Giulia Castellani

A THERMOMECHANICAL MODEL OF THE ANTARCTIC ICE SHELF

Università degli Studi di Milano
Facoltà di Scienze Matematiche, Fisiche e Naturali
Corso di Laurea Magistrale in Fisica
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Relatore: Prof. **Mauro Giudici**
Correlatore: Prof. Guido Parravicini
Correlatore: Dott. Chiara Vassena

1 Introduction

The Antarctic continent plays an essential role in the equilibrium of Earth's climate since it interacts with all the other parts of our planet (hydrosphere, atmosphere and lithosphere) through exchanges of energy and mass. Antarctica regulates the atmospheric and oceanic circulation, in fact the great difference in temperature from the pole to the equator creates the gradient force which governs the global circulation. Moreover, the Antarctic ice-sheet stores 80% of the world fresh water [Manzoni, 2001] and its reaction to climate forcing affects sea level rising worldwide. It is thus clear the importance of understanting the behaviour of the continent as reaction to the future climate changes. A first step in this direction is made by studying the past behaviour of the continent and a tool whidely used in this context is the development of numerical models [Huybrechts, 1992]. Within this framework, the aim of this work is to develop a model which is able to describe the evolution of the Antarctic continent during the last 220000 years and to study the response of the continent to changes in temperature and snowfall, paying particular attention to the behaviour of the ice-shelves.

2 Model development

In order to develop the numerical model, the fundamental equations governing the dynamics of glaciers [Paterson, 1994] are introduced: the constitutive relation for glaciers' flow known as *Glen's flow law*, which states that the strain rate has a non-linear dependance on the deviatoric stresses and on temperature; the mass conservation law, that for glaciers leads to the formulation of the so-called *ice-sheet equation*; the stress-equilibrium equation that for glaciers and ice-sheets reduces to the system of *Stokes' equations* and finally the general energy equation that describes the temperature evolution in a glacier. For all these equations, proper bounday conditions are presented. These equations are applied to the case of an ice-sheet with the introduction of the *shallow-ice-approximation* (SIA), based on the assumption that the horizontal extent of an ice-sheet is much bigger than its thickness [Baratelli et al., 2011], which allows the easily determination of the velocity field. The general relation for the basal sliding used in ice sheet modeling is introduced and discussed. In the case of floating ice-shelves the diagnostic equations for the determination of the velocity field are introduced through the *reduced model* by ([Cliff and Morland, 2004] and [Weis et al., 1999]), based as well on the small ratio of horizontal extent on ice thickness.

At the separation line between *grounded* ice and *floating* ice, called *grounding line*, kinematic boundary conditions are assigned: the depth-averaged velocity computed in the ice-sheet is assigned as boundary condition for the velocity in the ice-shelves. In order to compute the position of the grounding line we use the flotation criterion given by:

$$\rho H = \rho_w (z_{\mathrm{sl}} - b) , \tag{1}$$

where z_{sl} is the height of the sea level, ρ is the density of the ice, ρ_w is the density of the sea water and b is the topography. Finally the simplified equations are discretized with a finite difference scheme on a staggered grid and the iterative methods for the solution of the system of non linear algebraic equations that constitute the numerical model are recalled. The model has been implemented with a computer code developed from scratch and written in FORTRAN language. The model validation is performed by applying it to the case of a simple bedrock geometry in order to investigate possible problems of numerical instability due to the presence of ice shelves and to thermomechanical coupling. The developed model is finally applied to the Antarctic continent.

3 Results

The data needed as input data for the model are: topography [Nitsche et al., 2007], surface temperature [Comiso, 2000], geothermal heat flux [Shapiro and Ritzwoller, 2004], accumulation [Vaughan et al., 1999] and present day surface elevation [Bamber et al., 2009a] e [Bamber et al., 2009b]. The Vostok core [Petit et al., 1999] provides us with the temperature variations and the accumulation rate that can be used as climate forcing for the past. Several tests have been carried on with different values for different parameters, such as the basal melting rate for the ice-shelves M_b, the averaged viscosity for the ice-shelves $\bar{\eta}$ and the basal sliding coefficient B. the values obtain for the volume of the ice-sheet V , for the maximum surface elevation z_{m} and for the surface elevation at Dome C z_{DC} are listed in Table (1).

Tests	M_b [m/y]	$\bar{\eta}$ [Pa $\cdot$ y]	B [m/y Pa]	V [m^3]	z_{m} [m]	z_{DC}[m]
F	0.4	$25 \cdot 10^6$	0.002	$39.7 \cdot 10^{15}$	4464	3699
G	0.4	$25 \cdot 10^6$	0.004	–	–	–
H	0.2	$25 \cdot 10^6$	0.001	$41 \cdot 10^{15}$	4488	3713
I	0.4	$30 \cdot 10^5$	0.001	$27.5 \cdot 10^{15}$	4464	3602
L	0.4	$10 \cdot 10^6$	0.001	$39 \cdot 10^{15}$	4483	3705
M	0.4	$60 \cdot 10^5$	0.001	$31.2 \cdot 10^{15}$	4479	3650
N	0.4	$65 \cdot 10^5$	0.001	$36.1 \cdot 10^{15}$	4483	3672
O	0.4	$70 \cdot 10^5$	0.001	$36.7 \cdot 10^{15}$	4475	3660
P	0.4	$50 \cdot 10^5$	0.001	$29.1 \cdot 10^{15}$	4473	3628

Table 1: Tests carried on with different values for the input parameters.

The test wich shows the best agreement with the present day configuration of the continent regarding ice thickness and ice extension is test **M**, although the total volume of the ice-sheet is still greater than the observed volume and the maximum height reached at Dome A exceeds of about 200 m (present values are $26 \cdot 10^{15}$ m^3 for the total volume e 4200 m for the maximum surface elevation, from [Baroni, 2001]). This might be due to the fact that we do not take into account the ice-streams which allow the discharge of ice from the continent to the sea.
For experiment **M**, we show in Figure (1) the ice thickness and the temperature of the ice at the base. For test **M**, a comparison between the modelled and the observed ([Bohlander et al., 2004] and [Bohlander et al., 2007]) grounding line position is proposed in Figure (2). There is good agreement between the modelled and observed lines but the modelled grounding line is not able to reproduce some details, this is due to the horizontal grid used, which has a wide spatial step (100 km).

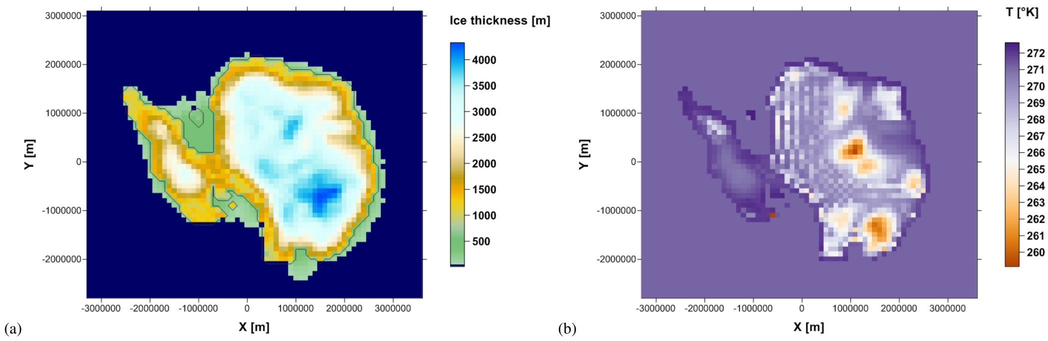

Figure 1: Ice thickness (a) and temperature at the base (b) obtained with experiment **M**. In figure (a) the black line represents the *grounding line*.

In Figure (3) the ice flux through the lateral sides of the ice-sheet and the difference in the response of ice-sheet and ice-shelves to temperature variations are shown. We can infer from Figure (a) that the trend shown by ice flux is in agreement with the trends of temperature and accumulation variations but it shows a temporal delay of about 1000 years, this is due to the time response of the continent. Form Figure (b) it is possible to see that the ice shelf is much more sensitive to the climate forcing than the ice sheet. This also means that ice-shelves are much more unstable than ice sheet and they will be the first to show variations due to global warming and climate change.

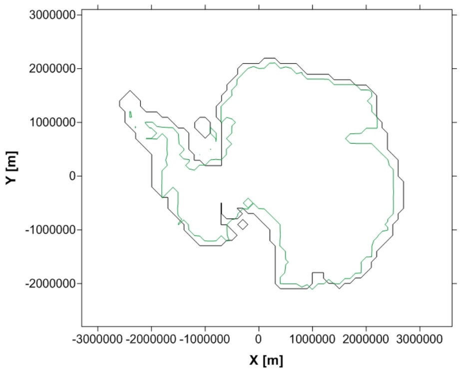

Figure 2: Comparison between the modelled (black) and the observed (green) grounding line position for test **M**.

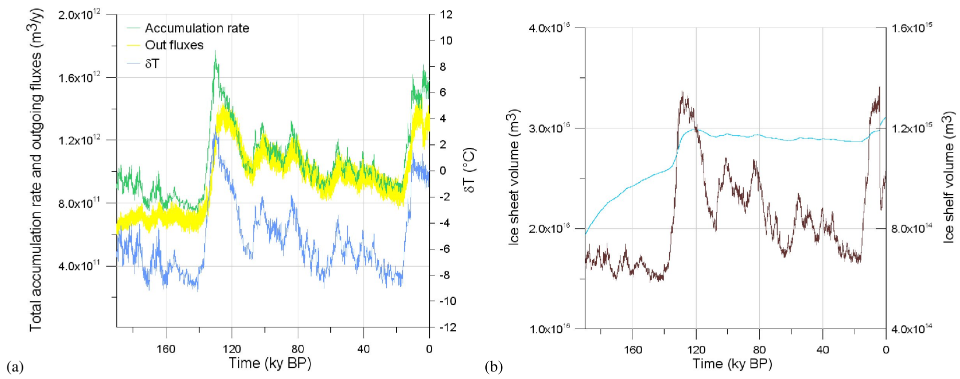

Figure 3: Figure (a): comparison between the temperature variation (blue line), the accumulation variations (green line) and the mass of ice flowing out to the ice sheet (yellow line) for test **M**. Figure (b): volume evolution in response to temperature variations of the ice sheet (blue line) and of the ice shelf (black line) for test **M**.

4 Conclusion

On the track of previous studies by several research groups from the early nineties, this thesis has faced the problem of modeling the response of marine ice-sheets to climatic changes in order to understand the possible response to future changes. The results are in good agreement with works from other european countries ([Ritz et al., 2001] and [Rommelaere and Ritz, 1996]).

With respect to previous thesis works, the main improvements of the model developed refer to the fact that it takes into account the different behaviour of the grounded and floating ice and faces the problem of the boundary conditions at the junction between ice-sheet and ice-shelves thus representing a first attempt in studying the problem of grounding line migration and ice shelves instabilities. The major factors that affect the model are the viscosity of the floating ice and the sea level changes, moreover the extension of the ice shelves is strongly affected by the basal melting rate at the separation between ice and ocean; this highlights the relevant role of the interaction between the ice sheet and the ocean through the floating ice-shelves and the necessity to investigate this problem, by improving models and by collecting field data.

A good fit of the present day configuration of the Antarctic continent has been reached, an optimization of the model can be obtained by the use of a finer grid and by the introduction of the dynamics of the ice-streams: both novelties could lead to a more detailed representation of the Antarctic ice dynamics.

The thesis work is the base of an article [Giudici et al., in press] which investigates the effects on several output of the model e.g., the velocity in the ice-shelves, the total volume, the melting rate at the base of the ice-sheet, due to uncertainties on the model parameters using a sensitivity analysis.

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