, 2006; *Masolov et al.*, 2006]. For some subglacial lakes, surface height changes have been observed which have been related to subglacial water discharges [*Wingham et al.*, 2006; *Fricker et al.*, 2007]. Regarding the largest subglacial lake on earth, Lake Vostok in central East Antarctica (Figure 1a), these recent insights raise the question, whether it is stationary at present or experiences water volume changes, too, as some models suggest [*Erlingsson*, 2006].

[3] Precise *in situ* determinations of the ice mass balance in central East Antarctica are not only of great interest in general [*Rémy and Parrenin*, 2004]. For subglacial lakes, in particular, the growth or thinning of the ice sheet has to be considered when concluding on subglacial water volume changes from height changes of the ice surface. Moreover, the specific conditions that apply to floating ice turn extended subglacial lakes into unique study objects for local mass balance determinations.

[4] With the present study we extend our understanding based on own previous investigations on Lake Vostok [*Wendt et al.*, 2005; *Masolov et al.*, 2006; *Wendt et al.*, 2006; *Roemer et al.*, 2007]. Here we present new results obtained from joint geodetic-geophysical field measurements in the area of Vostok station taken in January 2007. In combination with glaciological data, height changes of the ice surface above Lake Vostok as well as the local ice mass balance at Vostok station are inferred.

2. Observations

2.1. GPS

[5] In the Antarctic field season 2001/2002, a number of GPS markers were installed in the vicinity of Vostok station and on the southern part of subglacial Lake Vostok [*Wendt et al.*, 2006]. These sites included a marker at Vostok station (VS) and six markers arranged in a concentric hexagon around the station 2.5 km in diameter (D1–D6, Figure 1b). Geodetic GPS observations were carried out on these markers during this and the subsequent field season.

[6] In the season 2006/2007, the markers VS and D1–D6 were reoccupied with GPS with observation periods ranging from 40 hours to 10 days. The observation data obtained at these seven sites in all three seasons were processed with Bernese GPS software 5.0 [*Dach et al.*, 2007]. Using five permanent GPS stations in Antarctica as a reference, 3D coordinates and site velocities were estimated for each marker with respect to the IGb00 [*Ray et al.*, 2004] reference frame. The horizontal velocity components were reduced by the rotation of the Antarctic tectonic plate around an Euler pole situated at 63.0°S, 234.7°E [*Dietrich et al.*, 2004]. Thus, the flow vector components given in Table 1 are relative to the fixed Antarctic plate and hence relative to bedrock. In agreement with modeling results [*Ivins and James*, 2005] we assume that vertical bedrock motion due to glacial isostasy in the region of Lake Vostok is negligible. Hence, the vertical rates obtained from GPS for Vostok station can be assumed to describe vertical motions of the ice sheet relative to bedrock as well. An estimate of the accuracy of the obtained velocity components was inferred from the scatter of daily solutions w.r.t. the fit of a linear trend. A more detailed description of the analysis approach and the error estimation is given by *Wendt et al.* [2006]. For the seven markers, ellipsoidal coordinates, the velocity components and their accuracies are given in Table 1. Figure 2 shows the height changes observed on the VS marker over time.

[7] A strain analysis was performed in order to derive the deformation status of the internal geometry of the hexagon (Figure 1b). For this purpose, the horizontal velocities of the seven markers were introduced into a common adjustment algorithm yielding the strain parameters and the orientation of the principal strain axes (for methodological details see [*Wendt et al.*, 2006]). We obtained a maximum extension of

[1]Institut für Planetare Geodäsie, Technische Universität Dresden, Dresden, Germany.
[2]Polar Marine Geosurvey Expedition, St. Petersburg, Russia.
[3]Arctic and Antarctic Research Institute, St. Petersburg, Russia.
[4]Aerogeodeziya, St. Petersburg, Russia.
[5]Centro de Estudios Científicos, Valdivia, Chile.

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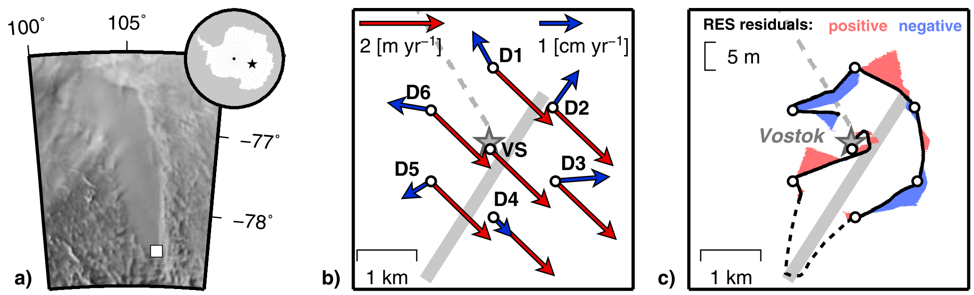

Figure 1. (a) Radarsat image [*Jezek et al.*, 2001] of the Lake Vostok region (Antarctica). The area under investigation is depicted by the white square. (b) Network configuration (circles) and results from repeated GPS observations. Red vectors show magnitude and direction of flow velocity (scale in upper left corner). Blue vectors denote residual velocity components after subtracting the VS vector and reflect the internal surface deformation (scale in upper right corner). The star marks the location of Vostok station, the grey lines depict the air strip (solid) and the convoy track to Mirny (dashed). (c) Track of radio echo sounding profile. The dashed segment was not used for the ice thickness plane fitting. Deviations of the measured ice thickness from the fitted plane are given along the profile (scale in upper left corner).

$8.07 \pm 0.42\ 10^{-6}\ yr^{-1}$ along an azimuth of 109°. An extension of $5.07 \pm 0.51\ 10^{-6}\ yr^{-1}$ appears also perpendicular to this direction.

2.2. Radio Echo Sounding

[8] During the field season 2006/2007, a radio echo sounding (RES) profile was recorded around the hexagon formed by the GPS markers. The ground-based radar equipment described by *Popov et al.* [2003] was operated on a sledge drawn by a tractor. The average along-track resolution of the profile amounts to 12 m. The track of the profile is depicted in Figure 1c. It does not follow exactly the outline of the regular polygon, because the air strip and the sector between D5 and D6 (reserved as clean area for glaciological sampling) could not be crossed by the heavy vehicle.

[9] From the recorded radio echo time sections, the ice thickness along the profile was extracted. Regarding the accuracy of an individual ice thickness value, two sources of uncertainty have to be considered: first, a systematic bias, which originates essentially from the uncertainty of the radio wave propagation velocity in ice, and second, the random measurement error, which is mainly determined by the resolution of the signal digitization. A relative error in the wave propagation velocity of 0.3% [*Popov et al.*, 2003] corresponds to a systematic error of 11.2 m considering the ice thicknesses at Vostok. The signal digitization resolution of approximately 4 m affects both the upper and the basal interfaces of the ice layer, hence the random error is estimated to be $4\ m\ \sqrt{2} = 5.7$ m.

[10] In order to determine the ice thickness and its gradient at VS site, a plane was fitted to 795 measurement values along the profile. The corresponding RMS of the residuals is 2.8 m which shows that the 5.7 m random error assessment discussed above is rather conservative. For the accuracy of the absolute ice thickness obtained from the adjustment for the VS location, the systematic effect is crucial since the number of measurements reduces only the random part of the error budget. Our resulting ice thickness

Table 1. Longitude λ, Latitude ϕ, Velocities v_{hor} and Azimuths a of Horizontal Ice Flow Relative to Bedrock, and Vertical Velocities v_{vert} for Seven Markers Around Vostok Station as Determined from GPS[a]

Site	λ 106°E, arcmin	ϕ 78°S, arcmin	v_{hor}, mm yr^{-1}	a, deg	v_{vert}, mm yr^{-1}
VS	49.951	27.959	1996 ± 1	133.67 ± 0.02	−59 ± 2
D1	50.084	27.219	1987 ± 2	133.59 ± 0.05	−59 ± 5
D2	52.775	27.583	1995 ± 2	133.36 ± 0.05	−59 ± 5
D3	52.892	28.245	2005 ± 2	133.40 ± 0.05	−65 ± 5
D4	50.111	28.568	2003 ± 2	133.68 ± 0.05	−62 ± 5
D5	47.287	28.249	1994 ± 2	133.89 ± 0.05	−61 ± 5
D6	47.287	27.603	1988 ± 2	133.84 ± 0.05	−68 ± 5

[a]IGb00 reference frame, epoch 2000.0.

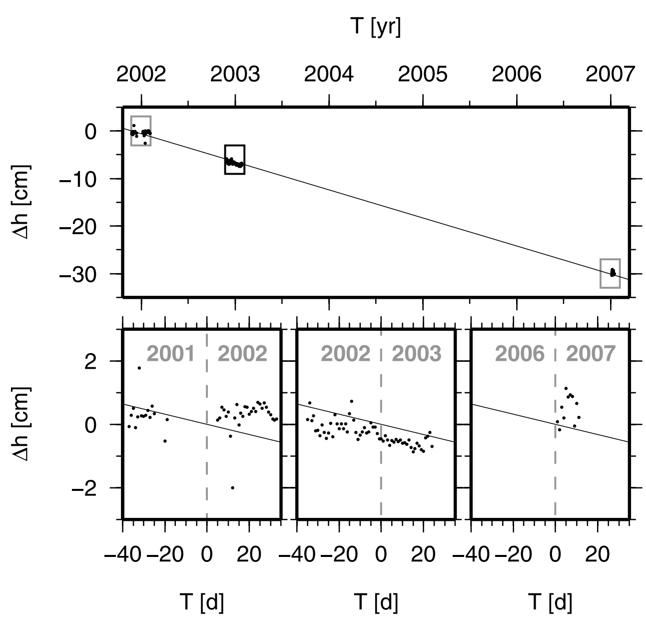

Figure 2. (top) Height change time series of the VS marker as observed by GPS during three epochs. Dots depict daily height values relative to the height obtained for the first day of observation. The solid line represents the derived linear trend. (bottom) The zoom diagrams (domain marked as boxes in top diagram) show in detail the daily height solutions (dots) w.r.t. the linear trend (solid line) for January 1st of the respective year.

Table 2. Numbers Introduced Into the Mass Conservation Equation

Quantity	Value ± Error	Unit	Origin
u	1379 ± 1	mm yr^{-1}	GPS (site VS)
v	1444 ± 1	mm yr^{-1}	GPS (site VS)
du/dx	5.40 ± 0.51	10^{-6} yr^{-1}	GPS, strain adjustment
dv/dy	7.74 ± 0.37	10^{-6} yr^{-1}	GPS, strain adjustment
Z	3770 ± 11	m	RES (plane fit, VS)
dZ/dx	−9.87 ± 0.09	10^{-3}	RES (plane fit)
dZ/dy	−1.77 ± 0.10	10^{-3}	RES (plane fit)
ρ	915.6 ± 1.0	kg m^{-3}	*Lipenkov et al.* [1997]
b_s	20.6 ± 0.3	mm yr^{-1} w.e.[a]	*Ekaykin et al.* [2004]
b_b	3.9 ± 0.6	mm yr^{-1} w.e.	*Wendt et al.* [2006]

[a]w.e. means water equivalent.

at VS of 3770 ± 11 m confirms the earlier results of 3775 ± 15 m (*Popov et al.* [2003], based on RES) and 3750 ± 30 m (*Popkov et al.* [1998], determined by vertical seismic profiling) for the 5G-1 ice-core site (less than 100 m from VS) within the error limits. The obtained ice thickness gradient indicates a thinning of the ice sheet towards the SSE of approximately 10 m km^{-1}. It is not affected by the systematic part in the error budget; and the error estimates (Table 2) resulting from the fit of a plane comprise the effects of both measurement noise and deviations of the actual ice thickness variations from that model plane. However, the obtained RMS value for a single measurement of 1.95 m calculated from the residuals confirms both the order of magnitude of the random part of the error budget and the validity of the simple plane approximation for the ice thickness gradients (Figure 1c).

2.3. Glaciological Data

[11] Our measurements are complemented by glaciological information on surface accumulation, basal accretion, and the vertical density profile. Based on the analysis of six boreholes and three deep pits around Vostok station, an estimate for the long-term mean surface accumulation rate for the period 1816–2004 of 20.6 ± 0.3 mm yr^{-1} w.e. (water equivalent) was found by *Ekaykin et al.* [2004]. Instrumental measurements at Vostok station during the period 1970–1995 yielded a mean surface accumulation rate of 22.9 ± 1.8 mm yr^{-1} w.e. [*Ekaykin et al.*, 2004]. The snow accumulation is characterized by large interannual fluctuations. Short-term accumulation measurements vary also significantly in space, partly as a result of snow dune drift. In order to reduce the impact of accumulation variations in space and time, we use the more precise accumulation rate valid for an almost 200 year period.

[12] According to the snow pit studies presented by *Ekaykin et al.* [2003] and including recent measurements up to 2007, the average snow density of the upper 20 cm at Vostok amounts to 0.33 g cm^{-3}. From measurements on the ice core retrieved at Vostok station, a vertical ice density profile down to a depth of 2540 m was obtained [*Lipenkov et al.*, 1997]. Based on this, the mean value of the 11 deepest density values (depth 2000–2540 m) of 0.923 g cm^{-3} is adopted here as an estimate for the ice density at the base. The assumption that this value is representative also for the depths 2540–3770 m results in a mean ice density along the vertical profile of the ice sheet at Vostok station of 0.916 g cm^{-3} with an estimated error of 0.01 g cm^{-3}.

[13] The rate of basal ice accretion along the flowline crossing Vostok station was estimated based on the detection and observation of the thickness of the accreted ice layer by airborne RES and the ice flow velocity determined by GPS [*Bell et al.*, 2002]. *Wendt et al.* [2006] recalculated the accretion rate for the flowline segment 26 km upstream from Vostok station using significantly improved values for the ice flow velocity, which also account for the acceleration across the lake. Flow velocity and distance were inverted into the travel time of the ice sheet along the flowline segment with a relative error of 10% [*Wendt et al.*, 2006]. Assuming a 10% relative error also for the thickness determination of the accreted ice layer in the work by *Bell et al.* [2002], we obtain an average accretion rate of 4.2 ± 0.6 mm yr^{-1} for this flowline segment. It is interesting to note that modeling results [*Tsyganova and Salamatin*, 2004] yielded an accretion rate of 5 mm yr^{-1} which is in good agreement with the result based on observations.

3. Results

3.1. Lake Surface Height Changes From GPS and Accumulation Data

[14] The height changes observed for the GPS markers (Table 1) reflect the vertical motion of the snow layer to which the markers are attached. These height changes are a combined effect of snow compaction, changes in ice thickness, changes in the lake's water volume, and the downslope flow (in this case negligible).

[15] The mean rate of height change for the seven markers amounts to −62.1 mm yr^{-1}. The error estimates for the height change rates given in Table 1 are derived from the scatter of the daily height solutions w.r.t. the linear trend. The average of the height rate errors for the seven markers amounts to ±4.7 mm yr^{-1}. An additional amount of ±1.2 mm yr^{-1} is considered here to account for the long-term reference frame stability [*Ray et al.*, 2004]. Thus the total RMS value of the determined mean height rate is estimated to be ±4.9 mm yr^{-1}.

[16] The small offset of all daily height values of a certain campaign w.r.t. the linear trend as visible in Figure 2 (bottom diagrams) suggests only slight deviations of the compaction signal from a strictly linear behavior over time. On the other hand, the standard deviation of the observed height change rates of the seven markers amounts to only 3.5 mm yr^{-1} compared to the mean value of the height change rate errors in Table 1 of ±4.7 mm yr^{-1}. Thus, we can conclude a rather homogeneous compaction signal at these sites.

[17] The continuing accumulation makes the snow surface raise relative to the GPS markers. We use a long-term mean accumulation rate for a comparison with the height change rates observed over five years. According to the 200-year mean accumulation rate and the snow density at the surface given in the previous paragraph, the surface height growth around the markers amounts to 62.4 ± 0.9 mm yr^{-1}. Comparing this value with the GPS derived height change rate of −62.1 ± 4.9 mm yr^{-1}, we obtain the height change rate of the snow surface of 0.3 ± 4.9 mm yr^{-1}. Thus, over the time spanned by the GPS observations, no

significant change in the surface height is detected. This result is based on data from Vostok station area only. However, it has to be emphasized that it contains valuable information about the entire lake area. Due to hydrostatic equilibrium, any change in the lake water volume (outflow or inflow) would cause a signal at this position. Also mass changes of the ice sheet above the lake (e.g., non-uniform accumulation) would contribute to the vertical signal at Vostok station due to hydrostatic adjustment.

3.2. Local Ice Mass Balance at Vostok Station

[18] For a compartment of a floating ice sheet, the mass conservation equation [*Paterson*, 1994] holds:

$$b_s + b_b - \rho \frac{dZ}{dt} = \rho \left[Z \left(\frac{du}{dx} + \frac{dv}{dy} \right) + u \frac{dZ}{dx} + v \frac{dZ}{dy} \right]. \qquad (1)$$

[19] The right hand side of this equation contains the horizontal deformation expressed by the strain components du/dx, dv/dy in the horizontal coordinate directions x (S), y (E), multiplied by the ice thickness Z, with the gradient of the ice thickness dZ/dx, dZ/dy, multiplied by the flow velocities u and v in x- and y-direction, respectively. This right hand side term, multiplied by the mean density ρ, equals the sum of the change of ice thickness over time dZ/dt multiplied by the mean density, the net accumulation rate b_s at the ice surface and the net melting/accretion rate b_b at the ice base.

[20] We apply this equation to the ice sheet compartment bounded by the hexagon of GPS markers for the determination of the local ice mass balance state dZ/dt at Vostok station introducing exclusively observational data. While the horizontal ice flow velocities and strain components result from the GPS observations, the ice thickness and its gradient originate from the RES profile. For ρ, the mean density inferred from the data of *Lipenkov et al.* [1997] is adapted and b_s is taken from *Ekaykin et al.* [2004] (see section 2.3). For b_b, we use the value presented by *Wendt et al.* [2006], scaled by the basal ice density given above. The values introduced in equation (1), their errors and origin are summarized in Table 2.

[21] Solving equation (1) for dZ/dt, we obtain a change in ice thickness of -6.6 ± 2.5 mm yr^{-1}. The largest contribution to the stated error emanates from the uncertainties of the strain values. However, these are dominated by the nonfulfillment of the assumption of a homogeneous strain rather than by measurement errors. If the surface accumulation rate determined from observations over about 25 years is applied instead of the value valid over 200 years, the ice thickness change rate decreases and becomes -4.1 ± 3.2 mm yr^{-1}. In contrast to the height change rate obtained in the previous paragraph, this result is valid only locally for the Vostok station area.

4. Conclusions

[22] The results of repeated in situ observations indicate that the subglacial Lake Vostok system as reflected by the surface height has been very close to equilibrium over the past five years. We have shown that the ice sheet beneath Vostok station has been close to steady state, too. The obtained thinning rate of 6.6 mm yr^{-1} does not exceed the 3-sigma range of its error. At present, the accuracies of our results are not achievable by alternative methods including satellite altimeter data (both radar and laser [see, e.g., *Roemer et al.*, 2007]). The presented work will be continued as a contribution to the International Polar Year 2007/2008 project *SALE United* [*Kennicutt*, 2005].

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R. Dietrich, M. Fritsche, and A. Richter, Institut für Planetare Geodäsie, Technische Universität Dresden, D-01062 Dresden, Germany. (richter@ipg.geo.tu-dresden.de)

V. Y. Lipenkov and V. V. Lukin, Arctic and Antarctic Research Institute, St. Petersburg 199397, Russia.

V. N. Masolov and S. V. Popov, Polar Marine Geosurvey Expedition, St. Petersburg 188512, Russia.

A. Y. Matveev and A. V. Yuskevich, Aerogeodeziya, St. Petersburg 188512, Russia.

J. Wendt, Centro de Estudios Científicos, Av. Arturo Prat 514, Valdivia, Chile.