Modelling accreted ice in subglacial Lake Vostok, Antarctica

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The distribution and thickness of accreted ice at the ice–lake interface of subglacial Lake Vostok, East Antarctica, is calculated conflating various sources: (1) The modelled basal mass balance at the ice–lake interface based on two different bathymetry models, (2) different ice flow trajectories obtained from satellite interferometry and ice penetrating radar measurements, and (3) reasonable ice flow velocity. Our results show that the accreted ice distribution is highly sensitive to the ice draft and to the used flow line directions. The volume and thickness of the accreted ice depends significantly on the ice flow velocity. According to our modelling, we estimate the accreted ice area, volume and mean thickness to be $10\,800 \pm 500\,\mathrm{km}^2$, $980 \pm 200\,\mathrm{km}^3$, and $90 \pm 45\,\mathrm{m}$, respectively, for an ice flow velocity of 3.6 m/a. Only about $36 \pm 2\%$ of Lake Vostok's surface is in contact with meteoric ice, melted by about $2.65 \pm 0.10\,\mathrm{cm/a}$. This has impacts on the sedimentation rate and the supply of nutrients, oxygen, and/or other components only present in meteoric ice but not in accreted lake ice. We estimate the residence time of the lake water at about $32\,000 \pm 4000$ years.

1. Introduction

Lake Vostok, in the heart of Antarctica, is covered by about 4000 m of ice and was first discovered by radio echo sounding in the 1970s [*Oswald and Robin*, 1973; *Robin et al.*, 1977] and later confirmed by satellite altimetry [*Ridley et al.*, 1993] and seismic sounding [*Kapitsa et al.*, 1996]. From isostatic considerations it follows, that the slight surface inclination will be ten times enhanced at the ice–lake interface [e.g., *Siegert*, 2005b]. A detailed map of the ice thickness is available from ice penetrating radar measurements [*Studinger et al.*, 2003], but at the lake's edges steeper gradients increase the uncertainty of the reflection signal interpretation. The lake's water column thickness cannot be measured with radar. Nevertheless, different bathymetric models have been constructed in the past by the interpretation of airborne gravimetric data constrained with seismic data [*Studinger et al.*, 2004; *Roy et al.*, 2005; *Filina et al.*, 2008]. Other, simpler models, have been used for numerical flow modelling purposes only [e.g., *Williams*, 2001; *Mayer et al.*, 2003].

At the ice–lake interface melting and freezing occurs. The basal (im-)balance is mainly determined by the ratio between the energy gain from geothermal heat flux and the energy loss due to heat flux into the ice sheet [*Filina et al.*, 2008; *Thoma et al.*, 2008]. In general, the geothermal heat flux dominates and results in an average lake volume gain of about $1.6\,\mathrm{m}^3/\mathrm{s}$. However, the distribution of melting and freezing areas is mainly determined by the slope of the overlying ice sheet: The freezing point is pressure- (depth-) dependend, hence, melting dominates where the ice sheet dips deeper into the lake, while in shallower areas freezing occurs.

Internal radar reflectors in the lower part of the ice sheet close to Vostok Station were interpreted as the transition between higher concentrations of mineral inclusions in the meteoric ice and low concentration levels in the accreted ice [*Bell et al.*, 2002]. Tracking of internal layers and the reflection from the ice–lake interface allows the quantification of ice accretion along flow trajectories and the spatial distribution of accreted ice [*Siegert et al.*, 2000].

The ice flow direction and velocity across Lake Vostok can be estimated from satellite interferometry, ice–penetrating radar measurements, GPS data, feature tracking, or by numerical models [e.g., *Kapitsa et al.*, 1996; *Kwok et al.*, 2000; *Bell et al.*, 2002; *Tikku et al.*, 2004; *Pattyn et al.*, 2004]. In general, the ice flow across Lake Vostok is orthogonal to its (north–south orientated) axis with a southward deflection, but has changed during the past [*Bell et al.*, 2002; *Siegert*, 2005a].

In this study we calculate the distribution and thickness of the accreted ice at the bottom of the ice sheet above Lake Vostok for different boundary conditions. Therefore we calculate the basal mass balance with a numerical flow model for two different lake bathymetries and join the results with various ice flows.

2. Theoretical model and setup

We use the 3D-numerical flow model Rombax, already applied for subglacial studies by [*Thoma et al.*, 2007, 2008; *Filina et al.*, 2008] to calculate the basal mass balance at Lake Vostok's ice–lake interface. Two different bathymetric models (both based on the same airborne gravity dataset [*Studinger et al.*, 2003]) as geometric boundary conditions are considered: The bathymetry model of *Studinger et al.* [2004], already used in previous studies, and the more recent bathymetry model presented in *Filina et al.* [2008]. The impact of the updated water column thickness (but not the ice draft) on the water circulation within the lake and the mass balance at the ice–lake interface is described in *Filina et al.* [2008]. Here we also apply an updated, non-smoothed version of the ice thickness and the revised lake boundary used by *Filina et al.* [2008] to construct the improved bathymetry model.

Two different ice flow directions are considered: The satellite interferometry–based flow after *Kwok et al.* [2000], featuring an ice flow mainly crossing the lake from west to east, and the ice flow based on feature tracking after *Tikku et al.* [2004] with flowlines deflecting southwards while they cross the lake. The latter ice flow is also consistent with GPS data and ice penetrating radar measurements [*Bell et al.*, 2002]. Referencing to *Siegert and Ridley* [1998], the ice flow directions in these studies are consistent with the assumption that it is solely controlled by the flow of the surrounding

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grounded ice [west-eastward, *Kwok et al.*, 2000] or a modification of this surrounding flow by the lake tilt [southward deflecting, *Tikku et al.*, 2004], which is more consistent with numerical models [*Pattyn et al.*, 2004].

The ice velocity at Lake Vostok station fluctuates according to the respective studies between about 1.9 and 4.2 m/a [e.g., *Kwok et al.*, 2000; *Bell et al.*, 2002; *Tikku et al.*, 2004; *Wendt*, 2005], and the flow velocity does vary to a minor extent over the lake. However, for simplicity we apply constant values of 2 m/a and 4 m/a for the ice flow velocity to model the accreted ice. Integrating the modelled basal mass balance along flow lines allows us to calculate the distribution and thickness of accreted ice.

3. Results

3.1. Melting and Freezing

For convenience we will refer to the bathymetry models of *Studinger et al.* [2004] and *Filina et al.* [2008] as $\mathcal{B}_S$ and $\mathcal{B}_F$, respectively. Two aspects of these different bathymetry models are relevant when the circulation and basal mass balance are modelled: First, the improved water column thickness of $\mathcal{B}_F$ features a shallower northern basin, while the southern basin indicates a slightly deeper southward extending depression (Figure 1a). In the southern basin, the sedimentary layer surface, which defines the lake's bottom, has a steeper slope than the bedrock in $\mathcal{B}_S$. In *Filina et al.* [2008] the impacts of the updated water column thickness (hereafter referred to as *bathymetry effect*) on the modelling results are described. Second, the unfiltered ice thickness used by *Filina et al.* [2008] during the gravimetric data inversion results (in general) in a steeper slope at the lake's edges of $\mathcal{B}_F$. Figure 1b shows the difference in ice draft between $\mathcal{B}_S$ and $\mathcal{B}_F$. As the pressure–dependent freezing point is depth–dependent, this *draft effect* has a huge impact on the modelled basal mass balance as shown in Figure 1c–d. In Table 1 important aspects of the two bathymetry models $\mathcal{B}_S$ and $\mathcal{B}_F$ are compiled. Despite the larger area, the volume of $\mathcal{B}_F$ is reduced, mainly due to the much shallower northern basin. The basal ice loss, which is mainly controlled by the differences in geothermal heating, heat flux into the ice, and the lake's area [*Thoma et al.*, 2008], as well as the freezing area show only negligible differences. However, the mean melting and freezing rates are extremely sensitive to the ice draft. The *bathymetry effect* reduces these rates [*Filina et al.*, 2008], but this is overcompensated by the *draft effect*, resulting in a massive increase in the mean melting and freezing rates of $\mathcal{B}_F$. The magnitude of the *bathymetry effect* is about 10% of the *draft effect* for these specific model geometries. Besides the increased freezing at the lake's edges, a retreat of the southern freezing area is modelled (Figure 1d), which is also caused by the *draft effect* [compare *Filina et al.*, 2008].

3.2. Accreted ice

Figure2 shows the distribution (area) and thickness of accreted ice for different ice flow directions and both bathymetry models applied in this study. Table 2 summarises important parameters of the results. The southward ice flow deflection is clearly mirrored in the spatial accreted ice distributions of both bathymetry models $\mathcal{B}_S$ and $\mathcal{B}_F$, even if this deflection results only in an area decrease of about 2% compared to the eastward ice flow. With respect to the ice volume, the impact of the ice flow direction depends strongly on the bathymetry model used: While the accreted ice volume increase of $\mathcal{B}_S$ is about 33%, it is only about 2% for $\mathcal{B}_F$. Doubling the ice flow velocity from 2 to 4 m/a results only in a minor area decrease of 3% to 7% whereas the volume decreases by about 50%. The largest impact on the accreted ice results from the *draft effect* in the $\mathcal{B}_F$ model. The accreted ice area increases by about 65% and the ice volume increases by about 110% for the strait eastward ice flow, or even 209% for the southward deflecting ice flow. Consequently, the mean accreted ice thickness (ranging from 45 m to 159 m) as well as its thickness at Vostok Station (ranging from 188 m to 1728 m) are highly sensitive to the investigated parameters.

Table 1. Model parameters for the two bathymetry models $\mathcal{B}_S$ and $\mathcal{B}_F$.

		Bathymetry model		
		$\mathcal{B}_S$	$\mathcal{B}_F$	
Area	(km^2)	15620	16820	+7.6%
Volume	(km^3)	5456	5061	−7.2%
Basal ice loss	(km^3/a)	0.055	0.058	+5.2%
Freezing area	(km^2)	4413	4389	−0.1%
Average melt rate	(cm/a)	1.2	2.2	+83.3%
Average freeze rate	(cm/a)	1.7	2.8	+64.7%

4. Discussion and Conclusion

Williams [2001] and *Thoma et al.* [2007] already noted that an exact knowledge of the water column thickness and ice draft are crucial to model the flow regime and the basal mass balance of subglacial lakes. This study adds to this knowledge that the distribution and volume of the accreted ice is also highly dependent on the ice draft. By comparing the accreted ice distribution presented in *Tikku et al.* [2004] with our model results, we can estimate the reliability of our model results. The observed area of accreted ice in the eastern corner of the northern basin is reproduced by all models, but the distribution in the southern basin varies significantly. Our conclusion from the spatial distribution of accreted ice is that the more recent bathymetry model $\mathcal{B}_F$ by *Filina et al.* [2008], which includes a non-interpolated ice thickness, yields better results than the previous model $\mathcal{B}_S$ by *Studinger et al.* [2004], which is not able to reproduce a mostly accreted ice–covered southern basin. Furthermore, southward deflecting flow lines, derived from ice–penetrating radar feature tracking [*Tikku et al.*, 2004], give results closer to the observed accreted ice distribution compared to the east-westward orientated flow lines based on satellite interferometry images [*Kwok et al.*, 2000]. With the estimated thickness of 210 m accreted ice from the Vostok Ice Core [*Jouzel et al.*, 1999; *Siegert et al.*, 2001] as objective at the location of Vostok Station the model can be tuned by adjusting the ice flow velocity: For the bathymetry model $\mathcal{B}_F$ and the southward deflecting flow lines, an ice flow velocity of 3.6 m/a fits best. This value corresponds well with former estimated observations and results in an accreted ice area (volume, mean thickness) of 10833 km^2 (982 km^3, 91 m). For this model only about 36% of the lake's surface is in contact with meteoric ice, which is melted by about 2.65 cm/a. The lake's water residence time can be estimated by dividing the lake's volume through the meteoric ice area and the corresponding average melt rate which results in about 32 000±40000 years. Earlier estimates of this value range from significantly longer (e.g., *Kapitsa et al.* [1996], 125 000 yr and *Mayer and Siegert* [2000], 112 500 yr) to much shorter (e.g., *Jean-Baptiste et al.* [2001], 4 500 yr and *Bell et al.* [2002], 13 300 yr) periods. In any case, all these values are short compared to the Antarctic Ice Sheet's age of several million years [e.g., *Siegert*, 2000; *DeConto and Pollard*, 2003]. Hence, the lake's water will be replaced several times since its evolution. For future studies aiming to estimate the sedimentation rate, the supply of nutrients, oxygen, and/or

Table 2. Area, volume and mean accreted ice thickness for different model setups. The modelled accreted ice thickness at Vostok Station (VS-ait) and the mean melt rate in meteoric ice areas are also indicated.

		Bathymetry model of									
		$\mathcal{B}_S$ [*Studinger et al.*, 2004]					$\mathcal{B}_F$ [*Filina et al.*, 2008]				
Flow lines	Velocity	Area (km^2)	Volume (km^3)	Mean (m)	VS-ait (m)	Melt (cm/a)	Area (km^2)	Volume (km^3)	Mean (m)	VS-ait (m)	Melt (cm/a)
Eastward	2 m/a	6978	865	124	1056	1.25	11429	1816	159	1728	2.00
	4 m/a	6569	429	65	528	1.24	10902	902	83	864	1.98
Southward deflecting	2 m/a	6865	577	84	632	1.36	11145	1776	159	376	2.70
	4 m/a	6407	285	45	316	1.33	10768	882	82	188	2.69

other components, only present in meteoric ice but not in accreted ice, we propose to take this small meteoric interface area (36%) into account.

The presented technique can be easily applied to other subglacial lakes as soon as reliable information about bathymetry and ice flow trajectories becomes available. Good future candidates are e.g., Lake Concordia[*Tikku et al.*, 2005; *Filina et al.*, 2006] and Lake Ellsworth [*Siegert et al.*, 2004, 2007].

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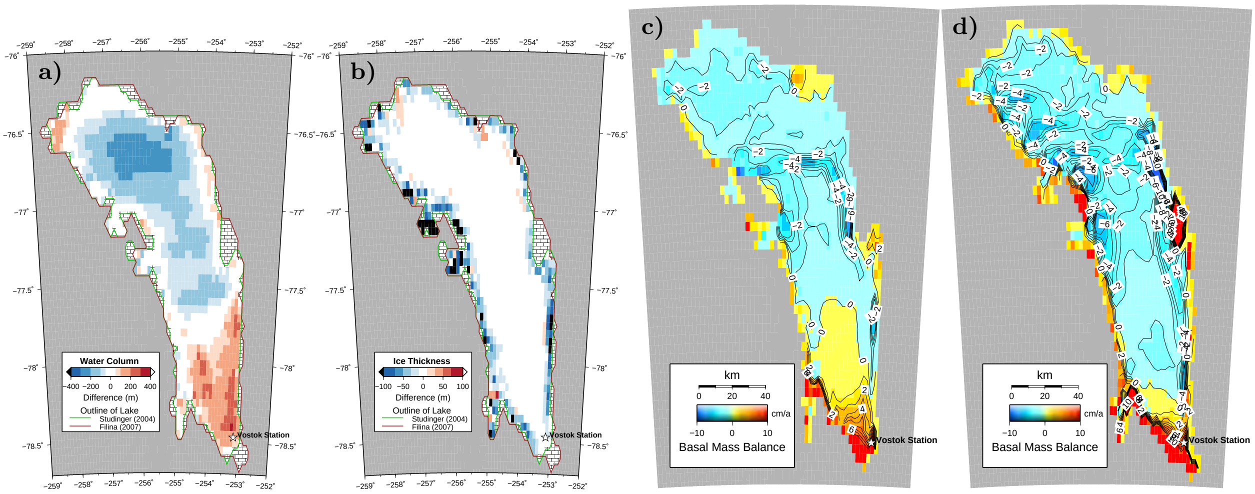

Figure 1. Differences in water column (a) and ice thickness (b) between the models of $\mathcal{B}_S$ and $\mathcal{B}_F$ [*Studinger et al.*, 2004; *Filina et al.*, 2008]. Patterned areas indicate regions where the lake's grounding lines differ.
Modelled basal mass balance at the ice–lake interface for the bathymetry models of *Studinger et al.* [2004] (c) and *Filina et al.* [2008] (d). Negative values (*blue/green*) indicate melting, positive (*yellow/red*) values freezing.

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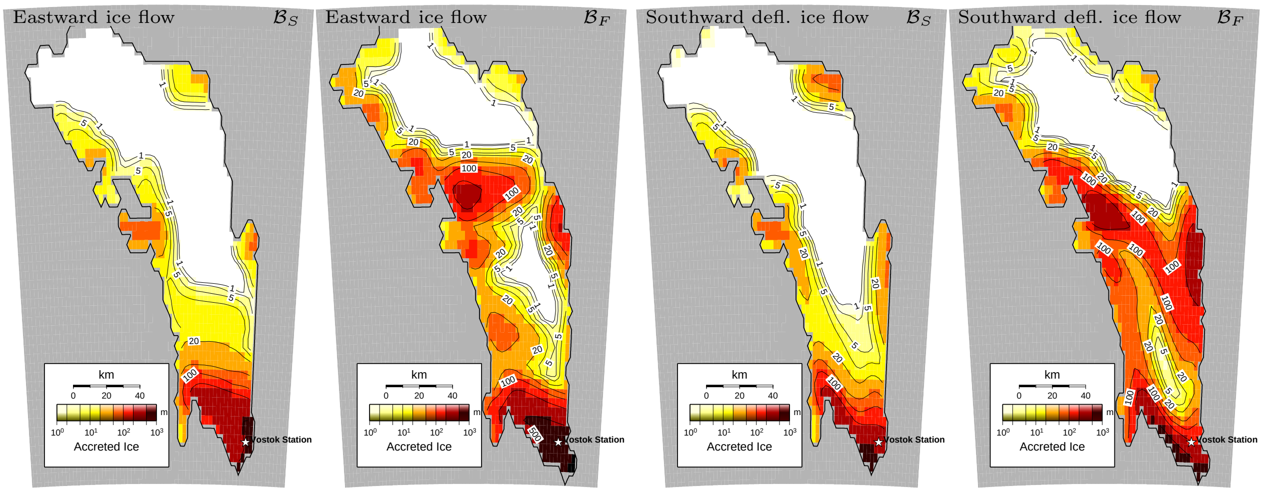

Figure 2. Modelled accreted ice thickness (in meter) at the ice–lake interface for the bathymetry models $\mathcal{B}_S$ of *Studinger et al.* [2004] and $\mathcal{B}_F$ of *Filina et al.* [2008] for an ice velocity of 4 m/a. The corresponding ice flow line direction is indicated.