Modelling tracer dispersion in subglacial Lake Vostok, Antarctica

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Summary Lake Vostok, isolated from direct exchange with the atmosphere by about 4 km of ice for millions of years, provides a unique environment. This inaccessibility raises the importance of numerical models to investigate the physical conditions within the lake. A topographic ridge splits the lake into a northern and southern part. Basic considerations reveal that the high pressure leads to convective flow in the lake. Using a three dimensional numerical model and the best available geometry, we analyse the baroclinic flow and the tracer dispersion within the lake. From our model experiments we find a different representation of the flow regime in the northern and southern basins. In the north and the northern part of the southern basin, where melting at the ice base dominates, convection provides a vertically well-mixed water column. In the south, where Vostok Station is located, basal freezing across about 3500 km^2 provides a vertically stable stratification of the water column's upper half. The different vertical stratifications lead to tracer concentration gradients in the water column which will influence the information retrieved from the Vostok ice core. The time needed for tracers to dissipate across the whole lake is strongly dependent on the location where they are released and amounts from years to decades.

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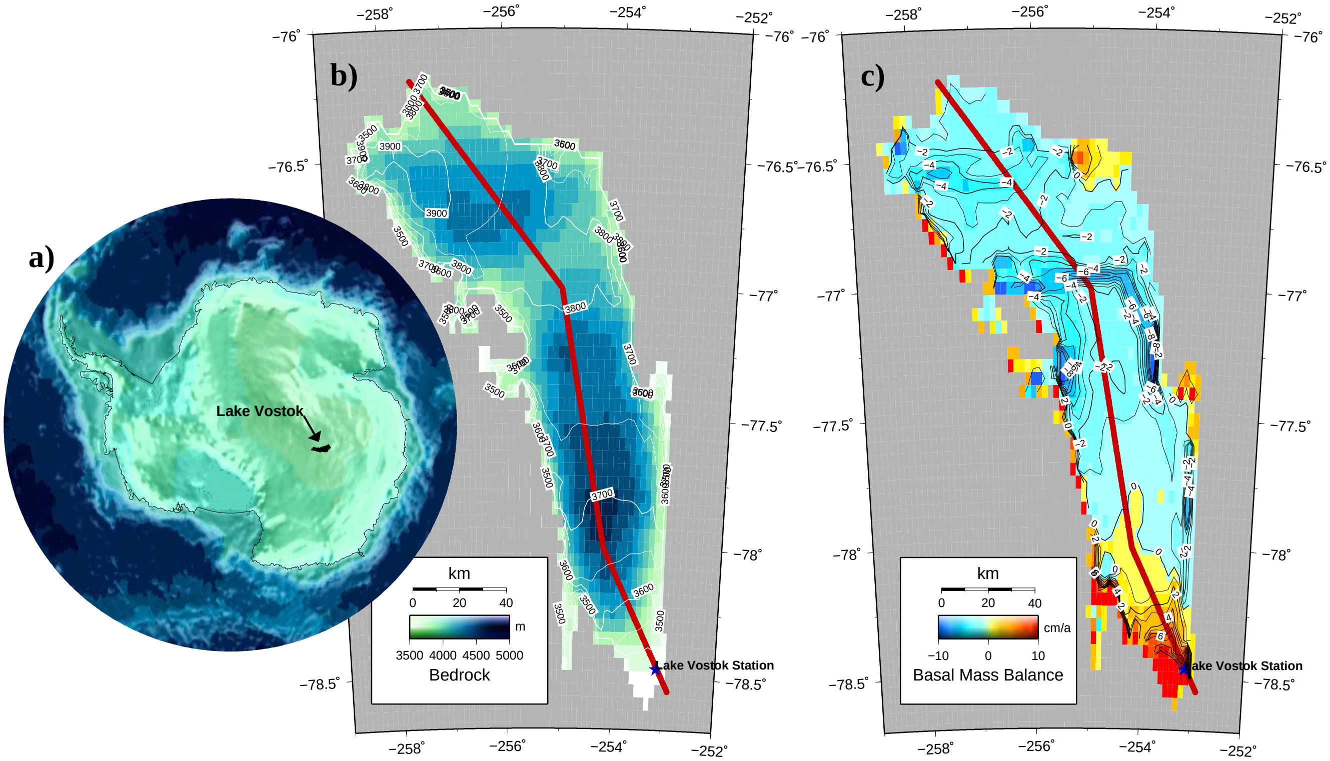

Figure 1. a) Lakes Vostok position in the Antarctic ice shield, b) Bathymetry of Lake Vostok, ice draft is shown as contours, and c) modelled basal mass balance at the ice-lake interface. The red lines indicates a profile track and the blue dots the position of the Russian research station.

Introduction

Lake Vostok lies in the heart of the Antarctic continent hidden beneath 4 km of ice (Figure 1a). The lake has been covered by the vast Antarctic Ice Sheet for up to 25 million years. The extreme inaccessibility of the water body makes direct measurements in the lake difficult. Hence, numerical models can contribute to a great extent to pre-investigate the lake's environment. During the last few years a wealth of information about the physiography and the physical conditions of subglacial Lake Vostok has been gathered. According to these new findings (Studinger et al., 2004), Lake Vostok is separated into two sub-basins by a shallow ridge of about 20 km width and a water column thickness of about 250 m. The southern basin has a water column thickness up to 870 m while the northern basin is slightly shallower with a water column thickness not exceeding 500 m (Figure 1b). This improved bathymetry is used as geometric boundary condition for the three-dimensional fluid dynamics model ROMBAX (Thoma et al., 2006), which is a revised version of a $\sigma-$coordinate ocean model (Grosfeld et al., 1997). New approximations of physical processes are added to take into account the uncommon conditions in subglacial Lake Vostok; these are described in more detail in Mayer et al. (2003) and Thoma et al. (2007).

Stability, circulation and tracer dispersion within Lake Vostok

The circulation within Lake Vostok is driven solely by buoyancy forces between water masses of different temperatures (in this study a pure freshwater model is used). These differences result from the geothermal heat source at the bottom, conductive heat loss into the ice, as well as latent heat sinks and sources due to melting and freezing processes at the ice-ocean interface. Figure 2 shows that for depths below about 2000 m the lake density decreases with increasing temperature, which range between -3.1°C and -2.8°C in Lake Vostok. Hence, geothermal heating at the bottom and cooling at the surface by conduction and melting (the latter is present in most areas of the lake, see Figure 1c) leads to vertically unstable conditions. Based on a standard model configuration, presented in Thoma et al. (2007), we release passive colour tracers at different sites within Lake Vostok after 150 years of integration time in order to investigate the lake's flow regime in more detail. The flow at the bottom and top along the terrain following layers is given by black arrows in Figures 3 and 4, respectively. In general, the baroclinic flow within Lake Vostok can be separated into three regimes: A week overturning cell in the northern basin, a stronger overturning cell in the northern part of the southern basin, and a gyre-like flow in the southern part of Lake Vostok where freezing takes place (Figure 1c). Upwelling dominates in the eastern part of Lake Vostok, while downwelling is mostly located along the western half. More details and discussion of the flow, the temperature distribution as well as the basal mass balance of the ice is given in Thoma et al. (2007). Here we concentrate on the tracer dispersion. Figures 3 and 4 show plane views (upper rows) and corresponding cross sections (lower rows) of tracers released in the northern (Figures 3a-b, 4a-b), south-western (Figures 3c-d, 4c-d), and south-eastern (Figures 3e-f, 4e-f) basin; brown arrows in the plane views indicate positions where the tracers are released, respectively. Green (orange) colours indicate tracers released at the bottom (ice-lake interface).

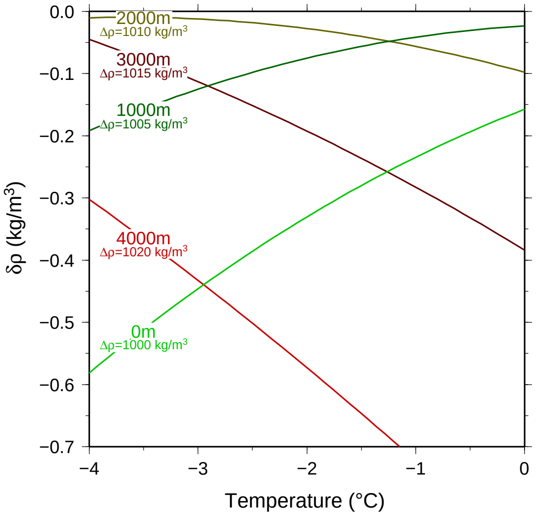

Figure 2. Relative potential density (Jackett and McDougall, 1995) of freshwater for specified depth and temperatures. The offset $\Delta\rho$ is given for each depth, respectively, and the potential density is given as $\rho = \Delta\rho + \delta\rho$.

Discussion

The calculated tracer propagation shown in Figures 3 and 4 are subject to a concentration threshold of 20%. Figure 2 indicates that for freshwater under about 4000 m of ice buoyancy strongly increases with temperature. Hence, in the northern basin cooling of the upper layer by ice melt (Figure 1c) and geothermal heat released at the bottom results in a vertically well mixed water column. This results in a swift balance of tracer concentrations in this part of the lake (Figure 3b, 4b) and independence of the horizontal tracer dispersal (Figure 3a, 4a) from the depth at which tracers are released. Figures 3a-b and 4a-b also show that after a residence time of about 10 years the 20% tracer-concentration-level propagates into the southern basin along the eastern edge of the lake, following the flow in the lower part of the water column. Since freezing mainly takes place in the southern part of the lake (Figure 1c), the addition of heat associated with crystallisation results in the stratification of the upper water column (Thoma et al., 2007), while temperature driven instabilities still dominate the lower parts. Hence, tracers released close to the bottom in the southern part of the lake (Figure 3c-f) are swiftly mixed into intermediate water depths, where corresponding flow components guide them northward (not shown), while tracers released in the upper layers (Figure 4c-f) are much longer confined there. Actually, the 20% tracer-concentration-level from the upper layers within the southern part of the lake needs about ten years to dip 100 m deeper (Figure 4d,f). The eastward directed bottom flow in the southern basin results in fast and confined eastward propagation of tracers released in the western part (Figure 3c-d). In contrast, tracers released in the east (Figure 3e-f), are affected by upwelling (strongest in the eastern part of the lake where the bottom flow converges), so that they are more diffused and spread faster as their western counterpart. Conversely, tracers released in the upper layers at the western side of the southern basin (Figure 4c-d), where downwelling dominates, show a slightly faster downward spreading than tracers released on the eastern side (Figure 4e-f).

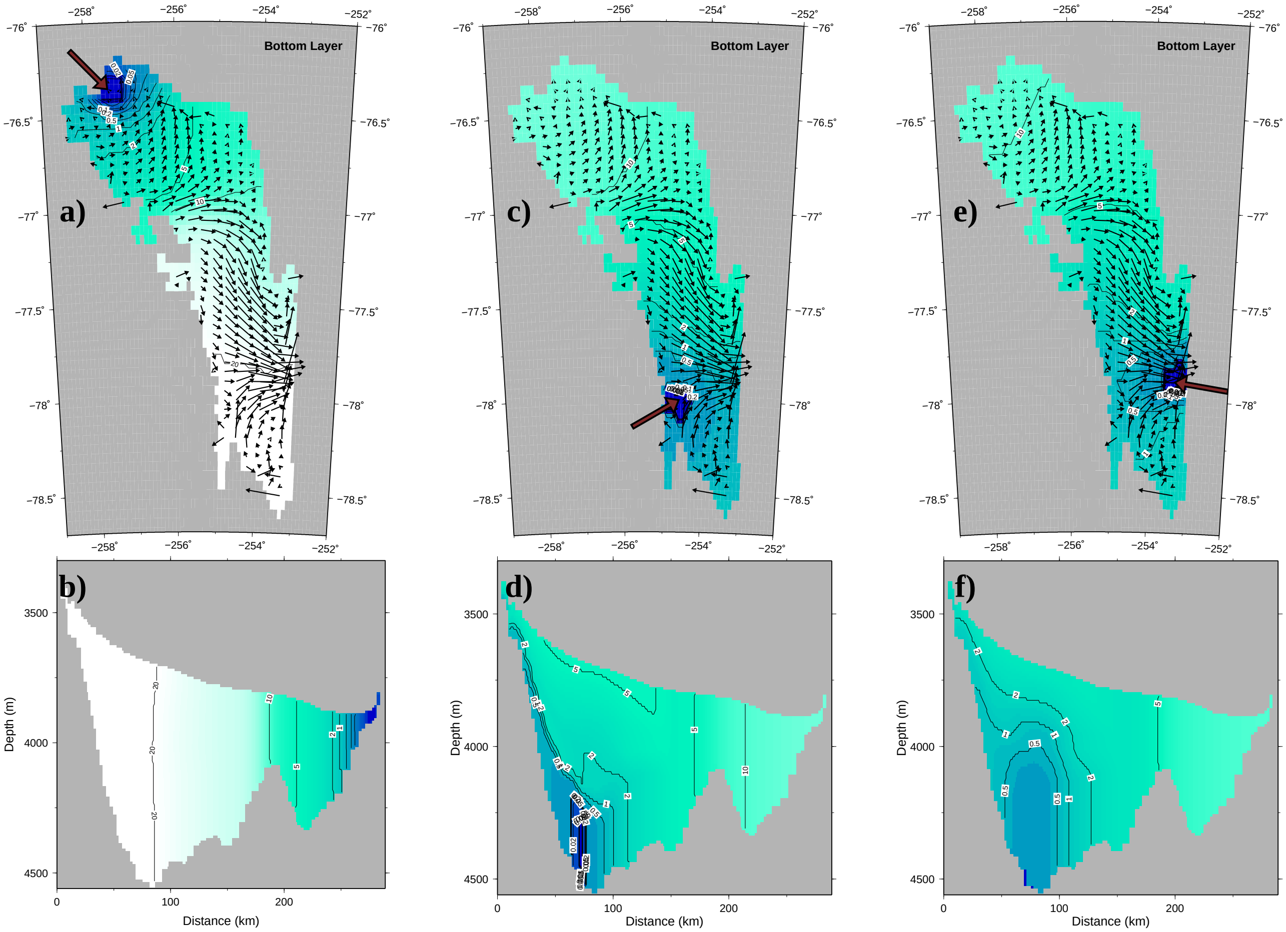

Figure 3. Passive tracer dispersion in years given in a logarithmic colour scale and contours for tracers injected in the bottom layer. In the upper row, brown arrows indicate positions where tracers are released and black arrows indicate bottom flow. The bottom row shows the corresponding cross-sections along the track shown in Figure 1.

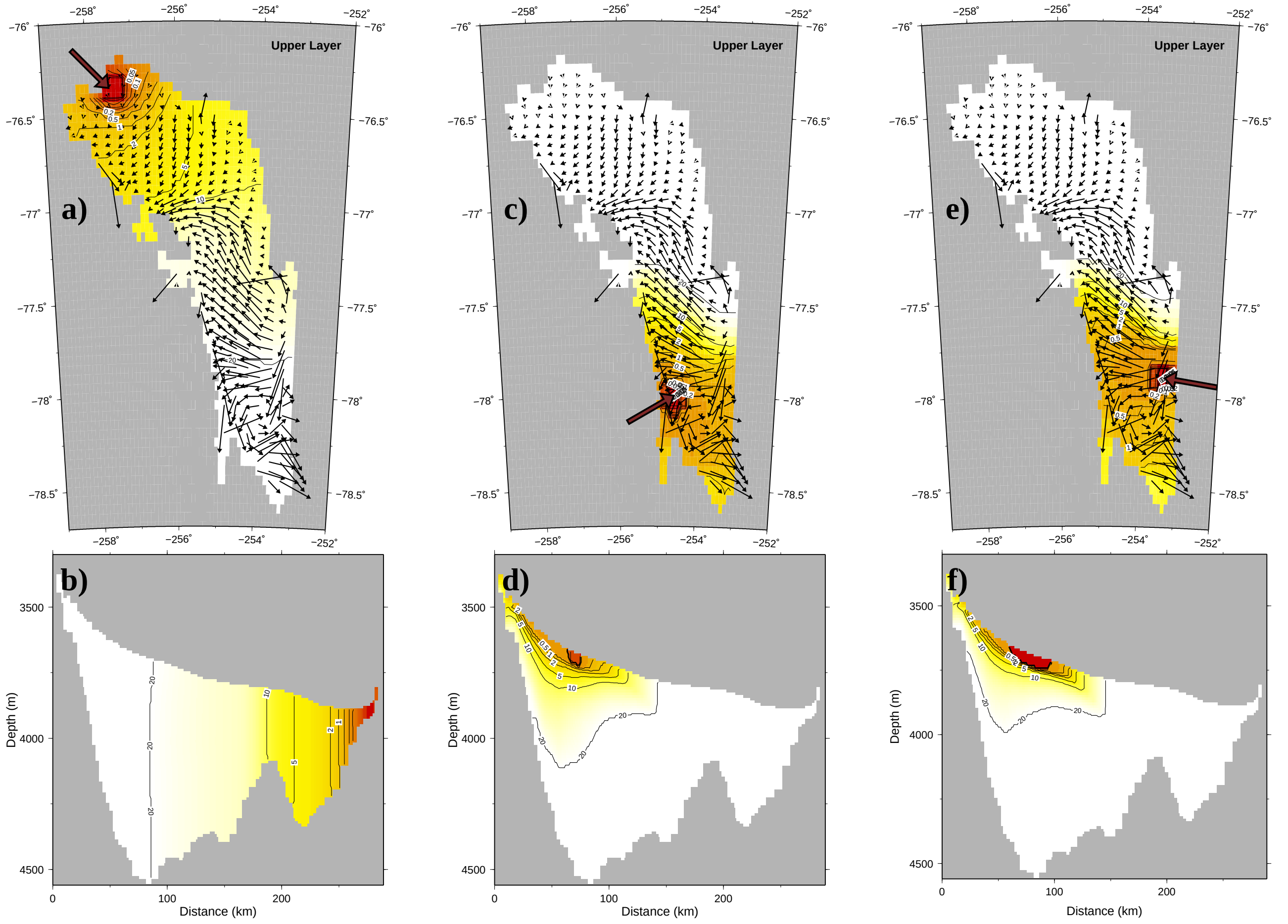

Figure 4. As for Figure 3, but for tracers released in the upper layer. Consequently black arrows indicate the flow in the upper layer.

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