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Causes of pre-collapse changes of the Larsen B ice shelf: Numerical modelling and assimilation of satellite observations

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Abstract

Satellite observations revealed that beside a rapid thinning, the Larsen B ice shelf (LBIS) was undergoing a significant acceleration before its collapse in 2002. This paper investigates the ice shelf acceleration between 1995 and 1999 using a combination of data assimilation and numerical modelling. Based on a flow model adjusted to the 1995 InSAR velocities, perturbation experiments are performed, such as ice front retreat, thinning, increase in tributary flow and rheological weakening. Furthermore, an inversion for ice shelf rheology and tributary flow velocity is performed for both the 1995 and the 1999 InSAR velocities. The perturbation experiments together with the inversion strongly suggest that the acceleration cannot solely be explained by the retreat of the ice shelf front but relies on a further significant rheological weakening of the already weak shear zones within the LBIS. Minor tributary acceleration is found to be an effect rather than a cause of the ice shelf acceleration. Furthermore, the observed acceleration cannot be explained by the observed recent thinning. We conclude that for smaller ice shelves such as the LBIS, such weak shear margins play a crucial role in controlling their dynamics and are the key to understand changes in the future. Finally, we compare the dynamic thinning likely to be associated with the observed acceleration with the observed thinning. For the ice shelf as a whole, this thinning accounts for 20% of the observed value, which implies that factors such as enhanced basal melt were the primary cause of the observed thinning.
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1. Introduction

Ice shelves have been found to play an important role for the dynamics of the Antarctic ice sheet, by buttressing the inland tributaries and thereby act as a coupling element between the ocean and the grounded inland ice (Alley et al., 2005). For example, observations and modelling work suggest that the recent rapid thinning and acceleration of the grounded part of Pine Island glacier in West Antarctica are responses of changes in its floating ice shelf (Rignot et al., 2002; Shepherd et al., 2002; Joughin et al., 2003; Payne et al., 2004; Dupont and Alley, 2005, 2006; Schmeltz et al., 2002). Accelerated flow and thinning have also been observed for the tributary glaciers of the Larsen ice shelf after its recent partial collapse (Scambos et al.,

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2004; Rignot et al., 2004). The disintegration of parts of the Larsen ice shelf (LIS) also illustrates how dynamic ice shelves are. Thus, understanding the controls of the dynamics of ice shelves is crucial in understanding the dynamics of the Antarctic ice sheet in particular in context of a warming climate.

Over the last few decades a significant and ongoing retreat of ice shelves has been observed on the Antarctic Peninsula and has been related to the strong warming the Antarctic Peninsula is experiencing since the 1950s (King, 1994; Vaughan et al., 2001). The most prominent example is the partial disintegration of the Larsen ice shelf (LIS; consisting of Larsen A, B and C) which is the largest ice shelf within the Antarctic Peninsula. In 1995 the Larsen A ice shelf (Rott et al., 1996) and in 2002 parts of the Larsen B ice shelf (LBIS) collapsed over periods of days or weeks. The mechanism of the collapse has been the focus of several studies (Rott et al., 1998; Scambos et al., 2000; MacAyeal et al., 2003) which suggest that the increased availability of surface meltwater due to the warming has a destabilizing effect on the ice shelf by enhancing crevasse fracture and therefore acts as a trigger for the collapse. However, previous to the collapse changes in the ice shelf dynamic have been detected on LIS. A thinning of the ice shelf of up 2.4 m a^{-1} has been detected by satellite altimetry between 1992 and 2001 (Shepherd et al., 2003). Observations from satellite interferometry for the LBIS revealed an acceleration in ice shelf flow of up to 50% (Rignot et al., 2004; Vieli et al., 2006). These changes suggest that the LBIS reacted to the changing climate significantly before its collapse. In contrast to the mechanism of ice shelf collapse, the causes and effects of these pre-collapse changes and in particular the link to the changing climate are poorly understood. It has been speculated that the observed thinning is mainly related to enhanced melting at the base of the ice shelf due to ocean warming and may have made the ice shelf susceptible to crevasse fracture (Shepherd et al., 2003).

This study aims to investigate controls and the temporal changes of the flow and the dynamics of the pre-collapsing Larsen B ice shelf, through combining a numerical ice shelf flow model with observations from satellite interferometry using data assimilation techniques. As in Vieli et al. (Vieli et al., 2006) we simultaneously optimize for ice rheology and the velocities at the ice shelf tributaries to adjust our model to the observed interferometric velocities, but here velocity data from two different time periods are used. On the basis of the adjusted model, we further perform forward modelling perturbation experiments to investigate the observed pre-collapse flow acceleration and the effect of the observed thinning on the dynamics of the LBIS.

Previous modelling studies mainly focussed on the stress field of the LBIS to investigate its instability due to crevasse fracture (Scambos et al., 2000; Doake et al., 1998) and the amount of observational data available to tune the models was limited to a few velocity point measurements (Rack et al., 2000). These authors also used a somewhat arbitrary pattern of rheological softening along the margins to match the observed ice shelf flow. The data assimilation technique used in this study provides a more objective method to adjust our ice flow model to the observations. Also, the velocity data coverage is almost continuous and much more extensive and importantly consists of data from two different time periods that allows to investigate temporal changes.

2. Methodology and data

2.1. Numerical model and data assimilation procedure

The flow model and assimilation method is described in Vieli et al. (2006) and consists of a numerical ice shelf model (the forward model) and the control method used to adjust the forward model and assimilate velocity observations from satellites. The model calculates the two dimensional horizontal flow of the ice shelf based on vertically integrated equations describing the leading-order stress balance of a floating ice mass (MacAyeal, 1989). It uses Glen's flow law (Glen, 1955) as constitutive equation for which the effective viscosity ν is given by

$$\nu = \frac{1}{2} B^{n} \tau^{1-n} \tag{1}$$

where τ is the effective stress, B is the vertically averaged rate factor or ice rheology (in Pa $a^{1/n}$) and the flow law exponent is $n=3$. Within the model, stresses are substituted by the appropriate strain-rate relations resulting in two tightly coupled, highly nonlinear elliptic equations involving the effective viscosity and the two (unknown) horizontal velocity components. Along the ice shelf/inland boundary the two vertically averaged velocity components are specified and at the ice shelf/ocean boundary the depth averaged sea water pressure is specified. Given the geometry of the ice shelf, the rheology field B and the velocities along the ice shelf boundaries, the model calculates the horizontal flow

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